Estimation of Roughness Coefficients for Natural Stream Channels with Vegetated Banks

Water-Supply Paper 2441

Prepared in cooperation with
with the New York State
Department of Transportation

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By WILLIAM F. COON

Prepared in cooperation with the New York State
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U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2441

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
THOMAS J. CASADEVALL, Acting Director

1998

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Library of Congress Cataloging in Publication Data

Coon, William F.
Estimation of roughness coefficients for natural stream channels with vegetated banks / by William F. Coon ; prepared in cooperation with the New York State Department of Transportation.
p. cm. — (U.S. Geological Survey water-supply paper : 2441) Includes bibliographical references.
Supt. of Docs. no. : I19.13:W2441
1. Channels (hydraulic engineering) 2. Frictional resistance (Hydrodynamics) 3. Grassed waterways. I. New York (State). Dept. of Transportation. II. Title. III. Series.
TC175.C627 1997
627'.042—dc20 94–40178
CIP

ISBN 0-607-88701-X

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CONVERSION FACTORS

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square foot (ft^2)	0.09294	square meter
square mile (mi^2)	2.590	square kilometer
foot per second (ft/s)	0.3048	meter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
pound, avoirdupos (lb)	0.4536	kilogram
foot-pound per second per square foot ($[ft\text{-}lb/s]/ft^2$)	14.59	watt per square meter
pounds per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter

LIST OF SYMBOLS

- A Cross-sectional area of flow (ft^2).
- D Hydraulic or mean depth (ft).
- d_p Particle diameter that equals or exceeds that of p percent of the bed material (ft).
- F Froude number.
- g Gravitational acceleration constant (ft/s^2).
- h Hydraulic (piezometer) head (ft).
- h_f Energy loss due to boundary friction (ft).
- h_v Velocity head (ft).
- K Conveyance (ft^3/s).
- k Expansion or contraction energy-loss coefficient.
- L Length of channel reach (ft).
- L_m Channel meander length (ft).
- L_s Valley or straight-channel length (ft).
- m Adjustment factor for degree of channel meandering; total number of cross sections in a reach.
- n Manning's roughness coefficient ($ft^{1/6}$).
- n_0 Base value of n for the surface material of a straight, uniform channel ($ft^{1/6}$).
- n_1 Additive value of n to account for the effect of cross-section irregularity ($ft^{1/6}$).
- n_2 Additive value of n to account for variations in size and shape of the channel ($ft^{1/6}$).
- n_3 Additive value of n to account for the effect of obstructions ($ft^{1/6}$).
- n_4 Additive value of n to account for the type and density of vegetation ($ft^{1/6}$).
- P Wetted perimeter (ft).
- Q Discharge (ft^3/s).
- R Hydraulic radius (ft).
- R/d_p Relative smoothness.
- S_f Energy gradient or friction slope (ft/ft).
- S_w Slope of water surface (ft/ft).
- SP Stream power [(ft-lb/s)/ft^2].
- T Top width of stream (ft).
- V Mean velocity of flow (ft/s).
- $\propto$ Velocity-head or kinetic-energy coefficient.
- θ Angle of channel slope (degrees).

GLOSSARY OF TERMS

Bank, left and right. Reference terms used to specify whether a bank is on one's left or right when one is facing downstream.

Bedform. Alluvial-channel-bottom feature whose form is dependent on bed-material size, flow depth, and flow velocity. Bedforms are ripples, dunes, antidunes, and plane bed.

Conveyance. A measure of the carrying capacity of a channel section, defined by the equation

$$K = (1.486/n)AR^{2/3}$$

where
- K = conveyance, in cubic feet per second;
- n = Manning's roughness coefficient, in feet$^{1/6}$;
- A = cross-sectional area of flow, in square feet; and
- R = hydraulic radius, in feet.

Correlation coefficient. A numerical expression of the degree of association between two variables. A positive correlation coefficient indicates that one variable increases as the other increases; a negative correlation coefficient indicates that one variable increases as the other decreases. The value of the correlation coefficient lies between +1.0 and −1.0; the closer the correlation value is to +1.0 or −1.0, the greater the degree of association.

Crest-stage gage. A device for recording the peak water-surface elevation during a flood by means of a cork line that adheres to a 1-inch-diameter wooden rod placed inside a 2-inch-diameter metal pipe that has been secured to a tree or pipe post.

Cross-sectional area of flow. The cross-sectional area of the water normal to the direction of flow in a channel.

Degree of meandering. As used with Cowan's (1956) method of roughness-coefficient estimation, the ratio of channel meander length, L_m, to valley or straight-channel length of a reach under consideration, L_s.

Energy gradient. Also referred to as friction slope; energy gradient is the slope of the line that represents the elevation of the total head of flow in an open channel. It is computed as the energy loss due to boundary friction per foot of a channel's length.

Flow regime. A range of flows producing similar bedforms, resistance to flow, and mode of sediment transport. The lower flow regime occurs with low discharges and produces bedforms of ripples, ripples on dunes, or dunes. The upper flow regime occurs with high discharges and produces bedforms of plane bed with sediment moving, standing waves, antidunes, or chutes and pools. Between these two stable regimes is the transition regime, which produces instability in the stage-to-discharge relations and in the typical bedforms.

Froude number. A ratio of inertial forces to gravitational forces, defined by the equation

$$F = V/(gD \cos \theta/\propto)^{0.5}$$

where
- F = Froude number;
- V = mean velocity of flow, in feet per second;
- g = gravitational acceleration constant, in feet per second squared, that equals 32.2;
- D = hydraulic or mean depth, in feet;
- θ = angle of the channel slope, in degrees; and
- $\propto$ = velocity-head coefficient.

Grain size, coarse and fine. Coarse-grained bed material generally refers to those particles (gravel, cobble, boulder) whose size can be individually measured with a graduated rule or caliper; fine-grained material (sand, silt, clay) is measured by passage through a sieve or by rate of sedimentation. See also particle size.

Hydraulic depth. See mean depth.

Hydraulic radius. The ratio of the stream channel's cross-sectional area to its wetted perimeter in a plane normal to the direction of flow.

Manning's roughness coefficient (*n* value). A measure of the frictional resistance exerted by a channel on flow. The *n* value can also reflect other energy losses, such as those resulting from unsteady flow, extreme turbulence, and transport of suspended material and debris, that are difficult or impossible to isolate and quantify.

Base *n* value. Manning's roughness coefficient that quantifies the minimum roughness of a straight, uniformly shaped channel reach in the natural material involved. This value reflects only the boundary friction from the bed and bank sediments and does not include additive effects from other flow-retarding factors, such as channel-shape variation, obstructions, and vegetation.

Computed *n* value. As used in this report, a Manning's roughness coefficient that has been computed from known discharge, channel geometry, and water-surface profile. This *n* value reflects a stage-specific *n* value with or without increments of roughness attributable to vegetation, obstructions, and other flow-retarding factors.

Estimated *n* value. As used in this report, a Manning's roughness coefficient that has been obtained in one of the following ways: (1) computed from an *n*-value equation, (2) selected from a published *n*-value table, or (3) estimated by comparison with photographs of channels for which *n* values have been computed.

Mean depth. Also referred to as hydraulic depth; mean depth is the stream channel's cross-sectional area of flow divided by the top width of the free surface of water.

Particle size. The size of material on the bed of a stream, referenced to a specific diameter (either maximum, intermediate, or minimum) of the measured particles.

d_{50} —The particle diameter that equals or exceeds that of 50 percent of the particles—that is, the median size of the bed material.

d_{84} —The particle diameter that equals or exceeds that of 84 percent of the particles.

Relative smoothness. The ratio of hydraulic radius, R, or mean (or hydraulic) depth, D, to a characteristic particle size of the bed material, such as d_{50} or d_{84}.

Relative submergence. As used by Bathurst and others (1981), has the same meaning as relative smoothness; the ratio of depth to a characteristic element height (particle size) of the bed material.

Scale of roughness, small and large. Small-scale roughness refers to bed material of small particle size in relation to the depth of flow. Large-scale roughness refers to bed material of a particle size the same order of magnitude as the depth of flow. Bathurst and others (1981) have defined the scale of roughness by the ratio of mean depth, D, to the median size of the intermediate particle dimension, d_{50}, in the following way:

small-scale roughness: D/d_{50} greater than 7.5;

intermediate-scale roughness: D/d_{50} between 2 and 7.5; and

large-scale roughness: D/d_{50} less than 2.

Slope, friction. See energy gradient.

Slope, water-surface. The slope of the water surface, computed as the change in elevation per foot of a channel's length.

Slope-area method of discharge measurement. A computational procedure whereby stream discharge is calculated "on the basis of a uniform-flow equation involving channel characteristics, water-surface profiles, and a roughness or retardation coefficient" (Dalrymple and Benson, 1967).

Stream power. A measure of energy transfer; used in computing the regime of flow in sand channels and defined by the equation

$$SP = 62RS_wV$$

where

SP = stream power, in foot-pounds per second per square foot;
62 = approximate specific weight of water, in pounds per cubic foot;
R = hydraulic radius, in feet;
S_w = slope of water surface, in feet per foot; and
V = mean velocity of flow, in feet per second.

Submergence, percentage of. The amount of vegetation submerged at a given flow depth, or the ratio of the depth of inundation to the height of vegetation.

Top width of stream. Width of the free surface of water in a cross-sectional plane normal to the direction of flow in a channel.

Vegetation index. As used in this report, a numerical value that represents the type and relative density of streambank vegetation.

Velocity-head coefficient. A factor used to adjust the velocity head computed from the mean velocity in a channel section to give the true mean kinetic energy of the flow for nonuniform distribution of velocities.

Water-surface profile. A longitudinal plot of the water-surface elevation as a function of the distance downstream through a channel reach.

Wetted perimeter. The length of the line of intersection of the channel's wetted surface with a cross-sectional plane normal to the direction of flow.

Estimation of Roughness Coefficients for Natural Stream Channels with Vegetated Banks

By William F. Coon

Abstract

Water-surface profiles were recorded, and Manning's roughness coefficients were computed for a wide range of discharges at 21 sites on unregulated streams in New York State, excluding Long Island. All sites are at or near U.S. Geological Survey streamflow-gaging stations at which stage-to-discharge relations are relatively stable and overbank flow is absent or minimal. Crest-stage gages were used to record water-surface profiles. The channels in the study have the following ranges in hydraulic characteristics: hydraulic radius, 0.91 to 13.4 feet; water-surface slope, 0.0003 to 0.014; and instantaneous or peak discharge, 77 to 51,700 cubic feet per second. The 84th percentile of the intermediate diameter of bed material ranges from 0.14 to 3.0 feet. Computed Manning's roughness coefficients (*n* values) range from 0.024 to 0.129. On channels with coarse-grained bed material, the relation between the computed *n* value and flow depth can be predicted from the energy gradient, relative smoothness (ratio of hydraulic radius or mean depth to a characteristic particle size of the bed material), stream-top width, and channel-vegetation density. The percentage of wetted perimeter that is vegetated can be used as an indicator of energy losses that are attributable to streambank vegetation. Bank vegetation generally has no measurable effect on the roughness coefficients of streams wider than 100 feet if less than 25 percent of the wetted perimeter is vegetated. For wide channels in which larger percentages of wetted perimeter are vegetated, bank vegetation appears to have a small additive effect on the roughness coefficient. On narrow channels (30 to 63 feet wide) in which the wetted perimeter is typically more than 25 percent vegetated, the magnitude of the energy-loss effect of streambank vegetation depends on the season and on the type, density, and percent submergence of the vegetation. The presence of trees and brush on the banks of narrow channels increased the *n* value by as much as 0.005 in the nongrowing season and by an additional 0.002 to 0.012 during the growing season. This report discusses common methods of estimating Manning's roughness coefficients for stream channels, including use of published *n*-value data, comparison with photographs of channels for which *n* values have been computed, and *n*-value equations. It also describes a procedure for evaluating flow-retarding factors of a channel and contains photographs and hydraulic data on the 21 channels studied.

INTRODUCTION

Calculations of stream discharge and floodwater elevations require evaluation of the flow-impeding characteristics of stream channels and their banks. Manning's roughness coefficient (*n*) is commonly used to assign a quantitative value to represent the collective effect of these characteristics. The procedure for estimating *n* values generally is subjective, and the accuracy is largely dependent on a hydrologist's or engineer's experience in estimating these values over a wide range of hydraulic conditions. Even experienced hydrologists sometimes have difficulty in assessing accurately all the factors that contribute to flow resistance. For example, Riggs (1976) compared computed roughness coefficients for 30 reaches in the United States (from Barnes, 1967) with *n* values estimated by experienced hydrologists and concluded that experienced hydrologists can make acceptable estimates of n values for many, but not all, channels. Trieste and Jarrett (1987) noted that n values that were estimated by experienced hydrologists for five large floods (overflowing the bank) in natural channels were, on the average, about one-half of the computed values.

The roughness coefficient incorporates the many factors that contribute to the loss of energy in a stream channel. The major factor is channel-surface roughness, which is determined by the size, shape, and distribution of the grains of material that line the bed and sides of the channel (the wetted perimeter). Five other main factors are channel-surface irregularity, channel-shape variation, obstructions, type and density of vegetation, and degree of meandering (Cowan, 1956). Five additional factors that affect energy loss in a channel are depth of flow, seasonal changes in vegetation, amount of suspended material, bedload, and changes in channel configuration due to deposition and scouring (Chow, 1959). Several other factors that contribute to energy losses during large floods are unsteady flow, flood-plain flow that crosses the main channel in a meander bend, transport and jamming of debris, extreme turbulence, bedforms in noncohesive bed material, and shear stresses at the interface between flood plain and main channel (Trieste and Jarrett, 1987). The interaction of two or more of these factors could further affect channel-energy loss. Although these factors are identifiable, their individual contributions to the total roughness are difficult, if not impossible, to quantify. As a result, several methods for estimating n values have been developed.

In response to a need for assessment of roughness coefficients that are representative of channels throughout New York State, the U.S. Geological Survey (USGS), in cooperation with the New York State Department of Transportation, conducted a statewide roughness-coefficient study during 1983–88. Objectives were to (1) compute Manning's roughness coefficients (n) for selected channels with characteristics representative of New York streams; (2) quantify the increment of flow resistance that could be attributed to specific flow-retarding factors, particularly streambank vegetation; (3) assess the transferability of these values to other streams; and (4) compile and maintain for each site a file that contains a site description, hydraulic data, and photographs or slides that could be used for office- and field-training exercises.

Purpose and Scope

This report (1) summarizes related roughness-coefficient studies and discusses methods commonly used for estimating Manning's roughness coefficient; (2) presents the methods of n-value calculation, site selection, and data collection and computation for the 21 selected sites; (3) presents photographs and computed roughness coefficients and corresponding hydraulic data for a range of discharges at each of the study sites; (4) describes the change in roughness coefficient associated with some of the major factors that influence roughness coefficients—flow depth, energy gradient, size of bed material, and bank vegetation; (5) evaluates published n-value equations and their ability to reproduce the n values calculated from the study-site data; and (6) presents a procedure for assigning n values to natural channels not studied.

Review of Related Studies and Common Methods for Estimating Roughness Coefficients

The hydraulic complexities involved in estimating roughness coefficients have led to the development of several roughness-evaluation aids, including n-value tables, photographs for comparison, and equations. An estimation process developed by Cowan (1956) is commonly used to assign increments of "roughness," or adjustments, to the n value to account for the energy-loss effects attributable to major flow-retarding factors. Although these aids do not eliminate subjectivity in the selection of n values, they simplify the estimation process by including only the most significant flow-resisting factors on the assumption that the remaining factors have a negligible effect. These methods for estimating roughness coefficients and studies that deal with the energy-loss effect of vegetation are discussed in the following sections.

Published Coefficients

Benson and Dalrymple (1967), Chow (1959), and Bray (1979) present basic roughness coefficients that are based on the median particle size of the bed material that forms the wetted perimeter. Their works give ranges of base values for five natural-channel materials: firm earth, sand, gravel, cobbles, and boulders (table 1). The roughness coefficients that are selected for sand-bed channels require additional evaluation. Resistance to flow in sand-bed streams varies

Table 1. Base values of Manning's roughness coefficient

[Modified from Aldridge and Garrett (1973, table 1); —, no value given; >, greater than]

Type of channel and bed material	Median size or range of bed material		Base n value		
	Millimeters	Inches	Benson and Dalrymple (1967)[1]	Chow (1959)[2]	Bray (1979)
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					
Concrete	—	—	0.012–0.018	0.011	—
Rock cut	—	—	—	.025	—
Firm earth	—	—	0.025–0.032	.020	—
Coarse sand	1–2	0.04–0.08	0.026–0.035	—	—
Fine gravel	4–8	0.16–0.03	—	.024	—
Gravel	2–64	0.08–2.5	0.028–0.035	—	—
Coarse gravel	16–32	0.6–1.3	—	.028	—
Very coarse gravel	32–64	1.3–2.5	—	—	.032
Small cobble	64–128	2.5–5.0	—	—	.036
Cobble	64–256	2.5–10.1	0.030–0.050	—	—
Boulder	>256	>10.1	0.040–0.070	—	—

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

greatly and is a function of the velocity of flow, grain size, shear, and other variables. Together these variables determine the bedform that the movable bed material will take for a given discharge. The flows that produce the bedforms are classified as lower regime, transition regime, and upper regime (Simons and Richardson, 1966). The roughness coefficients for the lower and transition regimes are greatly affected by bedform roughness. No reliable method of selecting n values for these flow conditions has been developed. Roughness coefficients for the upper regime are largely dependent on the particle size and are given in table 1. After the hydraulic properties of a channel reach have been computed, the reliability of an n value selected from table 1 must be checked by confirming that the flow is in the upper regime. This is done by computing stream power from the equation

$$SP = 62RS_wV \tag{1}$$

where

SP = stream power, in foot-pounds per second per square foot;

62 = approximate specific weight of water, in pounds per cubic foot;

R = hydraulic radius, in feet;

S_w = slope of water surface, in feet per foot; and

V = mean velocity of flow, in feet per second.

This value is then plotted on figure 1, which shows the relation of stream power and median grain size to the type of flow regime (from Benson and Dalrymple, 1967, fig. 7). If the stream-power value plots above the upper line, the bed configuration can be assumed to be in the upper regime. If it plots below this line, a reliable n value cannot be assigned. Simons and Richardson (1966), Benson and Dalrymple (1967), Aldridge and Garrett (1973), and Jarrett (1985) present further discussion on this topic.

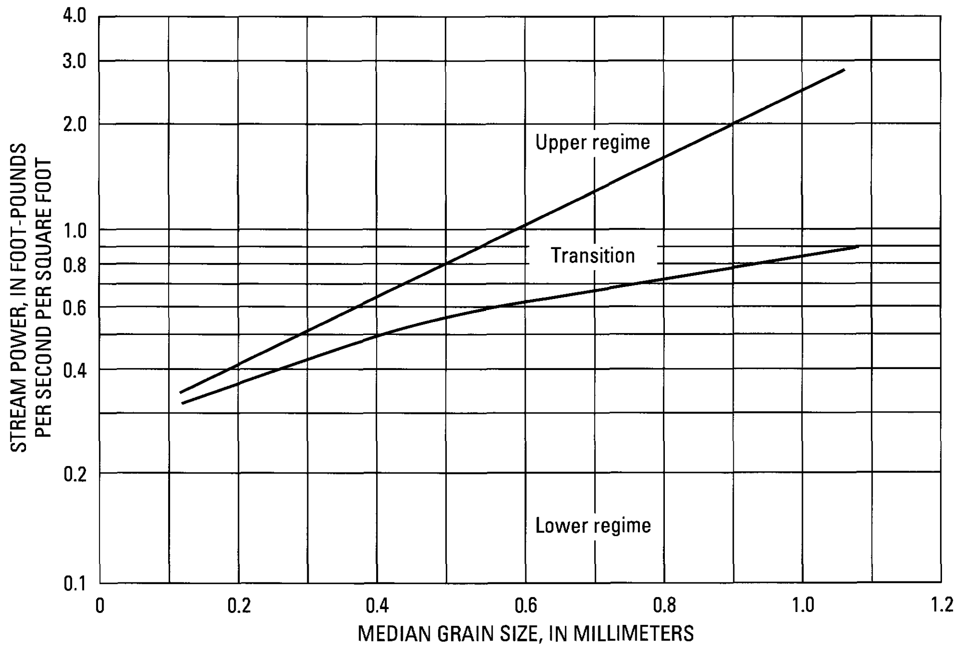


Figure 1. Relation of stream power and median grain size to type of flow regime (modified from Benson and Dalrymple, 1967, fig. 7).

Other tables of roughness coefficients can be found in hydraulic textbooks such as those by Chow (1959), Henderson (1966), and Brater and King (1976), and in channel-design manuals published by Federal agencies (U.S. Department of Agriculture, 1955; U.S. Department of Transportation, 1979). Tables 2 and 3 list values of Manning's roughness coefficient for natural channels and modified channels, respectively.

These tables represent a collection of data from many sources and include laboratory and (or) field computations of roughness coefficients for artificial, lined, excavated, dredged, and natural channels. Much of the tabulated data for natural streams results from several studies by the U.S. Department of Agriculture. For example, Ramser (1929) determined *n* values for drainage channels, Scobey (1939) for irrigation and similar canals, and Ree and Palmer (1949) for channels protected by vegetative linings. These studies present determinations of *n* values for given reaches under a range of flow conditions and provide the basis for the quantification of the increments of roughness that are attributable to five of the primary flow-retarding factors by Cowan (1956). (See section below, "Evaluation of Flow-Retarding Factors.")

Comparison of Photographs

The roughness coefficient associated with a given flow can be computed from known discharge, channel geometry, and water-surface elevations. Photographs of channels for which *n* values have been computed, along with particle-size and hydraulic data, have been published and can be used to compare with a site of interest and to estimate an *n* value. Ramser (1929) and Scobey (1939) present photographs of drainage channels and irrigation channels, respectively. Parts of these reports have been reproduced by Chow (1959) and Fasken (1963). Barnes (1967) illustrates 50 channels in color photographs of streams in the United States that represent a wide range of hydraulic characteristics. Aldridge and Garrett (1973) present photographs of 35 channels in Arizona, an arid region in which sand is a major constituent of the bed material; computed roughness coefficients are given for 6 of these sites, and estimates by experienced hydrologists are given for the other 29 sites.

Equations

Researchers have collected detailed data on natural channels for which roughness coefficients have been calculated and have attempted to identify and

Table 2. Values of Manning's roughness coefficient for natural channels
[Modified from Chow (1959, table 5–6), published with permission of McGraw-Hill]

Type of channel and description	Roughness coefficient		
	Minimum	Normal	Maximum
A. Minor streams (top width at flood stage less than 100 ft)			
1. Streams on plain:			
a. Clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
b. Same as above, but more stones and weeds	.030	.035	.040
c. Clean, winding, some pools and shoals	.033	.040	.045
d. Same as above, but some weeds and stones	.035	.045	.050
e. Same as above, lower stages more ineffective slopes and sections	.040	.048	.055
f. Same as type d, but more stones	.045	.050	.060
g. Sluggish reaches, weedy, deep pools	.050	.070	.080
h. Very weedy reaches, deep pools or floodways with heavy stand of timber and underbrush	.075	.100	.150
2. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages:			
a. Bottom: gravels, cobbles, and few boulders	.030	.040	.050
b. Bottom: cobbles and large boulders	.040	.050	.070
B. Major streams (top width at flood stage greater than 100 ft). The *n* value is less than that for minor streams of similar description because banks offer less effective resistance			
1. Regular section with no boulders or brush	.025	—	.060
2. Irregular and rough section	.035	—	.100

define by means of equations the relations between flow resistance and hydraulic and particle-size characteristics of stream channels. These equations can then be used to estimate *n* values at sites with characteristics similar to those of the sites used in the development of the equations. Six of these equations, which are representative of the many forms that have been proposed by other investigators, are presented and described below.

Limerinos, 1970

Limerinos (1970), using 50 measurements of discharge and appropriate field surveys at 11 sites in California, relates the *n* value to hydraulic radius and particle size, as follows:

$$n = \frac{(0.0926)R^{1/6}}{1.16 + 2.0\log(R/d_{84})} \quad (2)$$

where

R = hydraulic radius, in feet, and

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

Limerinos (1970) selected straight reaches that had little increase in width in the downstream direction, were relatively wide and of simple trapezoidal shape, and were relatively free of flow-retarding effects associated with irregular channel features and vegetation. In so doing, he attempted to isolate the effect of bed material on the roughness coefficient. Median sizes of bed material (d_{50}'s) ranged from 0.02 feet (ft) (small gravel) to 0.83 ft (cobbles), although the d_{50}'s at all but one site were less than or equal to 0.53 ft. Slopes were mostly less than 0.002 (as reported in Jarrett, 1985), and hydraulic radii were less than 11.0 ft. Bray (1979) analyzed many similar equations and concluded that the Limerinos equation (eq. 2) provides the most reliable estimate of Manning's roughness coefficient for high within-bank flows in gravel-bed channels with small bed-material transport and insignificant channel-bed vegetation.

Bray, 1979

If bed-material data needed for Limerinos's (1970) equation are unavailable, Bray (1979) presents an alternative equation that relates *n* to water-surface slope alone:

Table 3. Values of Manning's roughness coefficient for modified channels
[From Jarrett (1985, table 5)]

Type of channel and description	Roughness coefficient		
	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:			
a. Sides are formed concrete	.017	.020	.025
b. Sides are random stone in mortar	.020	.023	.026
c. Sides are 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. Short grass, few weeds	.022	.027	.033
2. Earth, winding and sluggish:			
a. No vegetation	.023	.025	.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

$$n = 0.104 S_w^{0.177} \qquad (3)$$

where S_w = slope of water surface, in feet per foot.

This equation is based on high within-bank flow data from 67 gravel-bed river reaches in Alberta, Canada, where the intermediate d_{50} ranges from 0.06 to 0.48 ft. Sites that were selected had minimal bed-material transport, no significant vegetation in the channel bed, and no dominant bedform features. Water-surface slopes range from 0.00022 to 0.015, and channel widths from 47 to 1,790 ft. Ratios of mean (or hydraulic) depth to d_{50} (D/d_{50}) are between 5 and 166. Benson and Dalrymple (1967) point out that in wide, uniform channels where D/d_{50} is between 5 and 276, the roughness coefficient generally is expected to remain relatively constant with changing stage. The absence of a depth term in this equation reflects this conclusion. Therefore, this equation is inappropriate for channels where the n value is expected to vary with flow depth, such as high-gradient mountain streams and narrow channels with dense streambank vegetation.

Jarrett, 1984

Jarrett (1984), using 75 measurements of discharge and hydraulic geometry on 21 cobble- and boulder-bed mountain streams in Colorado, relates n

values for high-gradient streams to hydraulic radius and energy gradient, as follows:

$$n = 0.39 S_f^{0.38} R^{-0.16} \tag{4}$$

where

S_f = energy gradient, in feet per foot, and

R = hydraulic radius, in feet.

This equation is applicable to channels with energy gradients from 0.002 to 0.09 (Jarrett, 1990) and hydraulic radii from 0.5 to 7 ft. Jarrett (U.S. Geological Survey, oral commun., 1990) points out that, for channels in which the hydraulic radius is greater than 7 ft, the n value can be estimated from R = 7 ft in equation 4. This indicates that the roughness coefficient is relatively constant for depths of flow in channels where the hydraulic radius exceeds this upper limit. The ratios of hydraulic radius to d_{50} (R/d_{50}) for the flows recorded at Jarrett's (1984) study sites were mostly less than 5. Roughness coefficients in uniform channels where this criterion is met are expected to decrease with increasing stage (Benson and Dalrymple, 1967). The negative exponent on the R value in this equation implies this inverse relation. Additional adjustments to an n value computed by this equation are required for only extreme channel conditions as described in the section below, "Evaluation of Flow-Retarding Factors."

Sauer, 1990

Channel roughness and water-surface slope are closely correlated. Riggs (1976) used this relation to develop an equation that estimates discharge from only two variables in natural channels: flow area and slope. V.B. Sauer (U.S. Geological Survey, written commun., 1990), in an attempt to generate an n-value equation similar in form to that of Jarrett (1984), derived the following formula from Riggs's (1976) equation:

$$n = 0.11 S_w^{0.18} R^{0.08} \tag{5}$$

where

S_w = slope of water surface, in feet per foot, and

R = hydraulic radius, in feet.

This equation is based on data from Barnes (1967) and is applicable to channels with water-surface slopes between 0.0003 and 0.018 and with hydraulic radii up to 19 ft. Besides incorporating a wide range of hydraulic characteristics, this equation accounts for the roughness effects, not only from bed and bank material, but also from other flow-resisting factors, such as cross-sectional irregularities, variations in channel size and shape, and vegetated bank conditions. Therefore, roughness coefficients estimated by this equation would not be considered base n values. In fact, this equation would tend to overestimate base n values and would likely give reasonable estimates for channels whose n values are significantly affected by additional flow-retarding factors. This equation could not be used in a general manner, but is limited to specific applications, such as estimating n values on narrow channels with dense streambank vegetation. In such cases, the n value would be expected to increase with increasing stage, which is the relation implied by the positive exponent on the R value in this equation. Additional adjustments to an n value computed by this equation would probably be required for only extreme channel conditions, as described in the section below, "Evaluation of Flow-Retarding Factors."

Other Equations

Many equations were assessed for their ability to estimate the computed roughness coefficients from the New York study sites. Two of these equations produced fairly accurate estimates of the computed n values at some of the sites, but failed to estimate with the same degree of accuracy the n values at other sites with similar hydraulic and particle-size characteristics. Both equations—one developed by Strickler (1923), the other by D.C. Froehlich (U.S. Geological Survey, written commun., 1978)—are presented here.

Researchers disagree as to whether Strickler's (1923) experiments were conducted on sand-coated flumes or gravel-bed natural channels (French, 1985). Hence, different interpretations of his work have produced different n-value equations. Henderson (1966) presents the following equation, which he attributes to Strickler (1923):

$$n = 0.034 d_{50}^{1/6} \tag{6}$$

where d_{50}= the median size of the bed material, in feet.

Henderson (1966) claims that equation 6 is based on data that were collected on streams with gravel beds. This equation estimates the n value independently of stage and is appropriate only for relatively high within-bank flows.

Froehlich (written commun., 1978) developed an equation that relates the roughness coefficient to hydraulic radius, relative smoothness, and a depth-to-width factor. This equation, presented in Jobson and Froehlich (1988, p. 91), is as follows:

$$n = 0.245R^{0.14}(R/d_{50})^{-0.44}(R/T)^{0.30} \qquad (7)$$

where
R = hydraulic radius, in feet,
d_{50} = intermediate particle diameter, in feet, that equals or exceeds that of 50 percent of the particles, and
T = top width of stream, in feet.

Equation 7 is based on the diverse data from 15 sites, described by Barnes (1967), for which bed-material particle sizes are included (D.C. Froehlich, Dept. of Civil Engineering, University of Kentucky, oral commun., 1990), and therefore is subject to the same limitations as equation 5.

Evaluation of Flow-Retarding Factors

Roughness-coefficient tables, photographic comparisons, and previously cited equations provide a beginning point for evaluating channel-energy losses and estimating n values. Roughness coefficients obtained by these methods may or may not reflect energy losses that result from factors other than particle size and size distribution of bed material, that is, a base n value. If the initially selected n value does not represent all major roughness factors, it needs to be adjusted. Cowan (1956) provides guidelines for adjusting an n value for additional flow-retarding factors. The general approach is to (1) select a base n value for a straight, uniform, smooth channel in the natural materials of the streambed and banks; (2) add modifying values for channel-surface irregularity, channel-shape and -size variation, obstructions, and type and density of vegetation; and (3) multiply the sum of these values by an adjustment factor for the degree of channel meandering (table 4), as represented by the equation

$$n = (n_0 + n_1 + n_2 + n_3 + n_4)\, m \qquad (8)$$

where
n_0 = base value for a straight, uniform channel;
n_1 = additive value to account for the effect of cross-section irregularity;
n_2 = additive value to account for the variations in size and shape of the channel;
n_3 = additive value to account for the effect of obstructions;
n_4 = additive value to account for the type and density of vegetation; and
m = adjustment factor for the degree of channel meandering; determined by the ratio of channel meander length (L_m) to valley or straight-channel length (L_s).

The data that Cowan (1956) used to compute the adjustment values for these five flow-retarding factors presumably came from Ramser (1929). Between 1913 and 1928, Ramser collected roughness data on 61 drainage channels in 8 States before and after maintenance work was done on these channels. This work consisted of channelization (or straightening), dredging, and removal of channel vegetation and obstructions. By monitoring the hydraulic effects of this work and the subsequent revegetation of these channels, Ramser (1929) was able to document the resultant change in the roughness coefficient. Cowan (1956) refers to only one channel in Ramser (1929) to illustrate the proposed n-value-adjustment method, but Fasken (1963), who reproduced a part of Ramser's report, included a supplement that describes Cowan's approach for adjusting roughness coefficients, and presents several examples of the actual computation of modifying values from Ramser's data. Therefore, Ramser (1929) is assumed to be the source of data used by Cowan to compute the n-value adjustments presented in table 4, even though Cowan (1956) does not state this specifically.

Experienced hydrologists and engineers can account for adjustments for other flow-retarding factors in addition to those analyzed by Cowan (1956). Caution must be exercised, however, to ensure that a modifying value for one factor is neither duplicated by the effect of a second factor nor already incorporated in the initially selected n value. Cowan (1956) did not consider highly unstable sand channels in the development of this procedure. The modifying values for the various factors were developed from an analysis of 40 to 50 small- to medium-size channels with top widths mostly less than 60 ft. Therefore, use of these adjustment values is questionable for large channels in which the hydraulic radius exceeds 15 ft, and large adjustments generally are required only for narrow channels. As for the vegetation-adjustment values, many of the channel-vegetation examples in table 4 describe conditions for vegetation that is distributed uniformly across the entire section and not limited to the streambanks alone. Therefore, use of these values for channels with unvegetated bottoms could be excessive or unnecessary. This approach, described by Chow (1959) and Benson and Dalrymple (1967), is promoted in n-value-estimation reports by Aldridge and Garrett (1973), Arcement and Schneider (1989), and Jarrett (1985).

Considerations for Areas Affected by Vegetation

Many studies of roughness coefficients address the incremental contribution of vegetation in the channel or flood plain to the total hydraulic roughness. Most of these were laboratory experiments that simulated the resistance of vegetation to open-channel flow over large, rigid roughness features in flumes. Carter and others (1963) list the studies conducted through 1960. Additional references since 1960 are noted in Arcement and Schneider's (1987) comparison report on four approaches to evaluate vegetation-affected roughness coefficients. Although these studies have provided much information, direct application of the results to actual streams is limited by the complexities of natural channels or by the absence of field confirmation of laboratory results.

Other researchers, such as Ramser (1929), Ree and Palmer (1949), Ree and Crow (1977), Petryk and Bosmajian (1975), and Arcement and Schneider (1989), in conducting vegetation experiments on natural channels and overbank areas, have dealt with extremely dense vegetation within low-water channels or with vegetated flood plains. None since Ramser (1929), excluding the quantification of vegetation-affected increments of n values from Ramser's data by Cowan (1956), and the indirect inclusion of vegetation effects in the equation of V.B. Sauer (U.S. Geological Survey, Atlanta, Ga., written commun., 1990; this report, eq. 5), has conducted any field-based study on the incremental effect that streambank vegetation alone has on the total roughness coefficient. Of the flow-resisting factors analyzed by Cowan (1956), channel vegetation has the largest adjustment values and thus probably the greatest potential effect on the total roughness coefficient selected for a reach. Adjustments of n values (table 4) as high as 0.100 are suggested for "very large" vegetation conditions. These adjustments are limited in their applicability, however, as discussed in the preceding section, "Evaluation of Flow-Retarding Factors," and should not be used without consideration of the relative size of the channel. Arcement and Schneider (1989, p. 8) point out that (1) flow in wide channels having small depth-to-width ratios and no vegetation on the bed is minimally affected by bank vegetation, and the maximum adjustment is about 0.005; (2) flow in channels that are relatively narrow and have steep banks covered by dense vegetation that hangs over the channel can be significantly affected, and the maximum adjustment is about 0.03; and (3) the larger adjustment values given in table 4 apply only in places where vegetation covers most of the channel.

METHODS OF STUDY

The following sections present the hydraulic principles on which calculation of a channel's roughness coefficient is based and describe the methods of site selection, data collection, and computation that were used in this study. Also discussed are details of the measurement and (or) recording of water-surface profiles, stream discharge, streambed-particle size, and streambank vegetation, as well as documentation of the study-site conditions through photographs of the channel.

Hydraulic Principles

The most widely used uniform-flow formula for open-channel flow computations is the Manning equation (Chow, 1959, p. 99):

$$V = \frac{1.486}{n} R^{2/3} S_f^{1/2} \tag{9}$$

where

V = mean velocity of flow, in feet per second,
R = hydraulic radius, in feet,
S_f = energy gradient or friction slope, in feet per foot, and
n = Manning's roughness coefficient, in feet$^{1/6}$.

For any flow, the discharge at a channel section is expressed by

$$Q = VA \tag{10}$$

where

Q = discharge, in cubic feet per second,
V = mean velocity of flow, in feet per second, and
A = cross-sectional area of flow, in square feet.

Combining equations 9 and 10 results in the discharge formula

$$Q = \frac{1.486}{n} A R^{2/3} S_f^{1/2} \tag{11}$$

Table 4. Adjustment factors for the calculation of channel *n* values

[Original source of data presented in this table is Cowan (1956). Modifications from Chow (1959), Aldridge and Garrett (1973), and Jarrett (1985, table 1) are included. Italicized examples of vegetation are based on results of data presented in this report]

Channel condition	*n* value adjustment[1]	Example
Cross-section irregularities, n_1:		
Smooth	0.000	Compares with the smoothest channel attainable in a given bed material.
Minor	0.001–0.005	Compares with carefully dredged channels in good condition but having slightly eroded or scoured side slopes.
Moderate	0.006–0.010	Compares with 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 in 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 obstruction, 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.
Channel vegetation,[2] n_4:		
Negligible	0.000	*Any type or density of vegetation growing on the banks of channels more than about 100 ft wide with less than 25 percent of the wetted perimeter vegetated and no significant vegetation along channel bottoms. Mowed grass or vetch on banks of channels over 50 ft wide. (Could be applicable to narrower channels.)*
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. *Dense, woody brush, annual soft-stemmed plants, and possibly a few mature trees that cover 25 to 50 percent of the wetted perimeter in any season on the banks of channels 100 to about 250 ft wide and during the dormant season on the banks of channels 30 to about 100 ft wide.*

Table 4. Adjustment factors for the calculation of channel *n* values—Continued

Channel condition	*n* value adjustment[1]	Example
Channel vegetation,[2] n_4—Continued:		
Medium	0.010–0.025	Turf grass growing where the average depth of flow is from one or 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, *or tall grasses and soft-stemmed plants in the growing season*, growing along the banks and no significant vegetation along the channel bottoms where the hydraulic radius exceeds 2 ft. *Dense, woody brush, annual soft-stemmed plants, and possibly a few mature trees that cover 25 to 50 percent of the wetted perimeter on the banks of channels 30 to about 100 ft wide during the growing season.*
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 ft; 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 ft.
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, m[3,4]:		
Minor	1.00	Ratio of the channel meander length (L_m) to valley or straight-channel length (L_s) is 1.0 to 1.2.
Appreciable	1.15	L_m/L_s is 1.2 to 1.5.
Severe	1.30	L_m/L_s is greater than 1.5.

[1]Adjustments are based primarily on data from channels less than 60 ft wide and are probably applicable for channels as much as 100 ft wide, unless otherwise specified. Larger adjustments generally are necessary for narrower channels.

[2]Note the distinction in the examples between vegetation distributed uniformly across a channel, which is assumed, and bank vegetation alone.

[3]Adjustment values apply to flow confined in the channel and do not apply where downvalley flow crosses meanders.

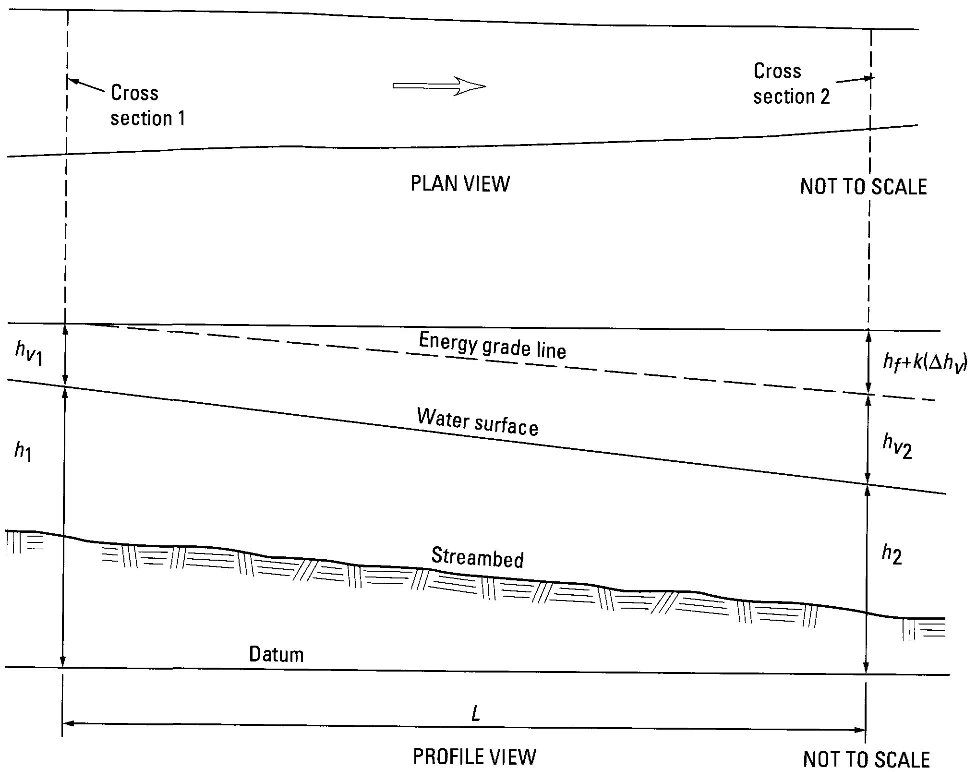
[4]Adjustments for cross-section irregularities, channel variations, effect of obstructions, and channel vegetation are added to the initial *n* value (tables 1, 2, or 3 or the estimation equations). This sum is multiplied by the adjustment factor for degree of meandering.

Reliable solution of the discharge equation is based on the assumption of uniform flow in which the area, hydraulic radius, and depth remain constant, and the slopes of the water surface, energy gradient, and streambed are parallel. In natural channels, these conditions are seldom met; therefore, equation 11 can be assumed valid for reaches of nonuniform flow if the energy gradient is modified to reflect only the energy losses due to boundary friction (Barnes, 1967). The energy equation for a reach of nonuniform open-channel flow between cross sections 1 and 2 shown in figure 2 is

$$(h + h_v)_1 = (h + h_v)_2 + (h_f)_{1.2} + k(\Delta h_v)_{1.2} \qquad (12)$$

where the subscript numerals 1 and 2 refer to the upstream and downstream sections, respectively,

- h = hydraulic head or elevation of the water surface at the respective sections above a common datum, in feet;
- h_f = energy loss due to boundary friction in the reach, in feet;
- Δh_v = upstream velocity head minus the downstream velocity head, in feet;
- $k(\Delta h_v)$ = energy loss due to acceleration or deceleration in a contracting or expanding reach, in feet;
- k = energy-loss coefficient, generally taken to be 0.0 for contracting reaches and 0.5 for expanding reaches, dimensionless; and



EXPLANATION

h = hydraulic head
h_v = velocity head
h_f = energy loss due to boundary friction
k = expansion or contraction energy-loss coefficient
L = length of channel reach

Figure 2. Open-channel flow reach (modified from Dalrymple and Benson, 1967, fig. 1).

h_v = velocity head at the respective section, in feet, that equals $\propto V^2/2g$,

where

$\propto$ = velocity-head or kinetic-energy coefficient, dimensionless;

V = mean velocity of flow, in feet per second; and

g = gravitational acceleration constant, in feet per second squared, that equals 32.2.

In this report, the velocity-head coefficient $\propto$ in the main channel is considered to be 1.00 for computational purposes. Jarrett (1984) indicates that, in natural channels, $\propto$ can be much greater than 1.00, but any resulting error in the computation of the n value is assumed to be minimal because the importance lies in the relative difference between the velocity-head coefficients of upstream and downstream cross sections, rather than their actual magnitudes.

The slope of the energy gradient, or friction slope, is thus defined as

$$S_f = \frac{h_f}{L} = \frac{\Delta h + \Delta h_v - k(\Delta h_v)}{L} \tag{13}$$

where

Δh = difference in water-surface elevation at the two sections, in feet; and

L = length of channel reach, in feet.

Other variables are as previously defined.

The quantity $(1.486/n)AR^{2/3}$ in the discharge formula (eq. 11) is called the conveyance and is computed for each cross section. The mean conveyance in the reach between any two sections is computed as the geometric mean of the conveyance of the two sections. The discharge equation in terms of conveyance is

$$Q = [K_1 K_2 S_f]^{1/2} \tag{14}$$

where K = conveyance, in cubic feet per second.

Following the method described by Barnes (1967) and Jarrett and Petsch (1985), Manning's roughness coefficient is computed for each reach from the known discharge, the water-surface profile, and the hydraulic properties of the reach as defined by the cross sections. The following equation is applicable to a multisection reach of m cross sections, designated 1, 2, 3, ..., $(m-1)$, m (the mth cross section is the one farthest downstream):

$$n = \frac{1.486}{Q}\left[\frac{(h+h_v)_1 - (h+h_v)_m - [(k\Delta h_v)_{1.2} + (k\Delta h_v)_{2.3} + \cdots + (k\Delta h_v)_{(m-1).m}]}{(L_{1.2}/Z_1Z_2) + (L_{2.3}/Z_2Z_3) + \cdots (L_{(m-1).m}/Z_{(m-1)}Z_m)}\right]^{1/2} \tag{15}$$

where $Z = AR^{2/3}$ and other quantities are as previously defined.

Dalrymple and Benson (1967) describe the procedure for computation of discharge by the slope-area method. Barnes (1967) and Jarrett (1984) used a modification of this procedure as defined by equation 15 to compute roughness coefficients for their n-value reports, and Jarrett and Petsch (1985) developed a computer program based on this procedure to facilitate the calculation and analysis of computed n values.

Site Selection

The 21 study sites were selected at or near current U.S. Geological Survey streamflow-gaging stations that have well-defined and relatively stable stage-to-discharge relations. Site locations are shown in figure 3. These sites were selected to meet, as closely as possible, the criteria for selection of a reach for computation of discharge by the slope-area method as outlined by Dalrymple and Benson (1967). Therefore, straight, uniform channels that showed minimal effect from flow-retarding factors were sought. To evaluate the flow-impeding effects of streambank vegetation, reaches with uniform type and density of vegetation were selected. None of the sites had notable vegetation in their low-water channels, and only sites where high flows are contained within the channel banks or where overflow, if any, is insignificant, were selected. The selected reaches ranged in stream-surface top width from 30 ft to more than 400 ft and in length from 101 to 1,340 ft.

Data Collection

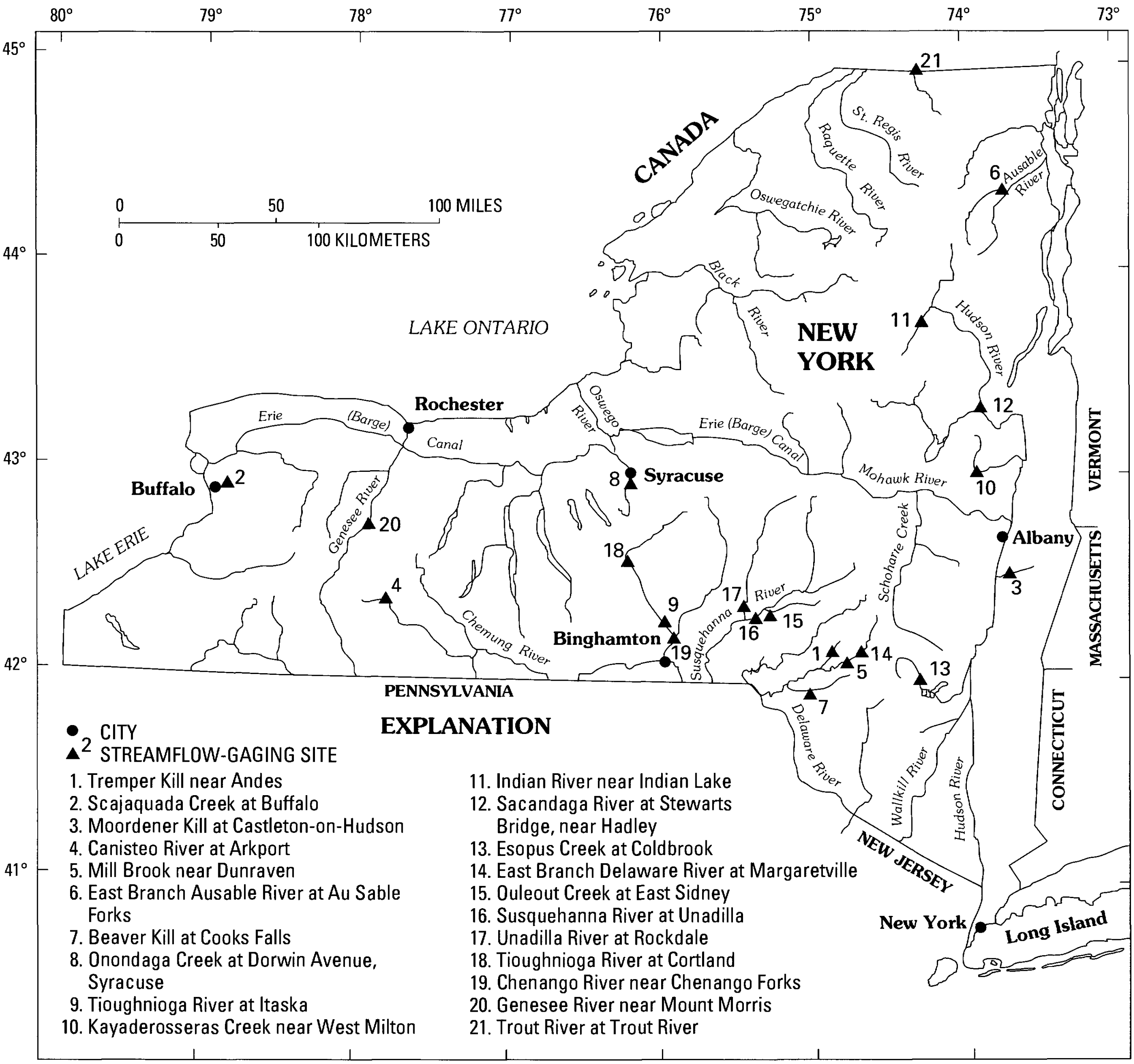
Water-surface profiles and stream discharges were obtained throughout the within-bank range in water levels at each of the study sites during 1983–88. Channel geometry was surveyed at the beginning of the study and resurveyed if fill or scour within the reach was suspected. Standard surveying procedures as outlined by Benson and Dalrymple (1967) were followed. The streambed-particle size was measured, streambank vegetation was described, and upstream and downstream views of each reach were photographed.

Water-Surface Profiles

Water-surface profiles of high flows were drawn from a preliminary indirect calculation of discharge by the slope-area method (Dalrymple and Benson, 1967) and used to locate appropriate cross sections at which hydraulic channel data could be obtained. Standard USGS crest-stage gages (Rantz and others, 1982, p. 77) were installed at each cross section to obtain water-surface profiles of high flows that occurred between site inspections. Water-surface elevations were obtained from leveling runs, routine inspections of crest-stage gages, and direct measurements from reference points. Depending on the timing of the direct measurements, many water-surface profiles that were measured during rising and falling stages of a floodflow produced erroneous slopes and were excluded from the study.

Stream Discharge

The discharge for each recorded water-surface profile was obtained from the discharge record of the nearby streamflow-gaging station. The stability of the stage-to-discharge relation at each site was checked by discharge measurements, which were conducted in accordance with standard USGS measurement procedures (Rantz and others, 1982). The generally "good" rating of daily discharge records at these sites through



Base from U.S. Geological Survey digital data, 1:2,000,000, 1972.
Standard parallels 29° 30' and 46° 30', central meridian –96° 00'
Albers Equal-Area Conic projection

Figure 3. Locations of study sites.

the period of study, 1983–88, implies a discharge accuracy within 10 percent of the true discharge. Water-surface profiles recorded during any periods when the stage-to-discharge relation was questionable either were deleted from the study or are noted in the data tables presented for each site in the section, "Station Descriptions, Hydraulic Data, and Channel Photographs for the 21 Study Sites."

Streambed-Particle Size

Measurement of streambed-particle size was done in accordance with the methods of Wolman (1954), Benson and Dalrymple (1967), and Kellerhals and Bray (1970), who outlined methods for obtaining representative samples of size and size distribution of coarse bed material. None of the study sites had bed material that was predominantly sand sized or finer.

Table 5. Range of hydraulic characteristics, particle sizes, and roughness coefficients among the 21 study sites in New York

Characteristic	Minimum	Maximum
Cross-sectional area of flow, A (square feet)	35.9	3,910
Top width of stream, T (feet)	29.7	429
Hydraulic radius, R (feet)	.91	13.4
Mean velocity, V (feet per second)	1.40	16.8
Froude number, F	.20	.91
Water-surface slope, S_w (feet per foot)	.0003	.0141
Energy gradient, S_f (feet per foot)	.0003	.0131
Percent wetted perimeter vegetated	0	48
Discharge, Q (cubic feet per second)	77	51,700
Particle size:		
Intermediate diameter:		
d_{50} (feet)	.05	1.2
d_{84} (feet)	.14	3.0
Minimum diameter d_{50} (feet)	.02	.80
Degree of meandering, m	1.00	1.01
Manning's roughness coefficient, n	.024	.129

Random grab samples of bed material were collected at equal increments across three to five cross sections within each study reach. All three dimensions of each particle were measured. At most sites, bed material was sampled concurrently with measurements of cross-section elevation.

Streambank Vegetation

The general type and relative density of streambank vegetation at each site were documented, and the elevation at which vegetation began on each bank was noted and used to compute the percentage of wetted perimeter that was vegetated for each profile. This elevation generally coincided with the edge of the low-water channel. The elevation was also noted at any point along the cross section where a substantial change in the type or density of vegetation was observed. For purposes of this report, the growing season is the 6-month period from May through October; the nongrowing season is from November through April. Though the actual growing season in New York does not usually extend to the end of October, the effect of dead, but standing, vegetation on channel-energy losses at this time of year can be similar to that of actively growing vegetation. This effect can persist in a channel until snow accumulates and compresses the vegetation.

Photographs

A downstream and upstream view of each study reach was photographed. These photographs show channel alignment, streambank-vegetation type and density, channel size in relation to the flow-resisting features of the channel, and where possible, bed material. As with other photographic n-value reports, hydrologists and engineers can use these photographs, along with the hydraulic data presented, to assist in estimating roughness coefficients for channels with similar characteristics.

Computation of Hydraulic Properties and Manning's Roughness Coefficients

Water-surface elevations and their associated discharges were input to the n-calculation computer program developed by Jarrett and Petsch (1985). For a given water-surface profile and discharge, the roughness coefficient was calculated for each pair of cross sections and for the entire reach, and the hydraulic properties were computed for each cross section. The intermediate diameter of the streambed particles was used to calculate the diameters that equal or exceed that of 50 percent and 84 percent (d_{50} and d_{84}) of the particles sampled at a site. The d_{50} for the minimum diameter of the particles also was calculated. In the following section, hydraulic and particle-size data, as well as the resulting computed roughness coefficients for each discharge and water-surface profile, are presented with the photographs of each site. Ranges of 14 major characteristics at the 21 sites are listed in table 5. Streambank vegetation ranged from grass alone to various combinations and densities of annual weeds, woody brush, and trees. The average wetted perimeter of the nonvegetated low-water channel and the average wetted perimeter that is vegetated were calculated for each water-surface profile and used to compute the percentage of wetted perimeter that is vegetated; this percentage ranged from 0 to 48 (table 5).

One variable that is included in the Manning equation but is not directly measurable is the velocity-head coefficient. For the n calculations, as well as most hydraulic computations of discharge or floodwater elevation, this value is assumed to be 1.00. As a measure of the validity of this assumption and an indicator of the uniformity of flow at a cross section, current-meter discharge measurements can be used to compute the velocity-head coefficients (Hulsing and others, 1966). This was done at the sites that have cableways or nonconstricting bridge openings, which permit high-flow discharge measurements within or close to the study reach. Only 8 of the 21 sites met this criterion; the range of computed velocity-head coefficients for these sites is given with the hydraulic data for each site in the following section. High-flow measurements at the other sites were made at cross sections far from the study site or at bridges that were constricted by the bridge opening or obstructed by piers. The velocity-head coefficients computed for these locations are not representative of the velocity distribution through the study reach and, therefore, are not included in this report.

STATION DESCRIPTIONS, HYDRAULIC DATA, AND CHANNEL PHOTOGRAPHS FOR THE 21 STUDY SITES

This section presents physical descriptions of the 21 study sites and the hydraulic data for each discharge and water-surface profile for which a roughness coefficient is computed. The tabulated values for area, stream-top width, hydraulic radius, velocity, and Froude number are averages of values computed for each cross section within a reach. The percentage of wetted perimeter that is vegetated is computed from the average values of the total wetted perimeter and the wetted perimeter that is vegetated at each cross section in the reach. Roughness coefficients for three sites—Esopus Creek at Coldbrook, Beaver Kill at Cooks Falls, and East Branch Ausable River at Au Sable Forks—which have been computed from data from earlier floods and are presented by Barnes (1967), are included herein for comparison with the recent computations. Vegetation indices, which are explained in the section, "Analysis of Roughness-Coefficient Data," are listed as a pair of numbers and represent average vegetation conditions for both streambanks for bankfull flows during the nongrowing and growing seasons, respectively. Velocity-head coefficients ($\propto$), where given, are computed from discharge measurements made at stages similar to those recorded during this study. Photographs of downstream and upstream views are intended to show channel alignment, streambank vegetation, channel size in relation to flow-resisting features, and where possible, bed material. Several sites have photographs that show similar views at different times of the year to document seasonal changes in vegetation density and to substantiate the resulting changes in the roughness coefficient. Comparison of photographs among sites of differing channel widths will clarify the relation between channel size and the measurable effect of streambank vegetation on the roughness coefficient. Reference scale in the photographs is provided by (1) a hydrographer (5-ft, 7-in tall) holding either a telescoping stadia rod (the length of which is stated in the photograph caption) or a 2.6-ft ×1.6-ft cross-section-identification card, or (2) a self-supported stadia rod. Graphs show the relation between Manning's roughness coefficient and hydraulic radius at each site. Plan-view diagrams of the study reaches show cross-section locations and orientation of photographs. Cross-section plots illustrate the variation of channel size and shape within the study reach. The horizontal lines on the cross-section plots depict the water-surface elevations of the maximum and minimum recorded discharges listed in the data table for each site. Data (tables 6–26) and graphs, diagrams, and photographs (figs. 4–66) are presented for the following sites:

1. Tremper Kill near Andes
2. Scajaquada Creek at Buffalo
3. Moordener Kill at Castleton-on-Hudson
4. Canisteo River at Arkport
5. Mill Brook near Dunraven
6. East Branch Ausable River at Au Sable Forks
7. Beaver Kill at Cooks Falls
8. Onondaga Creek at Dorwin Avenue, Syracuse
9. Tioughnioga River at Itaska
10. Kayaderosseras Creek near West Milton
11. Indian River near Indian Lake
12. Sacandaga River at Stewarts Bridge, near Hadley
13. Esopus Creek at Coldbrook
14. East Branch Delaware River at Margaretville
15. Ouleout Creek at East Sidney
16. Susquehanna River at Unadilla
17. Unadilla River at Rockdale
18. Tioughnioga River at Cortland
19. Chenango River near Chenango Forks
20. Genesee River near Mount Morris
21. Trout River at Trout River

Text continues on page 108.

Table 6. Station description and summary of hydraulic data, Tremper Kill near Andes, N.Y.

Location.—Latitude 42°07'12" N., longitude 74°49'08" W., Delaware County, on right bank 500 ft upstream from bridge on County Highway 1, about 1,700 ft upstream from Pepacton Reservoir, and 5 mi south of Andes. A 3-section, 166-ft-long reach; section 1 is about 220 ft upstream from bridge on County Highway 1.

USGS station-identification number.—01415000.

Drainage area.—32.2 mi^2.

Bed material.—Rounded cobbles and boulders. Intermediate diameter d_{50} = 0.70 ft and d_{84} = 1.45 ft. Minimum diameter d_{50} = 0.16 ft.

Bank description.—Left bank is steep and eroded and has boulders and exposed tree roots. Right bank is gradually sloped and is vegetated with a few large trees, some bamboo-like plants, but mostly tall grass and soft-stemmed plants. Vegetation indices: 1, nongrowing season; 2, growing season.

Remarks.—The *n* values computed for this site are affected by streambank vegetation.

Summary of Hydraulic Data

[ft, feet; ft^2, square feet; ft/s, feet per second; ft^3/s, cubic feet per second]

Discharge (ft^3/s)	Average values for reach: Area (ft^2)	Width (ft)	Hydraulic radius (ft)	Velocity (ft/s)	Froude number	Water-surface slope	Energy gradient	Percent wetted perimeter vegetated	Manning's *n*
Data collected during the nongrowing season									
85	35.9	37.1	0.91	2.38	0.43	0.01006	0.01001	24.2	0.059
241	65.9	41.5	1.49	3.66	.51	.01084	.01068	32.7	.054
[1]248	70.6	42.0	1.57	3.52	.48	.00934	.00941	33.9	.055
[1]271	71.3	42.1	1.58	3.81	.51	.00988	.00986	33.9	.053
[1]315	80.1	42.9	1.74	3.95	.51	.00964	.00962	35.5	.054
[1]355	86.9	43.5	1.85	4.11	.51	.00994	.00985	36.4	.055
597	120	47.6	2.34	4.98	.55	.01060	.01061	42.1	.054
1040	164	53.2	2.84	6.36	.64	.01229	.01205	48.2	.052
Data collected during the growing season									
175	60.9	41.0	1.40	2.88	0.42	0.01066	0.01057	31.7	0.066
[1]414	105	45.6	2.13	3.96	.46	.01054	.01043	39.5	.064
[1]419	106	45.6	2.14	3.98	.46	.01042	.01026	39.6	.065
[1]494	111	46.3	2.21	4.49	.51	.01060	.01045	40.5	.058
[1]691	141	50.3	2.59	4.92	.52	.01000	.01016	45.2	.058
832	156	52.2	2.76	5.35	.54	.01084	.01097	47.2	.057

[1]The *n* value computed for this discharge and water-surface profile is affected by 11 to 18 percent flow-area expansion in the reach. The *n* values computed for each subreach differ by 0.010 to 0.020.

Figure 4. Photographs of Tremper Kill near Andes, N.Y. *A*, Upstream from cross section 1, facing downstream during nongrowing season. *B*, Upstream from cross section 1, facing downstream during growing season. Self-supported 10-ft stadia rod is at section 2. *C*, Upstream from cross section 1, facing downstream during late fall. Hydrographer at section 2 is holding a 15-ft rod at the approximate water-surface elevation of the maximum recorded discharge. *D*, Downstream from cross section 3, facing upstream during nongrowing season. *E*, At cross section 3, facing upstream during growing season. Self-supported 10-ft stadia rod is at section 2. *F*, Downstream from cross section 3, facing upstream during late fall. Hydrographer at section 2 is holding a 15-ft rod at the approximate water-surface elevation of the maximum recorded discharge.

Figure 4. Continued.

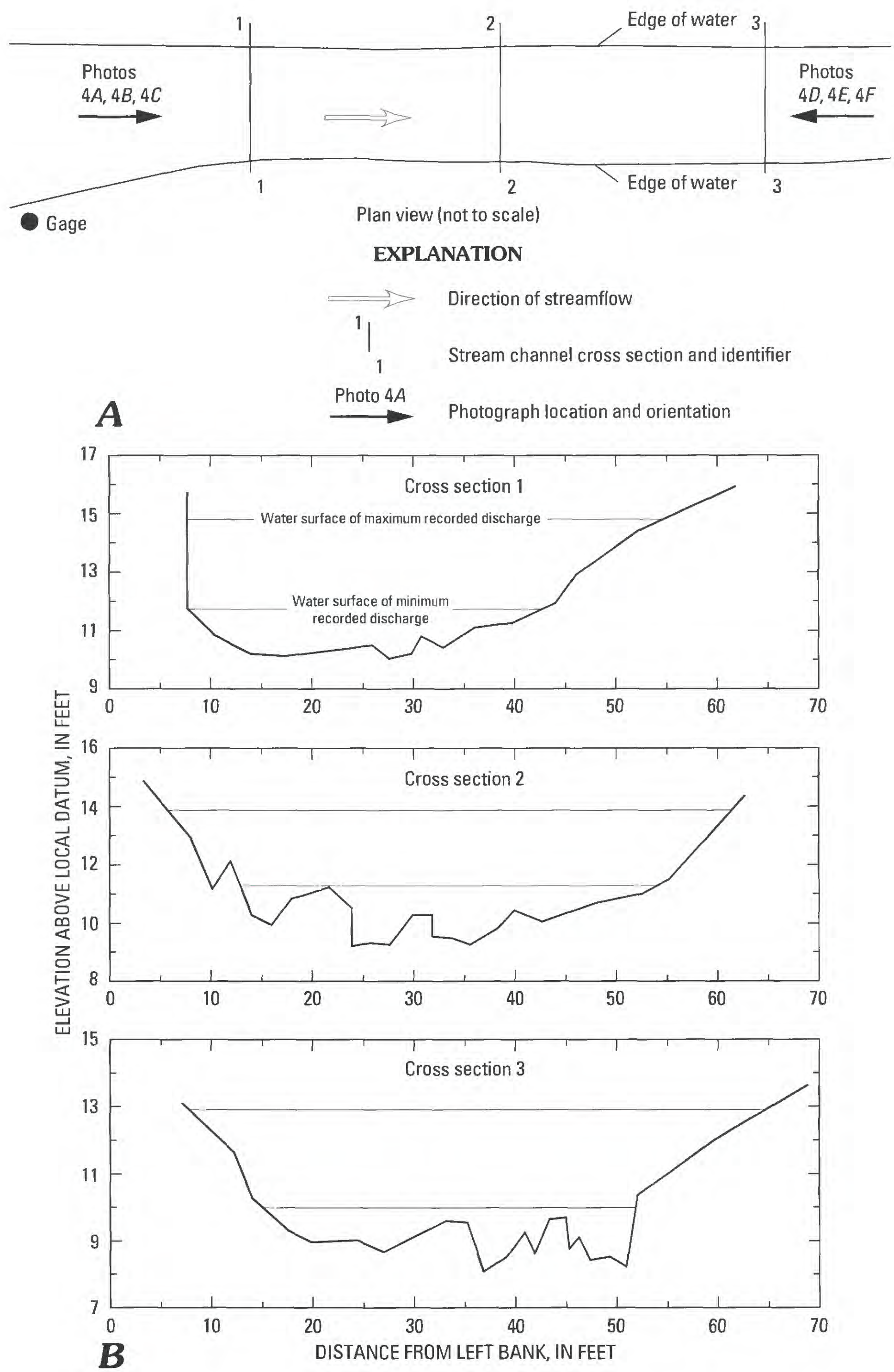


Figure 5. Plan view (*A*) and cross sections (*B*), Tremper Kill near Andes, N.Y. Photographs are shown in figure 4.

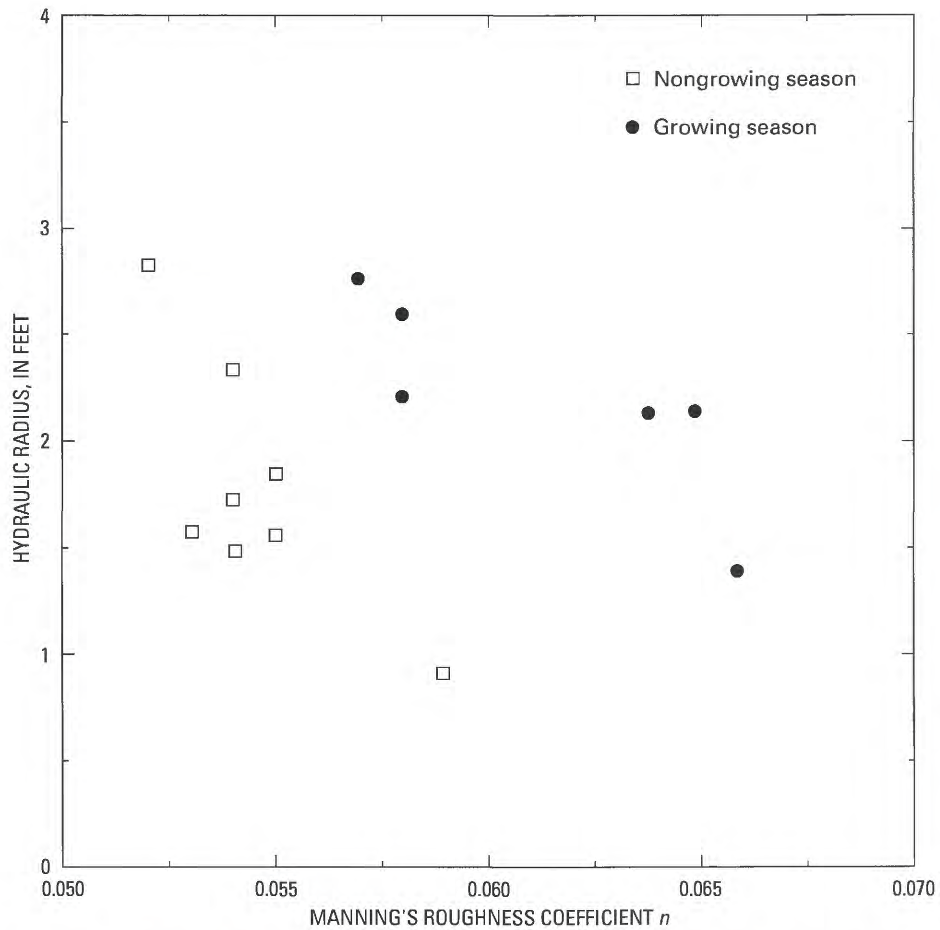


Figure 6. Relation between Manning's roughness coefficient and hydraulic radius at Tremper Kill near Andes, N.Y.

Table 7. Station description and summary of hydraulic data, Scajaquada Creek at Buffalo, N.Y.

Location.—Latitude 42°54'41" N., longitude 78°47'45" W., Erie County, on right bank 58 ft upstream from point where stream goes underground in concrete-lined tunnel, 86 ft upstream from Pine Ridge Road, 0.2 mi east of boundary line of City of Buffalo, and 6.2 mi upstream from mouth. A 3-section, 860-ft-long reach; section 1 is about 1,100 ft upstream from gage and just downstream from footbridge.

USGS station-identification number.—04216200.

Drainage area.—15.4 mi^2.

Bed material.—Gravel. Intermediate diameter d_{50} = 0.06 ft and d_{84} = 0.17 ft. Minimum diameter d_{50} = 0.04 ft.

Bank description.—This reach is a maintained grass- and vetch-lined channel with a dense growth of willow saplings and grass at the low-water edge. Vegetation indices: lower bank 3, nongrowing season; 4, growing season; bankfull 0, 0.

Remarks.—The *n* values computed at this site are affected by streambank vegetation and by 24 to 31 percent flow-area expansion in the reach. The velocity-head coefficients computed from discharge measurements made at this site range from 1.14 to 1.24 for discharges between 330 and 760 ft^3/s.

Summary of Hydraulic Data

[ft, feet; ft^2, square feet; ft/s, feet per second; ft^3/s, cubic feet per second]

Discharge (ft^3/s)	Average values for reach: Area (ft^2)	Width (ft)	Hydraulic radius (ft)	Velocity (ft/s)	Froude number	Water-surface slope	Energy gradient	Percent wetted perimeter vegetated	Manning's *n*
Data collected during the nongrowing season									
453	169	54.2	3.02	2.77	0.28	0.00037	0.00043	27.9	0.024
492	178	55.2	3.13	2.83	.28	.00048	.00053	29.3	.026
542	189	56.3	3.25	2.94	.29	.00044	.00050	30.7	.025
562	199	57.4	3.36	2.89	.28	.00043	.00048	32.1	.026
734	249	62.5	3.87	3.00	.27	.00050	.00055	37.7	.029
759	257	63.2	3.94	3.00	.26	.00050	.00055	38.5	.029
Data collected during the growing season									
329	136	50.5	2.62	2.49	0.27	0.00051	0.00055	22.5	0.027
332	134	50.4	2.60	2.54	.28	.00053	.00058	22.2	.027
370	146	51.8	2.75	2.59	.27	.00059	.00063	24.4	.029
430	165	53.6	2.98	2.66	.27	.00063	.00066	27.4	.031
455	172	54.6	3.06	2.70	.27	.00069	.00072	28.4	.032
476	181	55.6	3.16	2.68	.26	.00069	.00072	29.7	.033
544	197	57.3	3.35	2.81	.27	.00056	.00060	31.9	.030
578	207	58.2	3.45	2.85	.27	.00056	.00060	33.0	.030
656	228	60.3	3.66	2.93	.27	.00051	.00056	35.5	.029

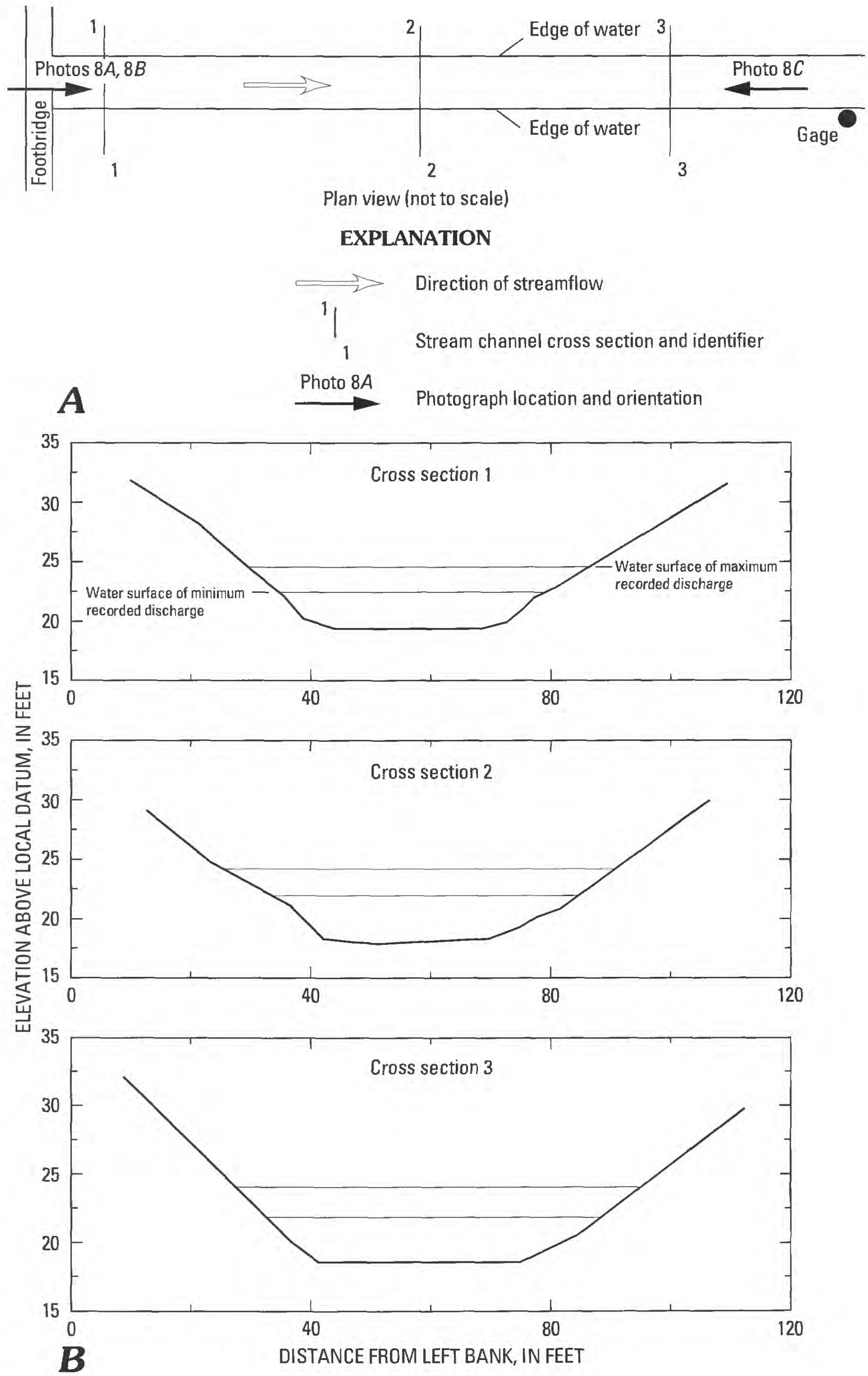


Figure 7. Plan view (*A*) and cross sections (*B*), Scajaquada Creek at Buffalo, N.Y. Photographs are shown in figure 8.

Figure 8. Photographs of Scajaquada Creek at Buffalo, N.Y. *A*, At cross section 1, facing downstream during growing season when banks have been mowed. Note van on top of right bank for scale. *B*, At cross section 1, facing downstream during growing season when banks are unmowed. *C*, Downstream from cross section 3, facing upstream during growing season. Footbridge in background is just upstream from section 1.

Figure 8. Continued.

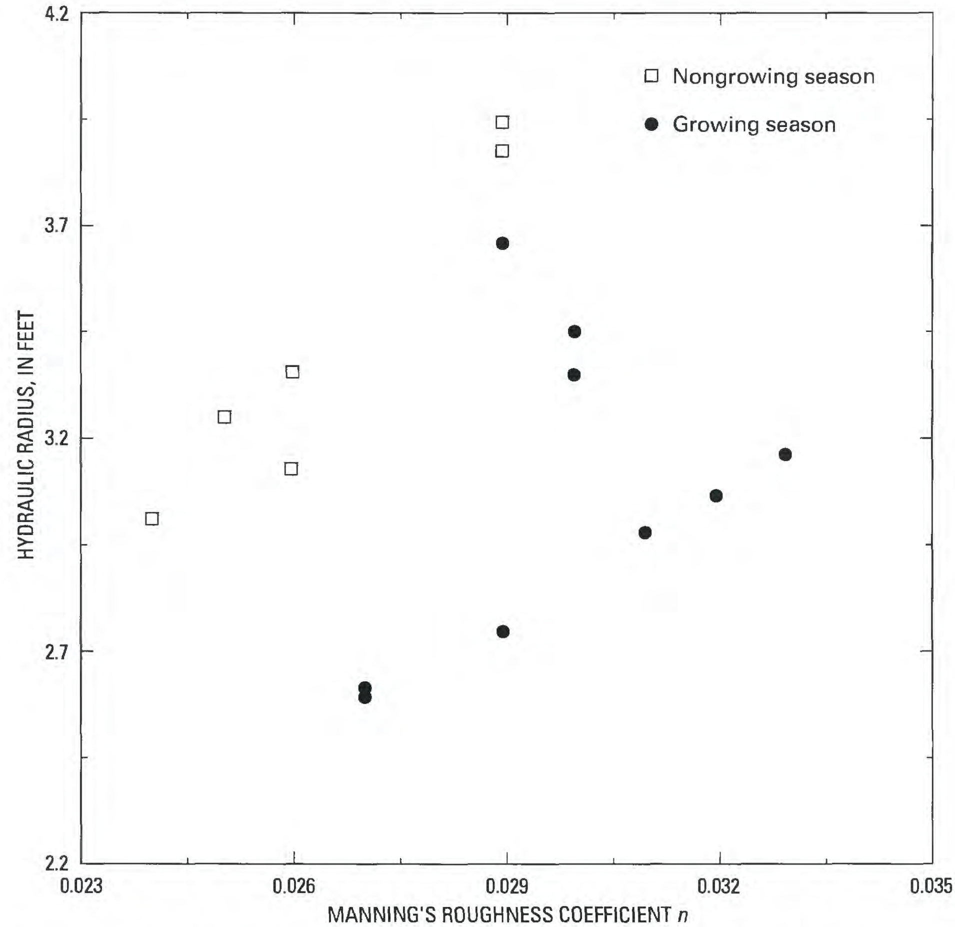


Figure 9. Relation between Manning's roughness coefficient and hydraulic radius at Scajaquada Creek at Buffalo, N.Y.

Table 8. Station description and summary of hydraulic data, Moordener Kill at Castleton-on-Hudson, N.Y.

Location.—Latitude 42°32'02" N., longitude 73°44'15" W., Rensselaer County, on left bank 800 ft downstream from bridge on State Highway 150, 0.2 mi east of village of Castleton-on-Hudson, 0.5 mi downstream from unnamed tributary, and 1.2 mi upstream from mouth. A 2-section, 141-ft-long reach is 0.25 mi upstream from bridge on State Highway 150.

USGS station-identification number.—01359750.

Drainage area.—32.6 mi^2.

Bed material.—Small gravel and sand over bedrock. Intermediate diameter $d_{50} = 0.05$ ft and $d_{84} = 0.14$ ft. Minimum diameter $d_{50} = 0.02$ ft.

Bank description.—Both banks have a few trees, 2 to 3 ft in diameter; sparsely spaced about 20 ft apart. Dense woody brush and vines cover most of the banks. Summertime growth of leaves, grasses, and soft-stemmed plants essentially doubles the vegetation cover. Vegetation indices: 2, nongrowing season; 4, growing season.

Remarks.—The *n* values computed for this site are affected by streambank vegetation.

Summary of Hydraulic Data

[ft, feet; ft^2, square feet; ft/s, feet per second; ft^3/s, cubic feet per second]

Discharge (ft^3/s)	Average values for reach					Water-surface slope	Energy gradient	Percent wetted perimeter vegetated	Manning's *n*
	Area (ft^2)	Width (ft)	Hydraulic radius (ft)	Velocity (ft/s)	Froude number				
[1,2]77	46.1	37.0	1.26	1.70	0.27	0.00156	0.00164	6.7	0.041
[1]122	56.4	38.1	1.48	2.18	.32	.00156	.00164	9.6	.036
[1]140	60.6	38.6	1.57	2.32	.33	.00121	.00130	10.9	.031
[3]250	93.2	42.3	2.16	2.68	.32	.00142	.00145	19.5	.035
333	104	43.5	2.33	3.20	.36	.00156	.00158	21.9	.032
[1,3]374	123	45.9	2.60	3.04	.33	.00170	.00166	26.5	.038
409	127	46.6	2.63	3.23	.34	.00149	.00147	27.4	.034

[1]The *n* value computed for this discharge and water-surface profile is affected by 14 to 22 percent flow-area expansion in the reach. The total water-surface fall is less than 0.25 ft.

[2]The data used for this *n*-value calculation were collected during the growing season.

[3]The data used for this *n*-value calculation were collected during the late fall before snow accumulation and appear to reflect the effect of streambank vegetation in a manner similar to data collected during the growing season.

Figure 10. Photographs of Moordener Kill at Castleton-on-Hudson, N.Y. *A*, At cross section 1, facing downstream along left bank during late fall. Hydrographer at section 2 is holding a stadia rod at the approximate water-surface elevation of the maximum recorded discharge. *B*, At cross section 1, facing downstream along left bank during growing season. Self-supported 10-ft stadia rod is near section 2. *C*, At cross section 2, facing upstream toward right bank during late fall. Hydrographer at section 1 is holding a stadia rod at the approximate water-surface elevation of the maximum recorded discharge. *D*, At cross section 2, facing upstream toward right bank during growing season. Self-supported 10-ft stadia rod is near section 1.

Figure 10. Continued.

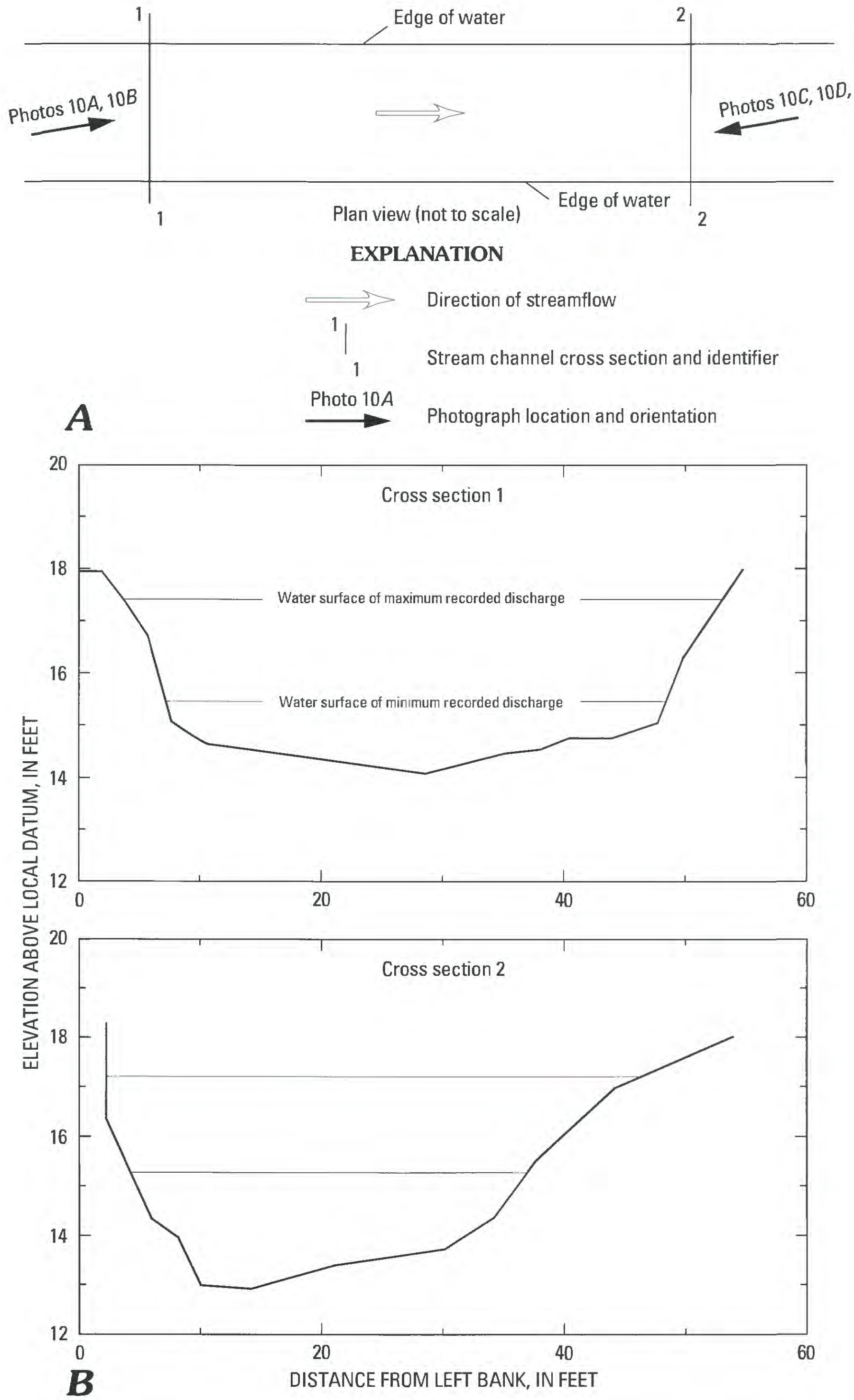


Figure 11. Plan view (*A*) and cross sections (*B*), Moordener Kill at Castleton-on-Hudson, N.Y. Photographs are shown in figure 10.

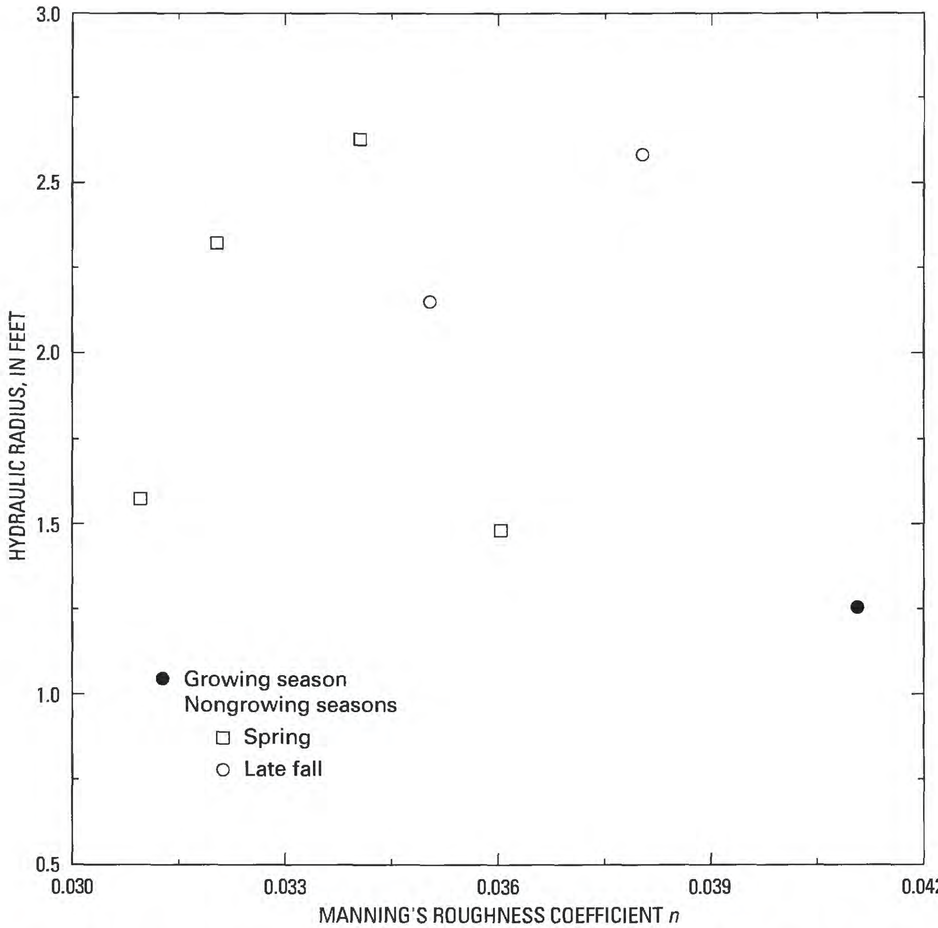


Figure 12. Relation between Manning's roughness coefficient and hydraulic radius at Moordener Kill at Castleton-on-Hudson, N.Y.

Table 9. Station description and summary of hydraulic data, Canisteo River at Arkport, N.Y.

Location.—Latitude 42°23'45" N., longitude 77°42'42" W., Steuben County, on left bank 0.2 mi downstream from Arkport Dam, and 0.9 mi west of Arkport. A 3-section, 269-ft-long reach; section 1 is about 430 ft upstream from gage.

USGS station-identification number.—01521500.

Drainage area.—30.6 mi^2.

Bed material.—Small cobbles, mostly flat. Intermediate diameter d_{50} = 0.32 ft and d_{84} = 0.49 ft. Minimum diameter d_{50} = 0.09 ft.

Bank description.—Both banks have brush and a few trees, 0.5 to 2.0 ft in diameter and spaced 20 to 50 ft apart. The brush is denser on the left bank than on the right. Both banks have exposed tree roots. Vegetation indices: 1.5, nongrowing season; 2.5, growing season.

Remarks.—Flows exceeding 500 ft^3/s are controlled by detention in Arkport Reservoir. A fallen tree trunk, about 0.5 ft in diameter, spans the channel between sections 2 and 3. The effect of this obstruction on the computed *n* values for the highest recorded flows is considered minimal. The *n* values computed at this site are affected by streambank vegetation.

Summary of Hydraulic Data

[ft, feet; ft^2, square feet; ft/s, feet per second; ft^3/s, cubic feet per second]

Discharge (ft^3/s)	Average values for reach: Area (ft^2)	Width (ft)	Hydraulic radius (ft)	Velocity (ft/s)	Froude number	Water-surface slope	Energy gradient	Percent wetted perimeter vegetated	Manning's *n*
				Data collected during the nongrowing season					
[1]145	57.2	30.2	1.84	2.57	0.33	0.00223	0.00233	19.6	0.042
[2]204	62.1	30.8	1.95	3.30	.41	.00286	.00296	21.4	.039
[2]262	71.2	31.8	2.16	3.70	.44	.00264	.00277	24.2	.036
[2]451	91.0	34.4	2.54	4.98	.54	.00256	.00276	30.2	.030
[2]489	97.4	35.3	2.64	5.03	.54	.00309	.00316	32.2	.032
[2]505	103	36.4	2.70	4.94	.52	.00256	.00274	34.2	.031
[2]511	96.0	35.2	2.62	5.34	.57	.00271	.00290	31.9	.029
[2]517	102	36.3	2.70	5.07	.53	.00256	.00275	34.0	.030
[2]517	104	36.5	2.73	4.98	.52	.00305	.00312	34.4	.033
[3]522	108	37.4	2.78	4.83	.50	.00297	.00308	36.1	.034
[2]564	108	37.2	2.77	5.27	.55	.00245	.00267	35.7	.029
[3]576	109	37.5	2.80	5.27	.54	.00286	.00301	36.2	.031
				Data collected during the growing season					
[1]177	53.5	29.7	1.75	3.36	.45	.00216	.00235	18.3	.031
[2]489	99.5	35.8	2.67	4.93	.52	.00290	.00300	33.0	.032
[2]582	104	36.7	2.73	5.59	.59	.00279	.00296	34.7	.029
[3]600	118	38.6	2.92	5.10	.51	.00305	.00316	38.0	.034
[3]632	119	38.8	2.95	5.29	.53	.00294	.00306	38.4	.033
[3]671	125	39.4	3.03	5.38	.53	.00301	.00314	39.5	.033

[1]The *n* value computed for this discharge and water-surface profile is affected by flow-area expansion of greater than 20 percent.

[2]The *n* value computed for this discharge and water-surface profile is affected by flow-area expansion of between 10 and 20 percent.

[3]The *n* value computed for this discharge and water-surface profile is affected by flow-area expansion of less than 10 percent.

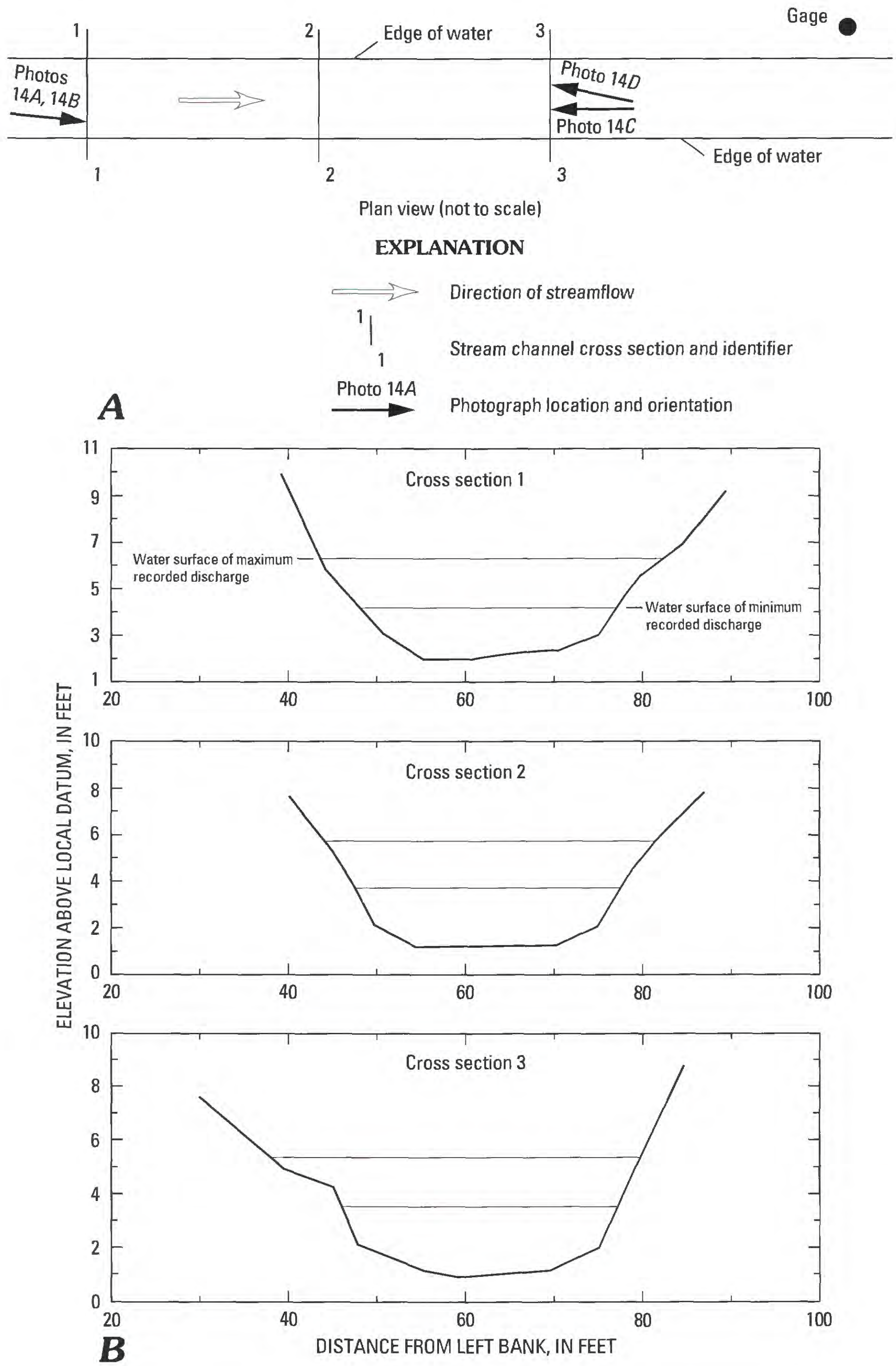


Figure 13. Plan view (*A*) and cross sections (*B*), Canisteo River at Arkport, N.Y. Photographs are shown in figure 14.

Figure 14. Photographs of Canisteo River at Arkport, N.Y. *A*, Near cross section 1, facing downstream toward right bank during late fall. Hydrographer at section 2 is holding a 15-ft rod at the approximate water-surface elevation of the maximum recorded discharge. *B*, Near cross section 1, facing downstream toward right bank during growing season. Self-supported stadia rod is between sections 1 and 2. *C*, Near cross section 3, facing upstream during late fall. Hydrographer at section 2 is holding a 15-ft rod at the approximate water-surface elevation of the maximum recorded discharge. *D*, Near cross section 3, facing upstream toward left bank during growing season. Self-supported stadia rod is between sections 2 and 3.

Figure 14. Continued.

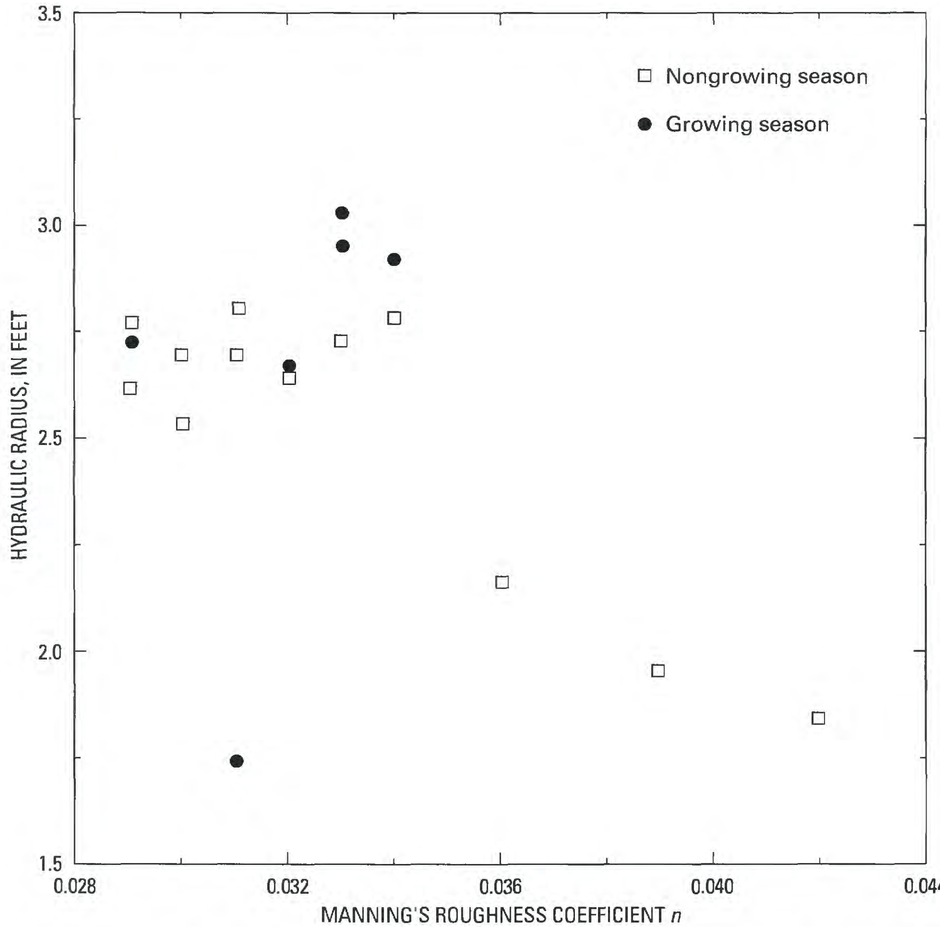


Figure 15. Relation between Manning's roughness coefficient and hydraulic radius at Canisteo River at Arkport, N.Y.

Table 10. Station description and summary of hydraulic data, Mill Brook near Dunraven, N.Y.

Location.—Latitude 42°06'22" N., longitude 74°43'51" W., Delaware County, on left bank 0.4 mi upstream from bridge on New York City Road 9 and Pepacton Reservoir, and 2.7 mi southwest of Dunraven. A 3-section, 227-ft-long reach; section 1 is about 0.2 mi upstream from bridge on New York City Road 9.

USGS station-identification number.—01414500.

Drainage area.—25.2 mi^2.

Bed material.—Rounded or flat cobbles and boulders. Intermediate diameter d_{50} = 0.45 ft and d_{84} = 0.91 ft. Minimum diameter d_{50} = 0.14 ft.

Bank description.—Left bank has low overflow area covered with grassy hummocks; brush and large rock riprap are beyond. Right bank is gradually sloped, vegetated with grasses above low-water channel and scattered trees halfway up bank and beyond. Vegetation indices: 1, nongrowing season; 2, growing season (low-overflow area not included).

Remarks.—The highest flow during the period of study was at a level below the point at which trees are found on the right bank. The percentages of wetted perimeter that are vegetated are high in comparison with those at other sites because the vegetated overflow area on the left bank is included in these values. The discharge record at this site during the study period is of fair to poor (rather than "good") accuracy.

Summary of Hydraulic Data

[ft, feet; ft^2, square feet; ft/s, feet per second; ft^3/s, cubic feet per second]

Discharge (ft^3/s)	Average values for reach					Water-surface slope	Energy gradient	Percent wetted perimeter vegetated	Manning's *n*
	Area (ft^2)	Width (ft)	Hydraulic radius (ft)	Velocity (ft/s)	Froude number				
[1]109	43.7	38.1	1.14	2.52	0.43	0.00991	0.00990	0	0.062
[2]169	63.4	43.4	1.38	2.67	.44	.01013	.01015	15.6	.069
[1]201	61.3	43.0	1.37	3.30	.50	.01115	.01095	13.1	.057
[3]217	63.2	44.0	1.34	3.44	.54	.01040	.01041	11.4	.054
[1,3]809	132	56.0	2.22	6.16	.71	.01035	.01064	29.3	.042
[1]1,720	215	61.9	3.26	8.04	.76	.01000	.01063	40.7	.042
[1]2,500	245	62.7	3.66	10.23	.91	.00978	.01080	42.0	.035

[1]The *n* value computed for this discharge and water-surface profile is affected by 10 to 22 percent flow-area expansion in the reach.
[2]The data used for this *n*-value calculation were collected during the growing season.
[3]Data from the middle cross section were not available for computations for this water-surface profile.

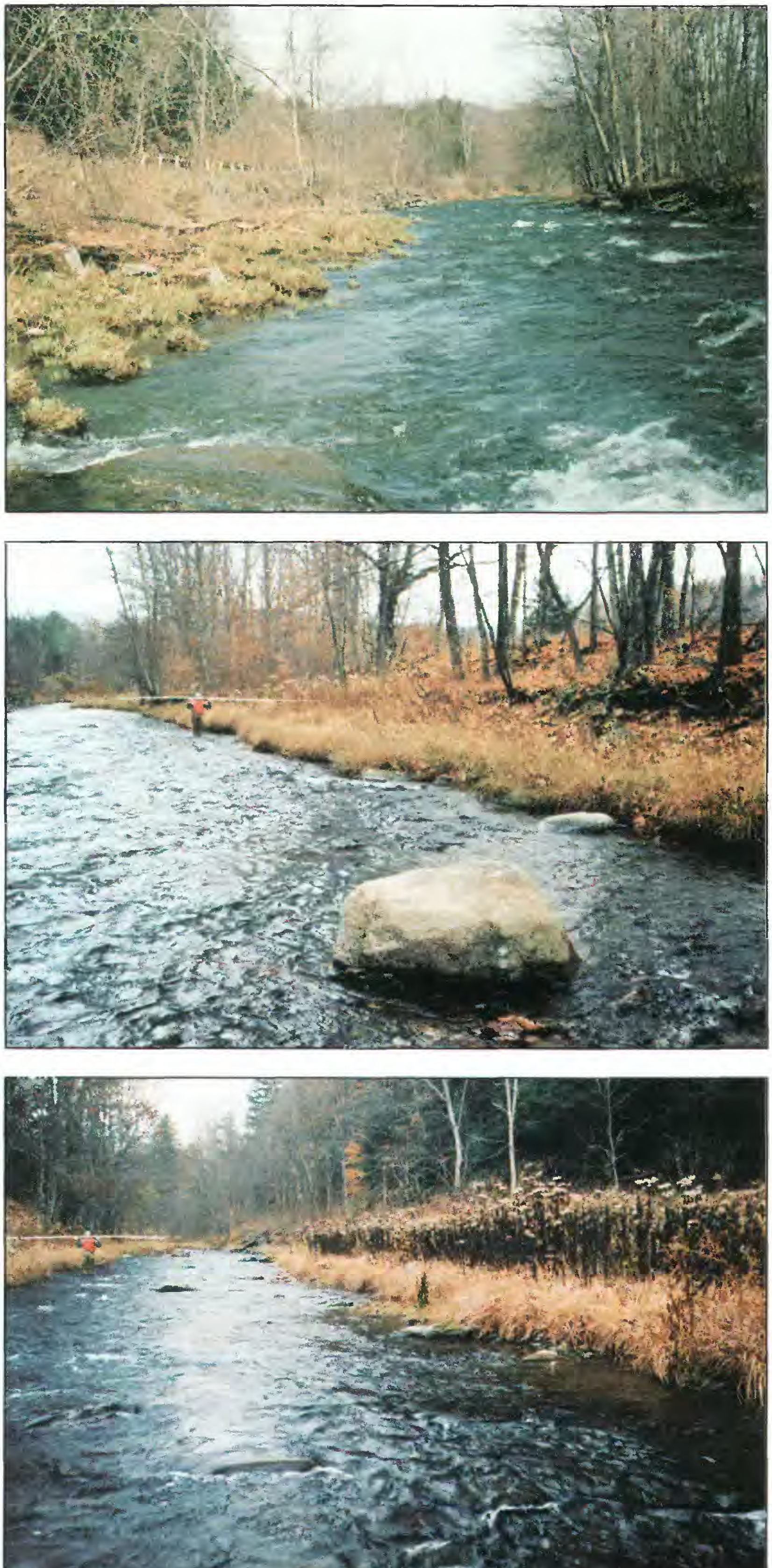


Figure 16. Photographs of Mill Brook near Dunraven, N.Y. *A*, At cross section 1, facing downstream toward left bank during nongrowing season. *B*, At cross section 1, facing downstream toward right bank during late fall. Hydrographer at section 2 is holding a 25-ft rod at the approximate water-surface elevation of the maximum recorded discharge. *C*, At cross section 3, facing upstream toward left bank during late fall. Hydrographer at section 2 is holding a 25-ft rod at the approximate water-surface elevation of the maximum recorded discharge.

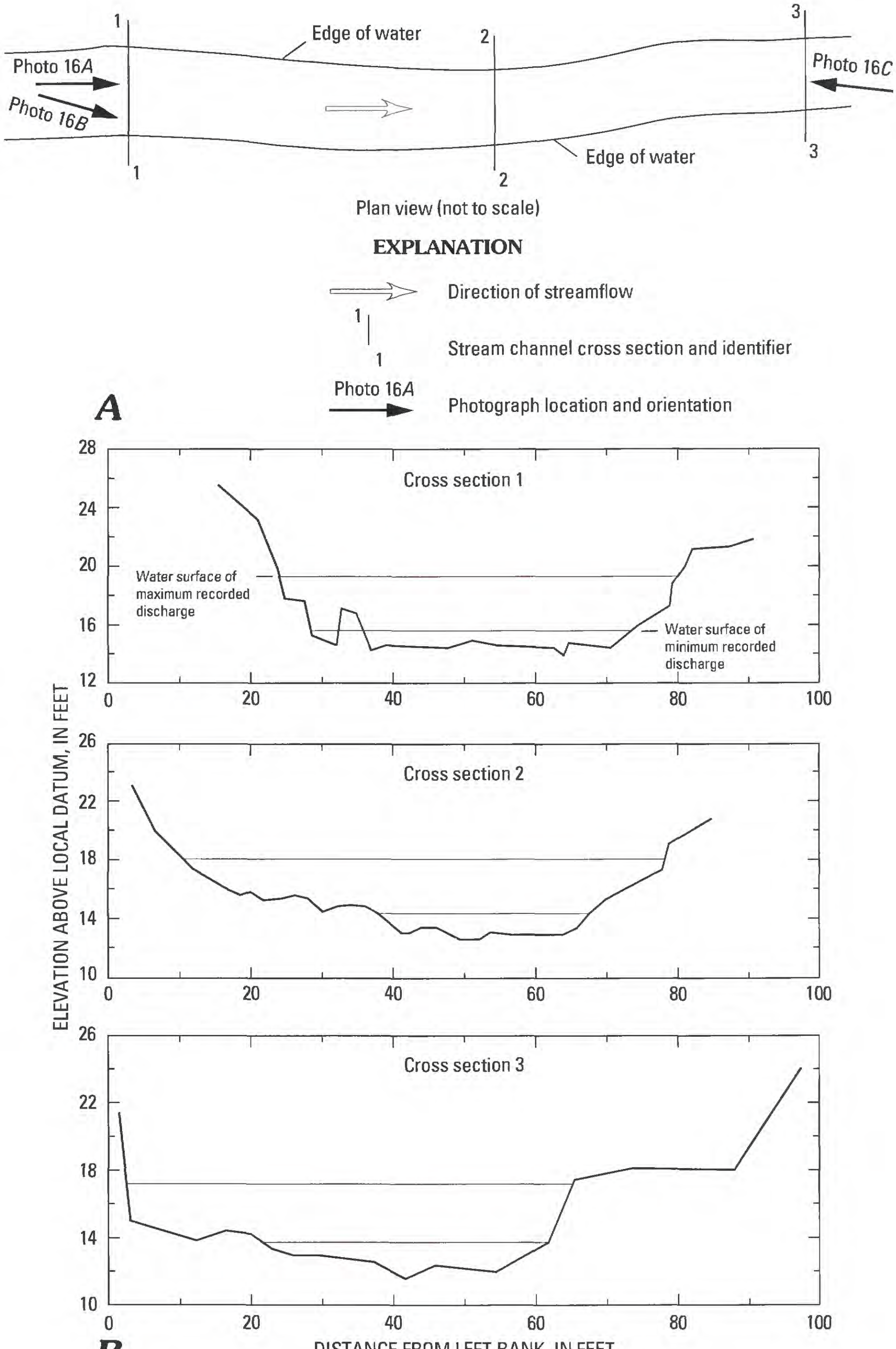


Figure 17. Plan view (*A*) and cross sections (*B*), Mill Brook near Dunraven, N.Y. Photographs are shown in figure 16.

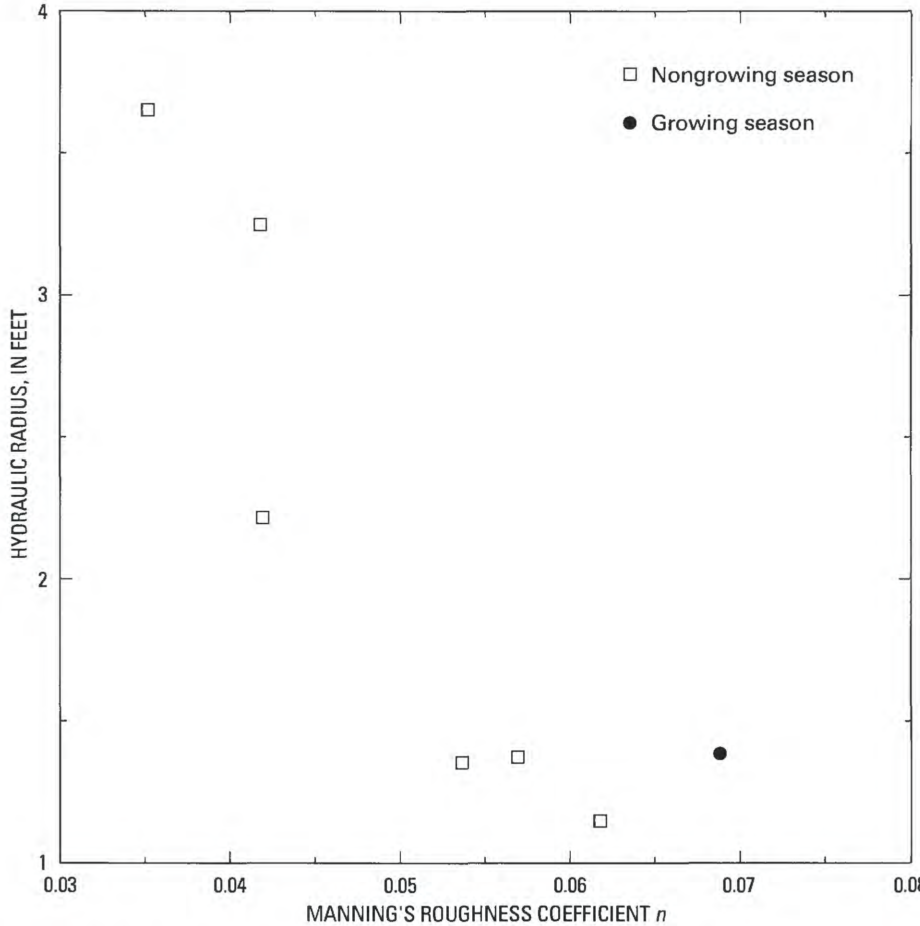


Figure 18. Relation between Manning's roughness coefficient and hydraulic radius at Mill Brook near Dunraven, N.Y.

Table 11. Station description and summary of hydraulic data, East Branch Ausable River at Au Sable Forks, N.Y.

Location.—Latitude 44°26'20" N., longitude 73°40'55" W., Essex County, on left bank 700 ft upstream from bridge on Burt Street in Au Sable Forks, and 0.5 mi upstream from confluence with West Branch. A 2-section, 202-ft-long reach is about 0.5 mi upstream from gage.

USGS station-identification number.—04275000.

Drainage area.—198 mi².

Bed material.—Cobbles and boulders as much as 7 ft in diameter. Intermediate diameter d_{50} = 1.0 ft and d_{84} = 2.5 ft. Minimum diameter d_{50} = 0.60 ft.

Bank description.—Both banks are vegetated with dense woody brush, annual plants, grass, and trees 0.5 to 1.5 ft in diameter. Trees are smaller and more densely spaced (about 50 ft apart) on left bank than on the right. Vegetation indices: 2.5, nongrowing season; 3, growing season.

Previous n-*value computation.*—The roughness coefficient was computed for the flood of March 31, 1951, at a site on this stream about 0.25 mi upstream of the study site. The data for that computation, taken from Barnes (1967), are included in the table below.

Remarks.—The *n* values computed at this site are presumed to be affected by streambank vegetation.

Summary of Hydraulic Data

[ft, feet; ft², square feet; ft/s, feet per second; ft³/s, cubic feet per second; —, no value presented]

Discharge (ft³/s)	Average values for reach					Water-surface slope	Energy gradient	Percent wetted perimeter vegetated	Manning's *n*
	Area (ft²)	Width (ft)	Hydraulic radius (ft)	Velocity (ft/s)	Froude number				
3,790	673	177	3.60	5.64	0.52	0.00861	0.00826	30.5	0.056
4,210	730	188	3.73	5.78	.52	.00871	.00835	33.7	.056
[1]5,720	907	209	4.18	6.31	.53	.00842	.00818	40.4	.055
6,290	978	213	4.42	6.44	.53	.00856	.00831	41.2	.057
8,790	1,230	224	5.32	7.13	.53	.00797	.00795	44.0	.057
10,800	1,400	230	5.85	7.74	.55	.00822	.00815	45.4	.056
[2]7,790	1,070	152	6.72	7.26	.48	.00562	—	—	.055

[1]The data used for this *n*-value calculation were collected during the growing season.

[2]From Barnes (1967).

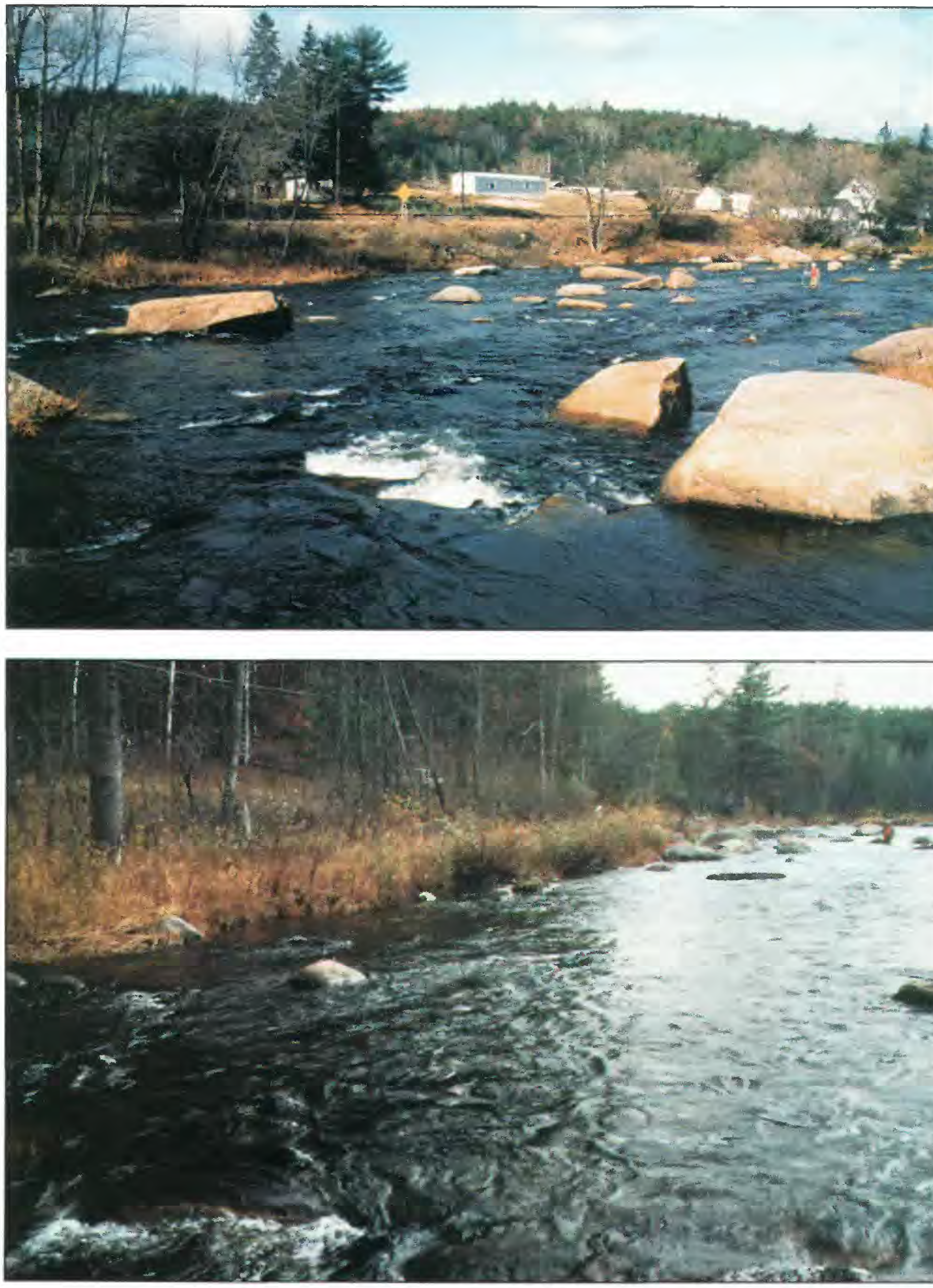


Figure 19. Photographs of East Branch Ausable River at Au Sable Forks, N.Y. *A*, Upstream from cross section 1, facing downstream and across the channel. Hydrographer is at section 2. *B*, Downstream from cross section 2, facing upstream along right bank. Hydrographer is at section 1.

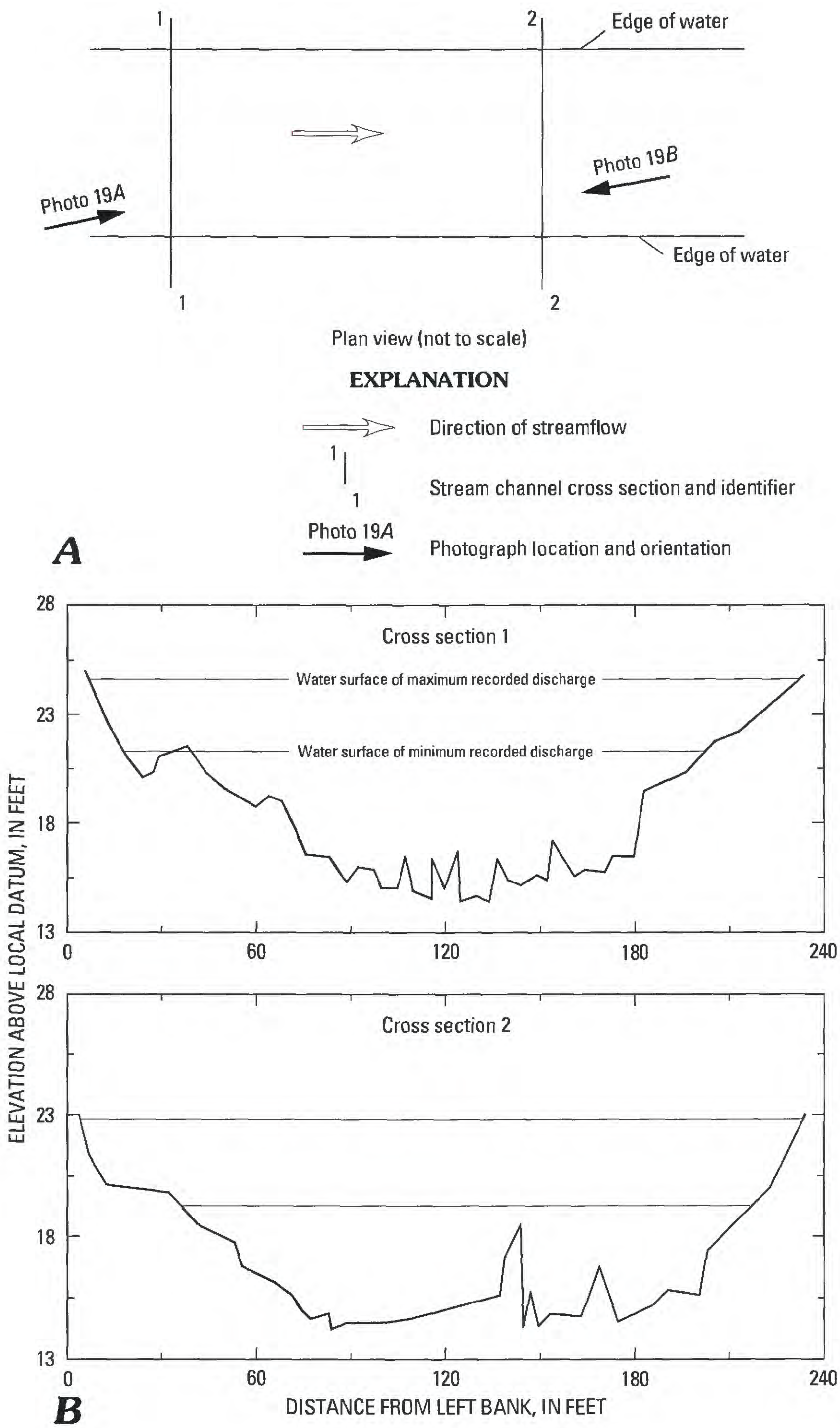


Figure 20. Plan view (*A*) and cross sections (*B*), East Branch Ausable River at Au Sable Forks, N.Y. Photographs are shown in figure 19.

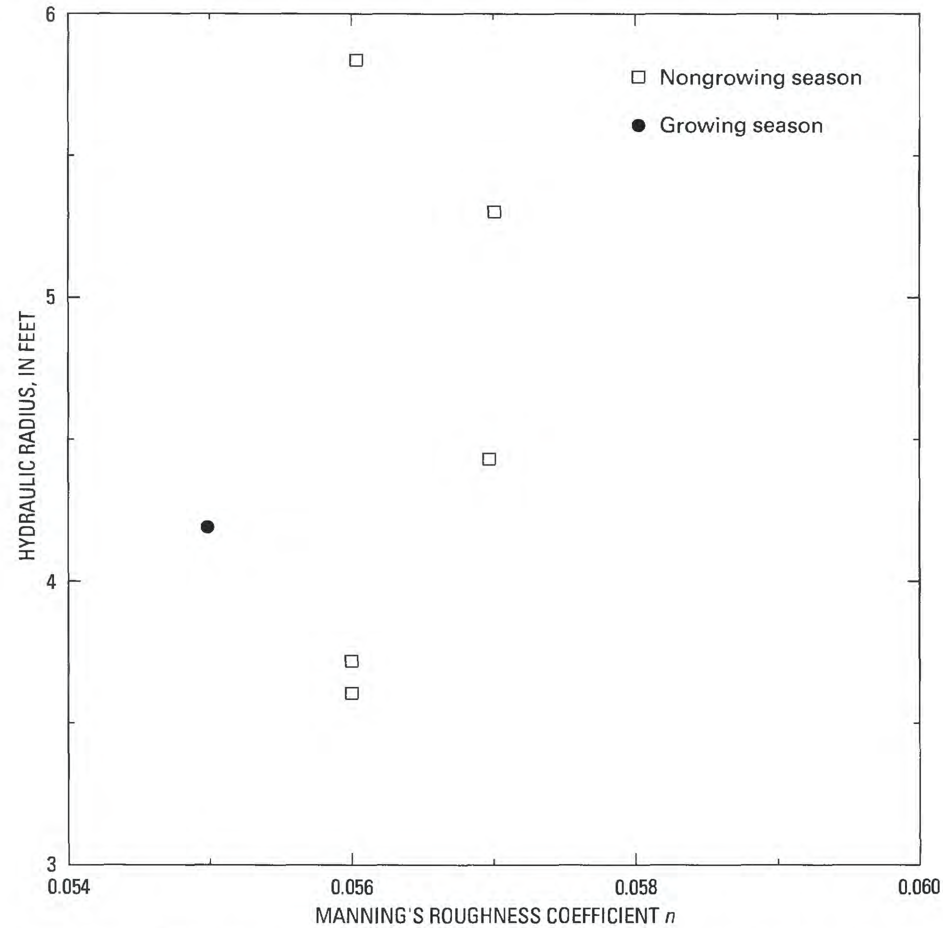


Figure 21. Relation between Manning's roughness coefficient and hydraulic radius at East Branch Ausable River at Au Sable Forks, N.Y.

Table 12. Station description and summary of hydraulic data, Beaver Kill at Cooks Falls, N.Y.

Location.—Latitude 41°56'47" N., longitude 74°58'48" W., Delaware County, on left bank 66 ft downstream from road bridge in Cooks Falls, and 5.5 mi downstream from Willowemoc Creek. A 3-section, 569-ft-long reach is 0.5 mi upstream from bridge in Cooks Falls and gage.

USGS station-identification number.—01420500.

Drainage area.—241 mi^2.

Bed material.—Rounded cobbles and boulders. Intermediate diameter d_{50} = 0.78 ft and d_{84} = 1.70 ft. Minimum diameter d_{50} = 0.30 ft.

Bank description.—Left bank is steep and has boulders, cobbles, and scattered trees of varying sizes. Tree density is greater on left bank than on right. Dense woody brush, willow saplings, and grasses cover low right bank. A few trees with diameters ranging from 0.5 to 2.0 ft occupy the high right bank. Vegetation indices: 2, nongrowing season; 3, growing season.

Previous n-value computation.—The roughness coefficient was computed for the flood of March 22, 1948, at a site on this stream about 0.5 mi downstream of the gage and 1.0 mi downstream of the study site. The data for that computation, taken from Barnes (1967), are included in the following table.

Summary of Hydraulic Data

[ft, feet; ft^2, square feet; ft/s, feet per second; ft^3/s, cubic feet per second; —, no value presented]

Discharge (ft^3/s)	Average values for reach					Water-surface slope	Energy gradient	Percent wetted perimeter vegetated	Manning's *n*
	Area (ft^2)	Width (ft)	Hydraulic radius (ft)	Velocity (ft/s)	Froude number				
[1]575	276	174	1.58	2.09	0.29	0.00409	0.00406	0	0.062
2,520	581	189	3.05	4.35	.44	.00417	.00405	0	.047
4,970	824	199	4.11	6.03	.52	.00408	.00397	.5	.040
[2]8,710	1,160	208	5.50	7.52	.56	.00448	.00432	5.2	.041
[2]9,520	1,200	209	5.68	7.93	.58	.00471	.00445	5.7	.040
[1,2]10,100	1,240	210	5.81	8.18	.59	.00439	.00424	6.1	.039
[2]10,500	1,230	210	5.80	8.54	.62	.00455	.00428	6.1	.037
19,800	1,710	219	7.66	11.61	.73	.00503	.00466	10.3	.034
23,900	1,900	222	8.39	12.56	.76	.00511	.00474	11.9	.034
[3]15,500	1,650	224	7.27	9.39	.61	.00338	—	—	.033

[1]The data used for this *n*-value calculation were collected during the growing season.

[2]The *n* value computed for this discharge and water-surface profile is affected by flow over a low bank on the right side of the reach.

[3]From Barnes (1967).

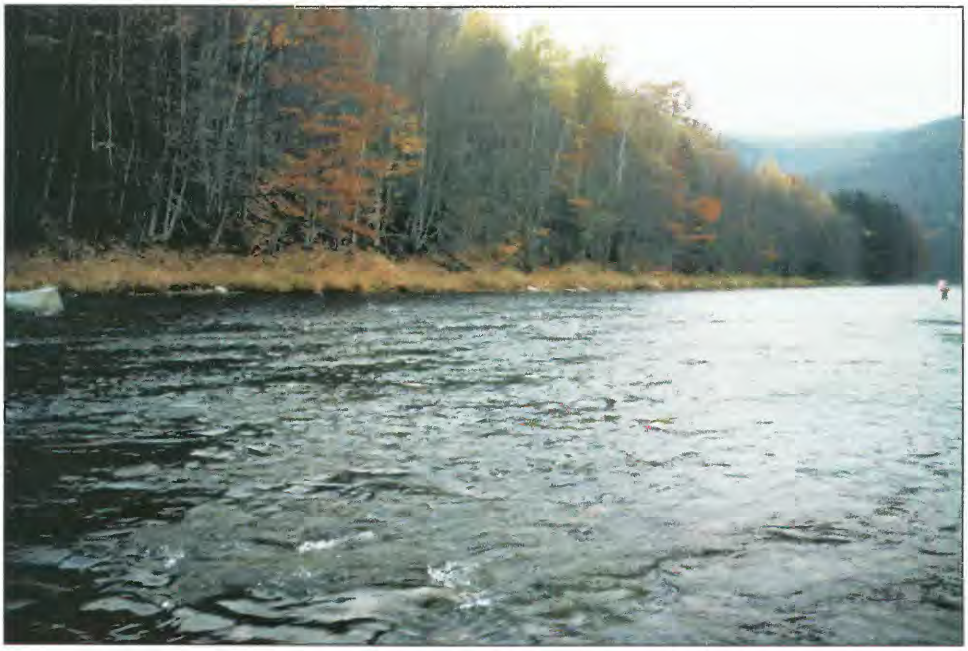


Figure 22. Photographs of Beaver Kill at Cooks Falls, N.Y. *A*, At cross section 1, facing downstream toward left bank during late fall. Hydrographer along right edge of photograph is at section 2. *B*, Upstream from cross section 1, facing downstream toward left bank during growing season. *C*, At cross section 3, facing upstream toward right bank during late fall. Hydrographer is at section 2. *D*, Downstream from cross section 3, facing upstream toward right bank during growing season.

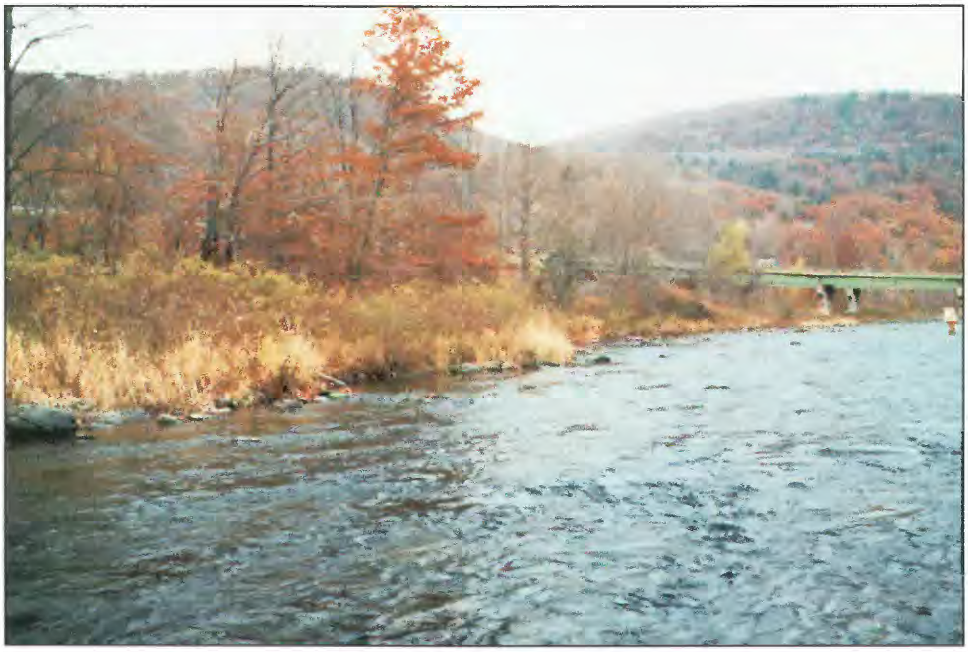


Figure 22. Continued.

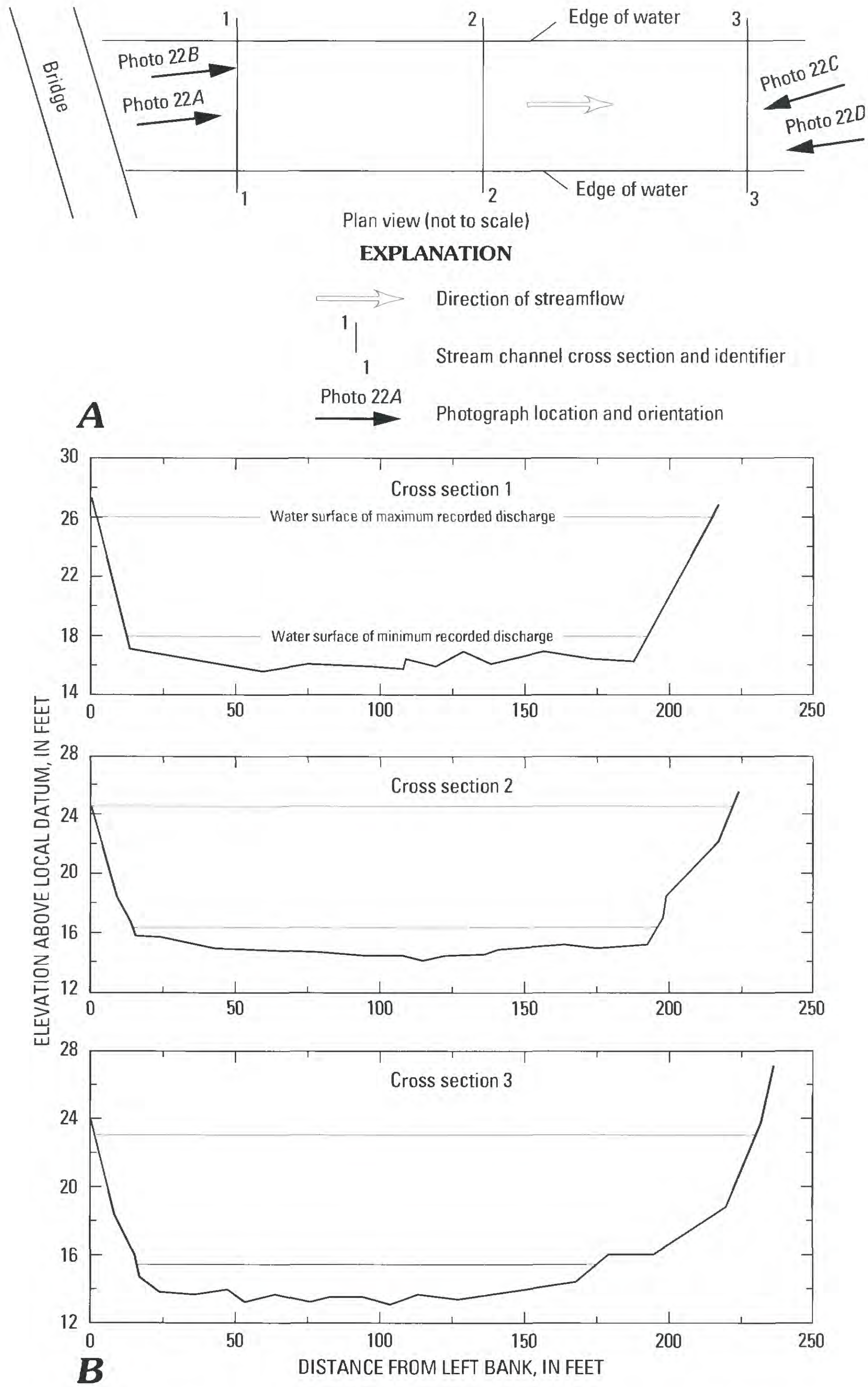


Figure 23. Plan view (*A*) and cross sections (*B*), Beaver Kill at Cooks Falls, N.Y. Photographs are shown in figure 22.

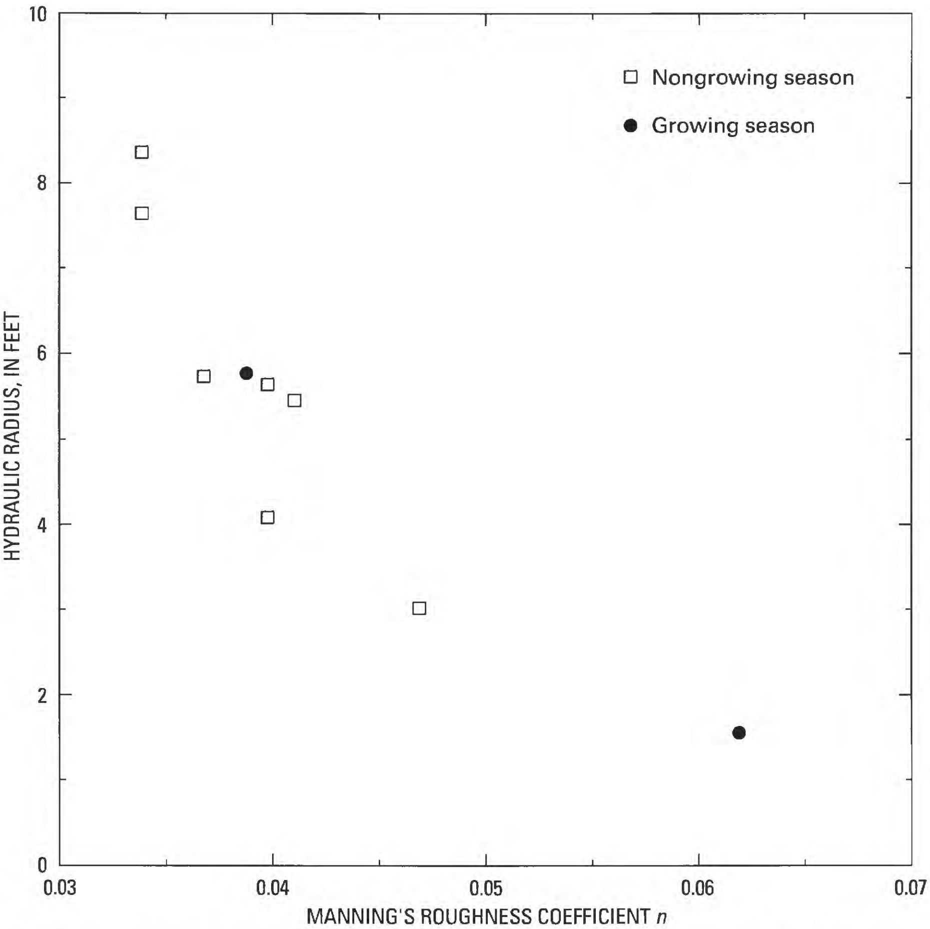


Figure 24. Relation between Manning's roughness coefficient and hydraulic radius at Beaver Kill at Cooks Falls, N.Y.

Table 13. Station description and summary of hydraulic data, Onondaga Creek at Dorwin Avenue, Syracuse, N.Y.

Location.—Latitude 42°59'00" N., longitude 76°09'04" W., Onondaga County, on left bank 550 ft upstream from bridge on Dorwin Avenue, at Syracuse, and 4 mi downstream from Onondaga Reservoir. A 2-section, 265-ft-long reach; section 1 is 185 ft downstream from bridge on Dorwin Avenue.

USGS station-identification number.—04239000.

Drainage area.—88.5 mi^2.

Bed material.—Gravel and small cobbles. Intermediate diameter d_{50} = 0.13 ft and d_{84} = 0.21 ft. Minimum diameter d_{50} = 0.07 ft.

Bank description.—This reach is a maintained grass-lined channel. Riprap lines the lower part of right bank. Vegetation indices: 0, nongrowing season; 0, growing season.

Remarks.—High flows are controlled by detention in Onondaga Reservoir.

Summary of Hydraulic Data

[ft, feet; ft^2, square feet; ft/s, feet per second; ft^3/s, cubic feet per second]

Discharge (ft^3/s)	Average values for reach					Water-surface slope	Energy gradient	Percent wetted perimeter vegetated	Manning's *n*
	Area (ft^2)	Width (ft)	Hydraulic radius (ft)	Velocity (ft/s)	Froude number				
[1]387	124	65.2	1.88	3.16	0.41	0.00192	0.00163	5.0	0.029
406	126	65.4	1.90	3.26	.42	.00181	.00152	5.1	.027
948	214	73.1	2.87	4.46	.46	.00192	.00150	15.6	.026
994	226	74.9	2.96	4.43	.45	.00200	.00157	17.7	.028
[2]1,890	328	85.2	4.10	5.80	.48	.00234	.00145	27.8	.026

[1]The data used for this *n*-value calculation were collected during the growing season.

[2]For this *n*-value calculation, a low overbank area on the left bank, which accounts for less than 7.5 percent of the total flow area, was divided from the rest of the cross section and assigned a roughness coefficient of 0.034. Failure to subdivide the cross sections in this manner would have produced an erroneously low *n* value.

Figure 25. Photographs of Onondaga Creek at Dorwin Avenue, Syracuse, N.Y. *A*, At cross section 1, facing downstream toward right bank. Hydrographer is at section 2. *B*, At cross section 2, facing upstream toward left bank. Hydrographer at section 1 is standing at the approximate water-surface elevation of the maximum recorded discharge.

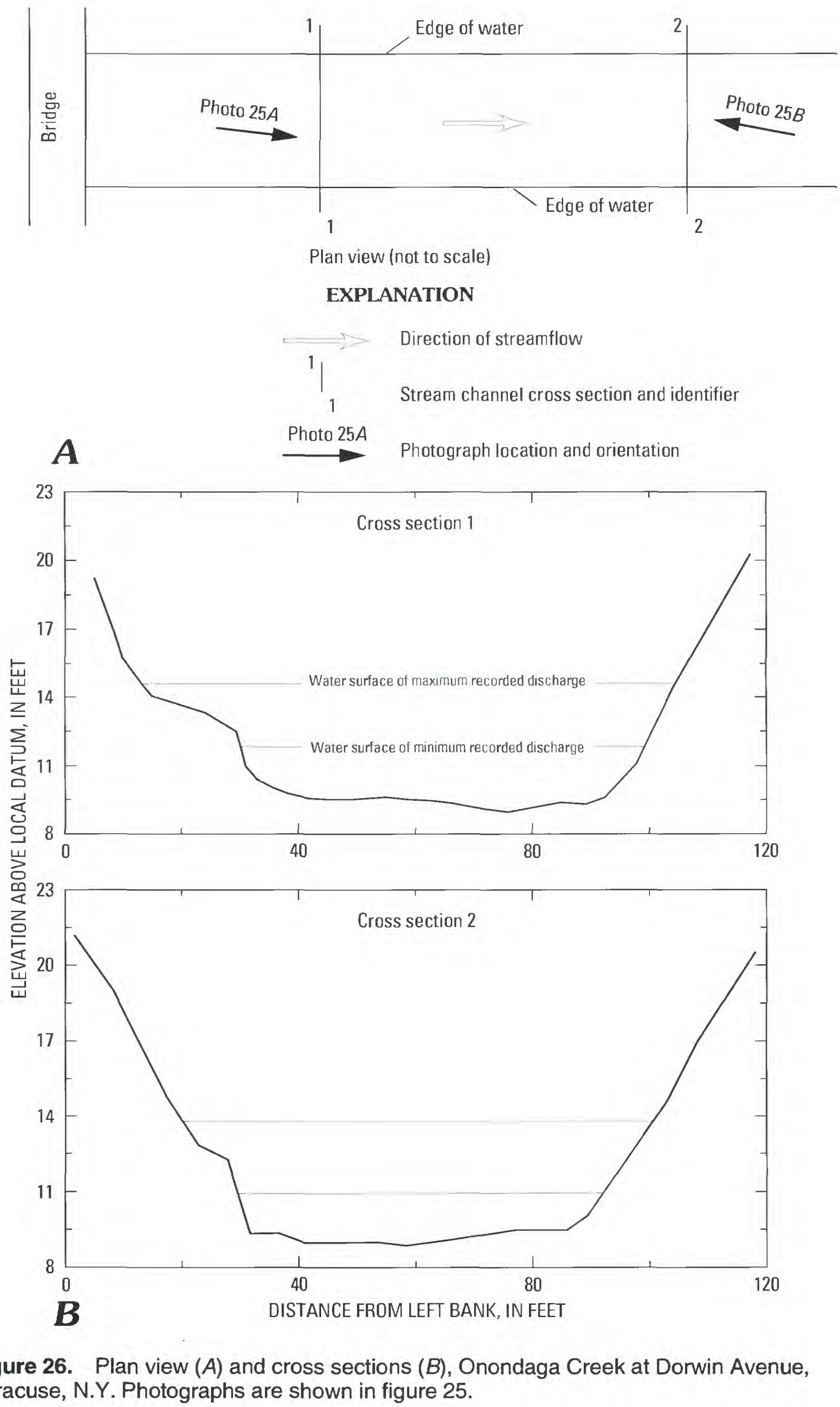


Figure 26. Plan view (*A*) and cross sections (*B*), Onondaga Creek at Dorwin Avenue, Syracuse, N.Y. Photographs are shown in figure 25.

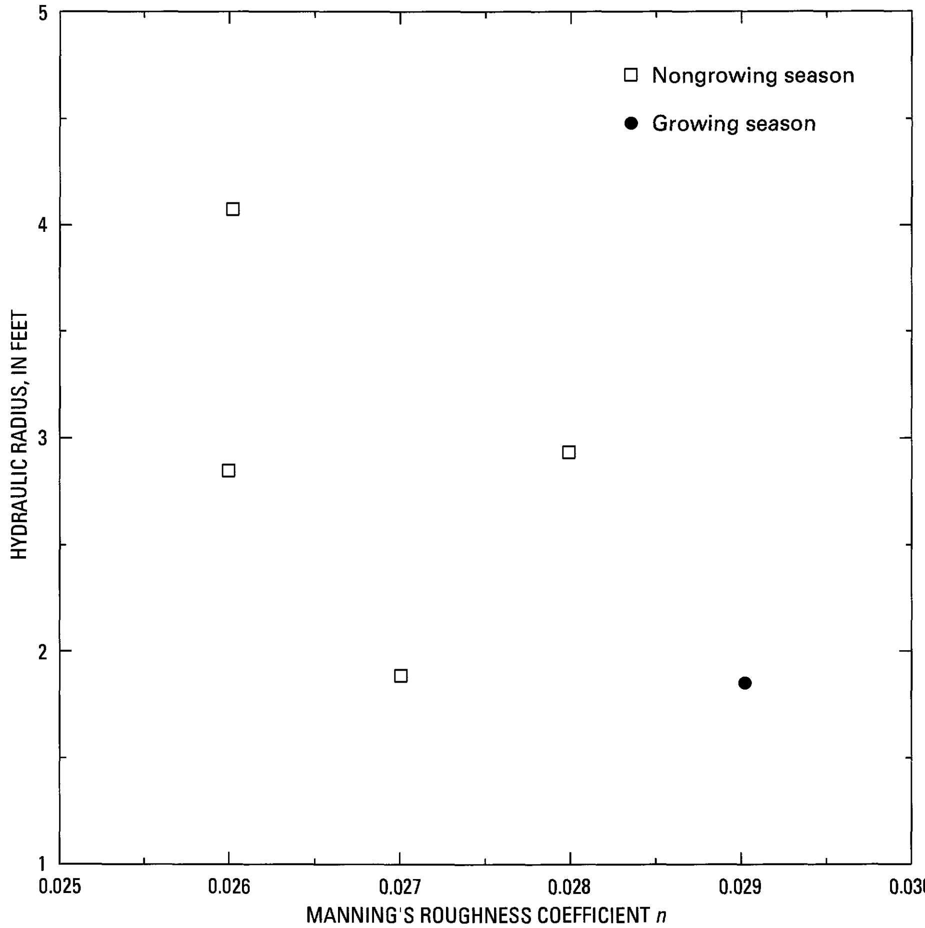


Figure 27. Relation between Manning's roughness coefficient and hydraulic radius at Onondaga Creek at Dorwin Avenue, Syracuse, N.Y.

Table 14. Station description and summary of hydraulic data, Tioughnioga River at Itaska, N.Y.

Location.—Latitude 42°17'53" N., longitude 75°54'33" W., Broome County, on right bank at Itaska, 3.8 mi downstream from Otselic River and village of Whitney Point, and 6 mi upstream from mouth. A 3-section, 1,030-ft-long reach; section 1 is at the gage.

USGS station-identification number.—01511500.

Drainage area.—730 mi^2.

Bed material.—Cobbles. Intermediate diameter d_{50} = 0.29 ft and d_{84} = 0.50 ft. Minimum diameter d_{50} = 0.09 ft.

Bank description.—Both banks have grass and brush; trees 1 to 2 ft in diameter are near top of bank. Low-overflow area on right bank at cross section 2 is vegetated with large trees spaced about 20 ft apart and summer growth of grass and ferns. Vegetation indices: 1, nongrowing season; 1.5, growing season (low-overflow area not included).

Remarks.—Floodflows are partly regulated by Whitney Point Lake. The percentages of wetted perimeter that are vegetated are high in comparison with other sites because the vegetated overflow area on the right bank at cross section 2 is included in these values. The velocity-head coefficients computed from discharge measurements made at this site range from 1.30 to 1.47 for discharges between 5,000 and 11,000 ft^3/s.

Summary of Hydraulic Data

[ft, feet; ft^2, square feet; ft/s, feet per second; ft^3/s, cubic feet per second]

Discharge (ft^3/s)	Average values for reach					Water-surface slope	Energy gradient	Percent wetted perimeter vegetated	Manning's *n*
	Area (ft^2)	Width (ft)	Hydraulic radius (ft)	Velocity (ft/s)	Froude number				
[1,2]503	370	211	1.65	1.40	0.20	0.00050	0.00050	0	0.030
[2]4,560	1,120	265	4.23	4.07	.35	.00111	.00108	17.6	.031
[2]5,420	1,230	269	4.57	4.41	.36	.00120	.00115	18.5	.031
5,640	1,280	270	4.74	4.40	.36	.00113	.00110	19.1	.031
[2]6,060	1,330	272	4.90	4.55	.36	.00119	.00114	19.4	.032
6,460	1,390	273	5.07	4.66	.36	.00118	.00113	20.0	.032
6,610	1,380	274	5.03	4.81	.38	.00133	.00126	20.0	.032
[2]7,570	1,520	277	5.45	5.00	.38	.00120	.00115	21.1	.031
[3]9,940	1,780	284	6.24	5.59	.39	.00132	.00122	24.6	.032
[3]10,100	1,810	285	6.33	5.58	.39	.00122	.00113	26.4	.031
[2,3]10,800	1,870	286	6.50	5.79	.40	.00132	.00122	29.7	.031
[3]10,900	1,880	286	6.53	5.81	.40	.00133	.00122	29.7	.032
[2,3]11,400	1,930	287	6.66	5.91	.40	.00136	.00125	32.5	.032

[1]The data used for this *n*-value calculation were collected during the growing season.

[2]The *n* values computed for each subreach differ by 0.004 to 0.008.

[3]The right-bank overflow area at cross section 3 is treated as ineffective-flow area for this *n*-value calculation. The data reflect this modification to the cross section.

Figure 28. Photographs of Tioughnioga River at Itaska, N.Y. *A*, At cross section 1, facing downstream toward right bank. *B*, At cross section 3, facing upstream along left bank. Hydrographer at section 2 is holding cross-section-identification card.

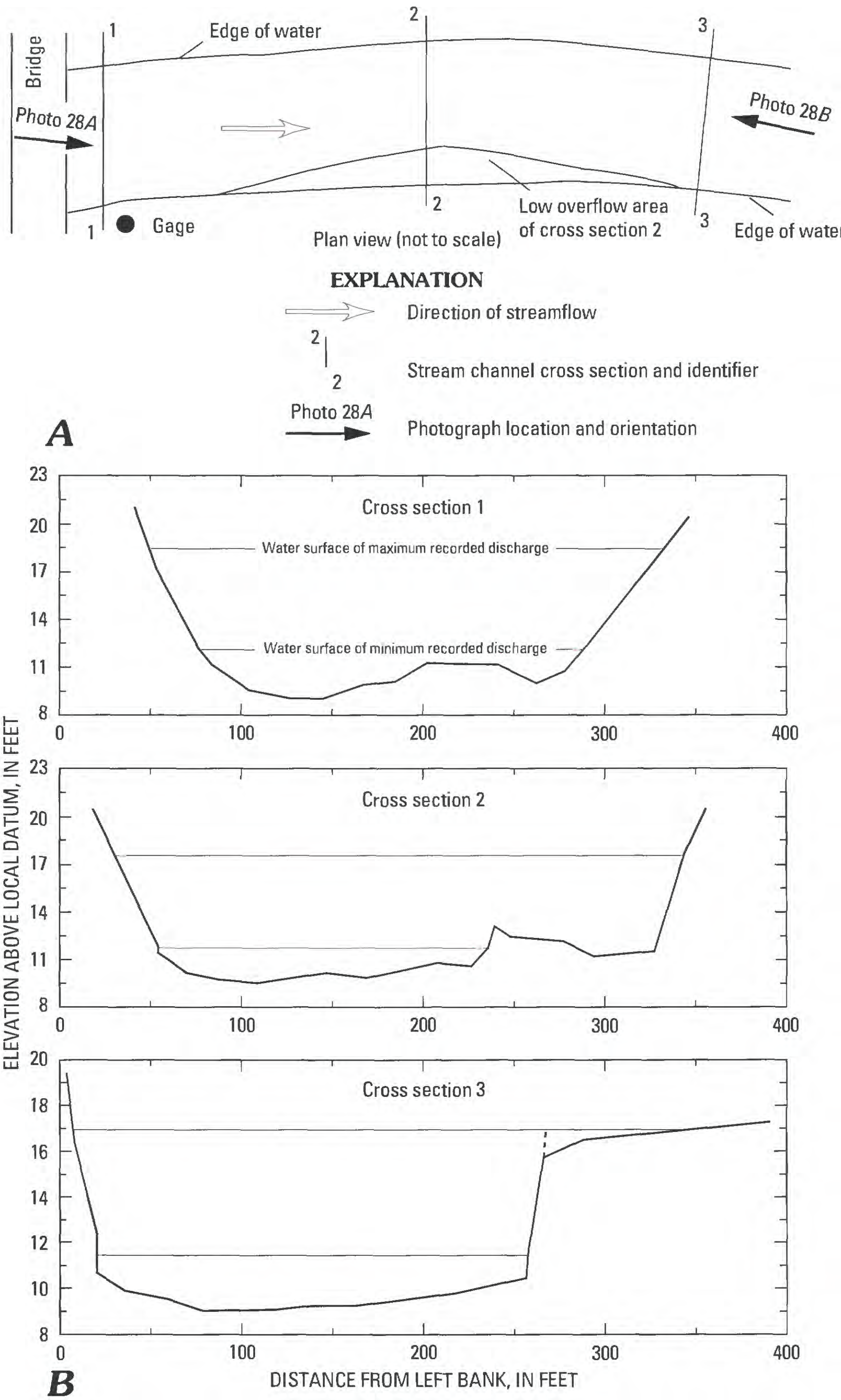


Figure 29. Plan view (*A*) and cross sections (*B*), Tioughnioga River at Itaska, N.Y. Photographs are shown in figure 28.

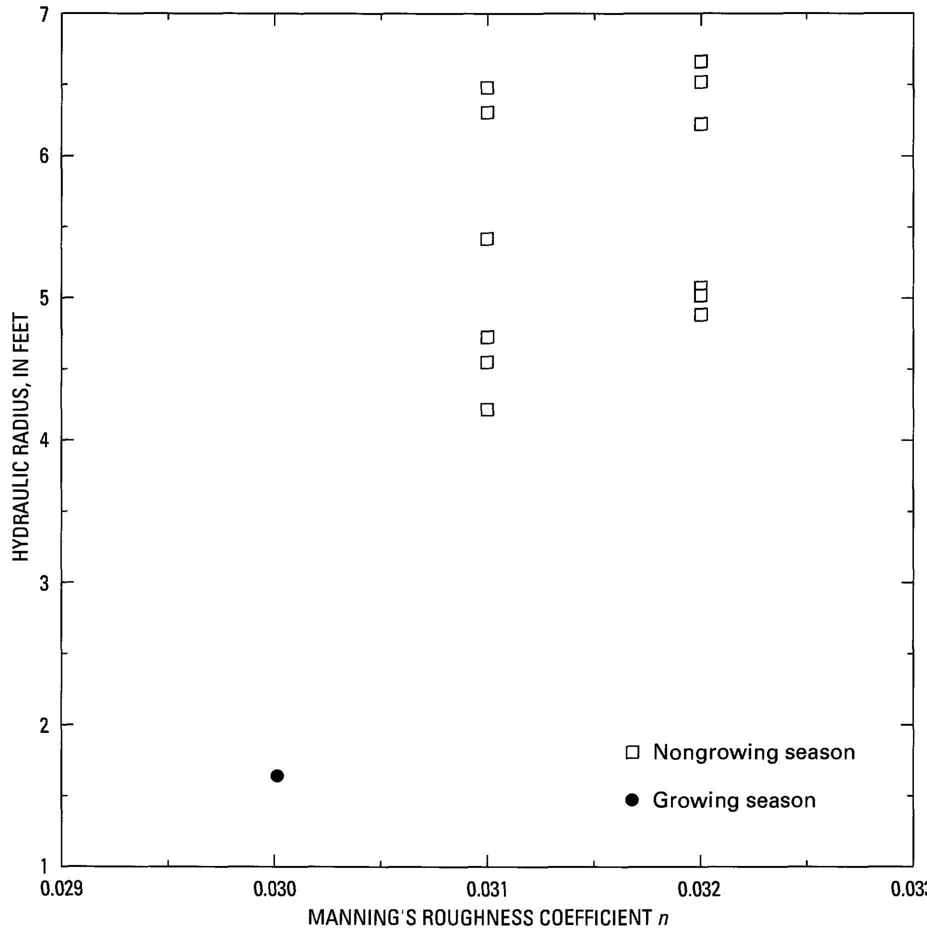


Figure 30. Relation between Manning's roughness coefficient and hydraulic radius at Tioughnioga River at Itaska, N.Y.

Table 15. Station description and summary of hydraulic data, Kayaderosseras Creek near West Milton, N.Y.

Location.—Latitude 43°02'18" N., longitude 73°54'35" W., Saratoga County, on left bank 600 ft downstream from Glowegee Creek, 1.0 mi east of West Milton, and 3.5 mi northwest of Ballston Spa. A 2-section, 203-ft-long reach; section 1 is at the gage.

USGS station-identification number.—01330500.

Drainage area.—90.0 mi^2.

Bed material.—Rounded cobbles and small boulders. Intermediate diameter d_{50} = 0.35 ft and d_{84} = 0.83 ft. Minimum diameter d_{50} = 0.20 ft.

Bank description.—Left bank is steep, vegetated with some brush and 0.5- to 1.0-ft-diameter trees spaced 15 to 20 ft apart. Right bank is scalloped, lined with exposed tree roots. Top of right bank is vegetated with 2-ft-diameter trees at water's edge and smaller trees beyond. Soft-stemmed plant growth is dense across the right-bank overflow area during the growing season. Vegetation indices: 2, nongrowing season; 3, growing season.

Remarks.—The high percentage of wetted perimeter that is vegetated for the flow of 1,700 ft^3/s reflects the additional vegetated overflow area on the right bank. The *n* values computed for this site are affected by streambank irregularities and by channel-size and -shape variations.

Summary of Hydraulic Data

[ft, feet; ft^2, square feet; ft/s, feet per second; ft^3/s, cubic feet per second]

Discharge (ft^3/s)	Average values for reach: Area (ft^2)	Width (ft)	Hydraulic radius (ft)	Velocity (ft/s)	Froude number	Water-surface slope	Energy gradient	Percent wetted perimeter vegetated	Manning's *n*
[1]877	293	78.7	3.57	3.13	0.32	0.00379	0.00317	12.6	0.063
952	306	80.1	3.65	3.26	.33	.00404	.00336	14.5	.064
[2]1,010	318	81.4	3.74	3.30	.32	.00384	.00318	15.8	.063
[1,2]1,050	325	82.2	3.80	3.36	.33	.00379	.00313	16.6	.062
[1,2]1,060	335	88.0	3.70	3.26	.31	.00296	.00242	21.9	.056
[2]1,070	334	87.7	3.69	3.32	.32	.00330	.00271	21.6	.059
[3]1,110	338	88.0	4.01	3.36	.32	.00365	.00340	22.0	.061
[3]1,700	446	99.0	4.62	3.90	.33	.00369	.00315	31.1	.057

[1]The data used for this *n*-value calculation were collected during the growing season.

[2]The right-bank overflow area at cross section 2 is treated as ineffective-flow area for this *n*-value calculation.

[3]For this *n*-value calculation, the overbank area at cross section 2, which accounts for 1.4 to 7.8 percent of the total flow area, was divided from the rest of the cross section and assigned a roughness coefficient of 0.080. Failure to subdivide the cross section in this manner would have produced erroneously low *n* values.

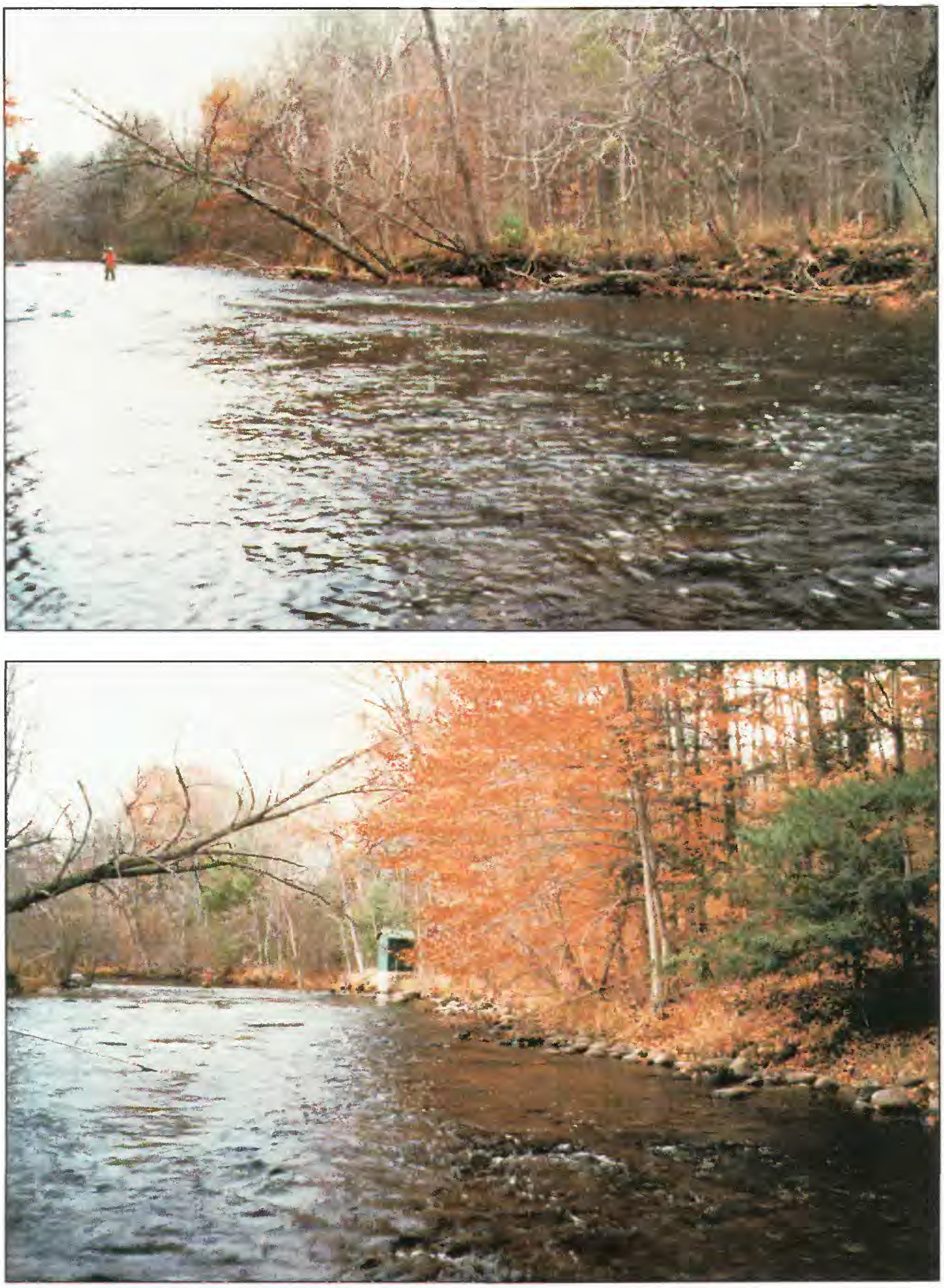


Figure 31. Photographs of Kayaderosseras Creek near West Milton, N.Y. *A*, At cross section 1, facing downstream toward right bank. Hydrographer is at section 2. *B*, Downstream from cross section 2, facing upstream toward left bank. Hydrographer and shelter at the streamflow-gaging station are at section 1.

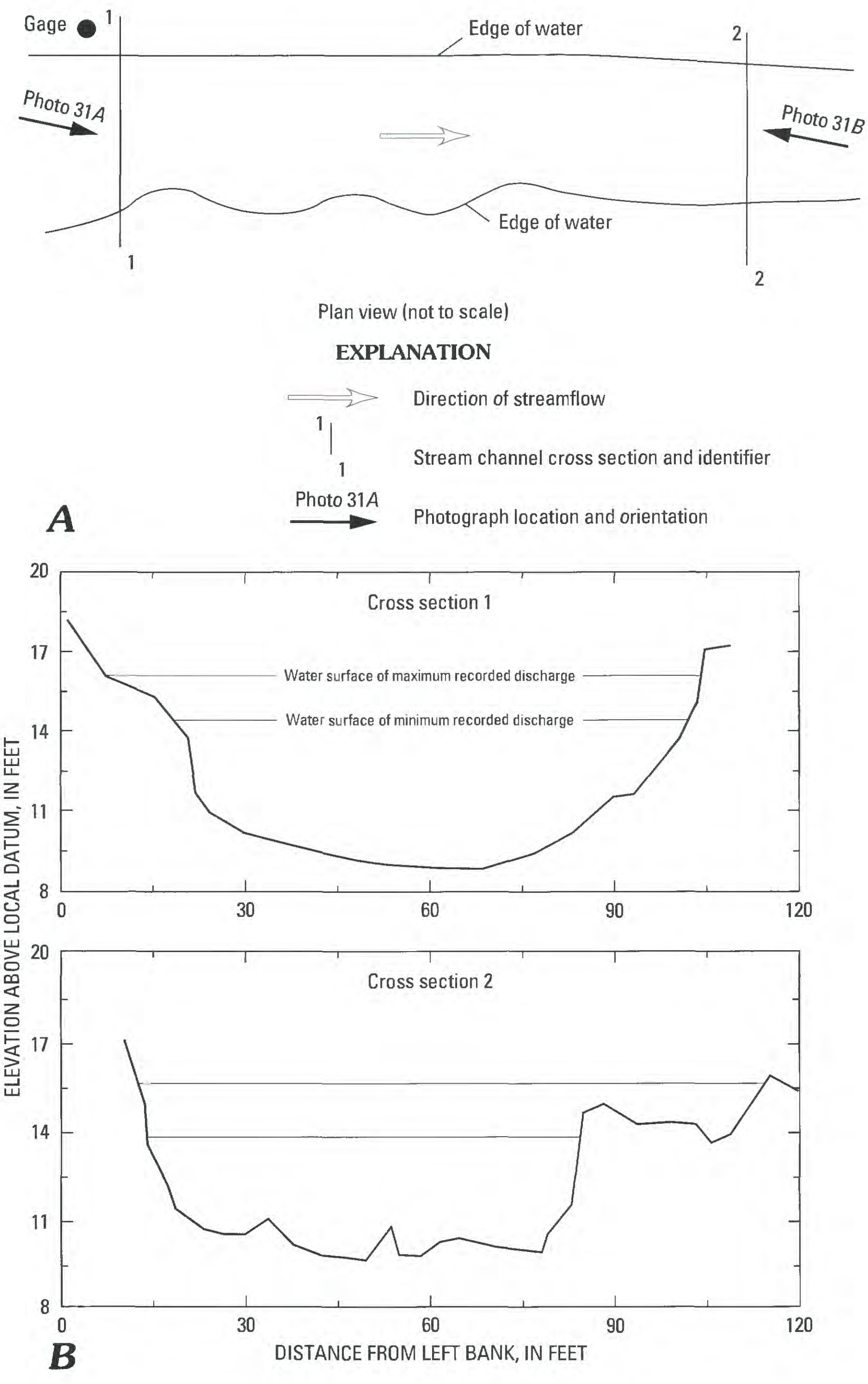


Figure 32. Plan view (*A*) and cross sections (*B*), Kayaderosseras Creek near West Milton, N.Y. Photographs are shown in figure 31.

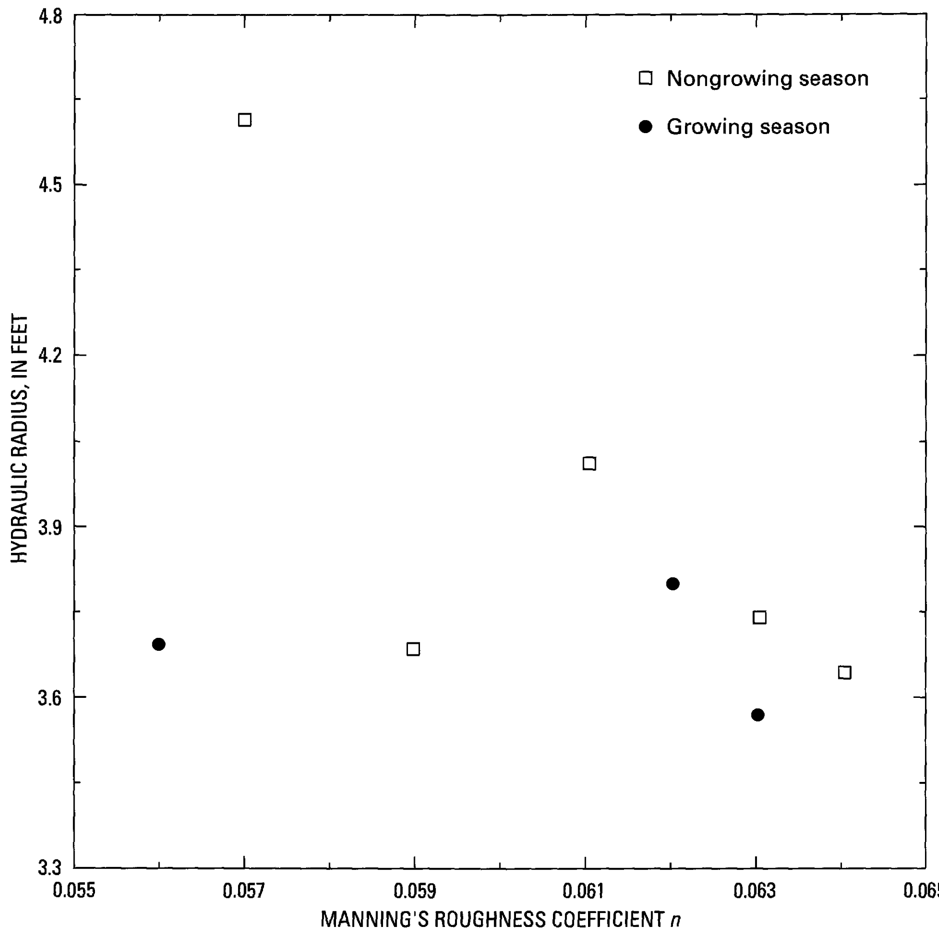


Figure 33. Relation between Manning's roughness coefficient and hydraulic radius at Kayaderosseras Creek near West Milton, N.Y.

Table 16. Station description and summary of hydraulic data, Indian River near Indian Lake, N.Y.

Location.—Latitude 43°45'30" N., longitude 74°16'05" W., Hamilton County, on right bank 0.8 mi downstream from Indian Lake Dam, 1.0 mi upstream from Big Brook, and 2.0 mi south of village of Indian Lake. A 2-section, 101-ft-long reach; section 1 is about 200 ft downstream from gage.

USGS station-identification number.—01315000.

Drainage area.—132 mi^2.

Bed material.—Boulders. Intermediate diameter d_{50} = 1.20 ft and d_{84} = 1.80 ft. Minimum diameter d_{50} = 0.50 ft.

Bank description.—Both banks lined with boulders 2 to 3 ft in diameter. Banks are vegetated with trees mostly 1 to 2 ft in diameter and spaced 10 to 15 ft apart. No brush or shrubs are growing among the trees. Some fallen trees at water's edge are aligned with flow. Vegetation indices: 2, nongrowing season; 2, growing season.

Remarks.—Flow is regulated by Indian Lake.

Summary of Hydraulic Data

[ft, feet; ft^2, square feet; ft/s, feet per second; ft^3/s, cubic feet per second]

Discharge (ft^3/s)	Average values for reach					Water-surface slope	Energy gradient	Percent wetted perimeter vegetated	Manning's *n*
	Area (ft^2)	Width (ft)	Hydraulic radius (ft)	Velocity (ft/s)	Froude number				
98	64.8	45.6	1.39	1.51	0.22	0.01109	0.01106	0	0.129
129	65.6	45.8	1.40	1.96	.29	.01050	.01049	0	.097
194	76.2	47.6	1.56	2.55	.35	.01079	.01071	0	.081
212	75.3	47.4	1.55	2.82	.39	.01119	.01103	0	.074
296	92.2	54.0	1.67	3.22	.43	.01139	.01116	0	.069
331	96.0	54.5	1.72	3.46	.46	.01198	.01161	0	.066
362	100	55.2	1.78	3.62	.48	.01277	.01221	0	.066
452	114	57.6	1.95	3.95	.50	.01248	.01199	0	.064
641	139	60.2	2.26	4.63	.54	.01376	.01293	0	.063
718	148	61.0	2.38	4.86	.55	.01386	.01300	0	.062
794	157	61.7	2.48	5.08	.56	.01406	.01312	0	.061

Figure 34. Photographs of Indian River near Indian Lake, N.Y. Hydrographer is holding a 10-ft rod at the approximate water-surface elevation of the maximum recorded discharge. *A*, Upstream from cross section 1, facing downstream toward right bank. Hydrographer is at section 2. *B*, Downstream from cross section 2, facing upstream toward left bank. Hydrographer is at section 1.

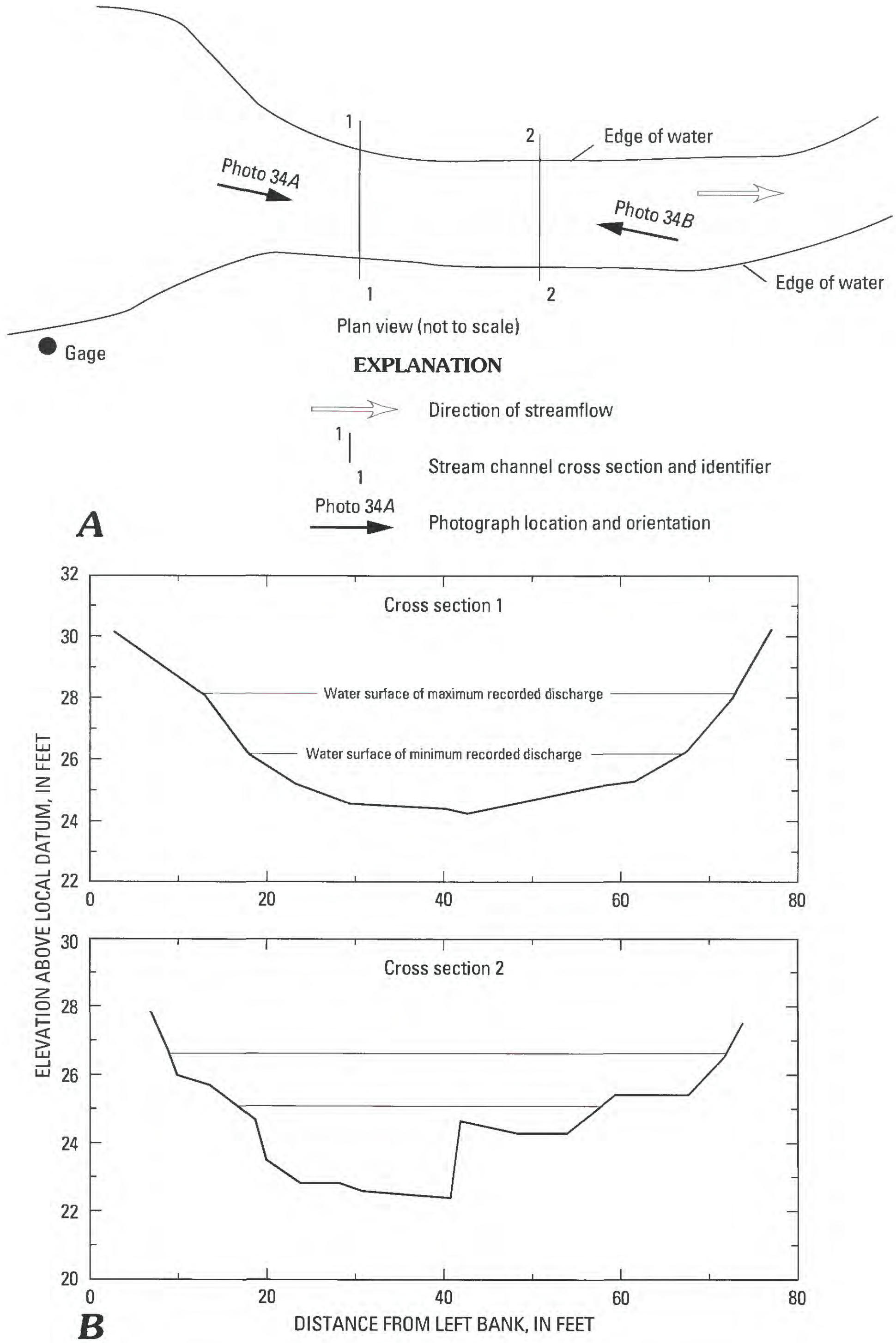


Figure 35. Plan view (*A*) and cross sections (*B*), Indian River near Indian Lake, N.Y. Photographs are shown in figure 34.

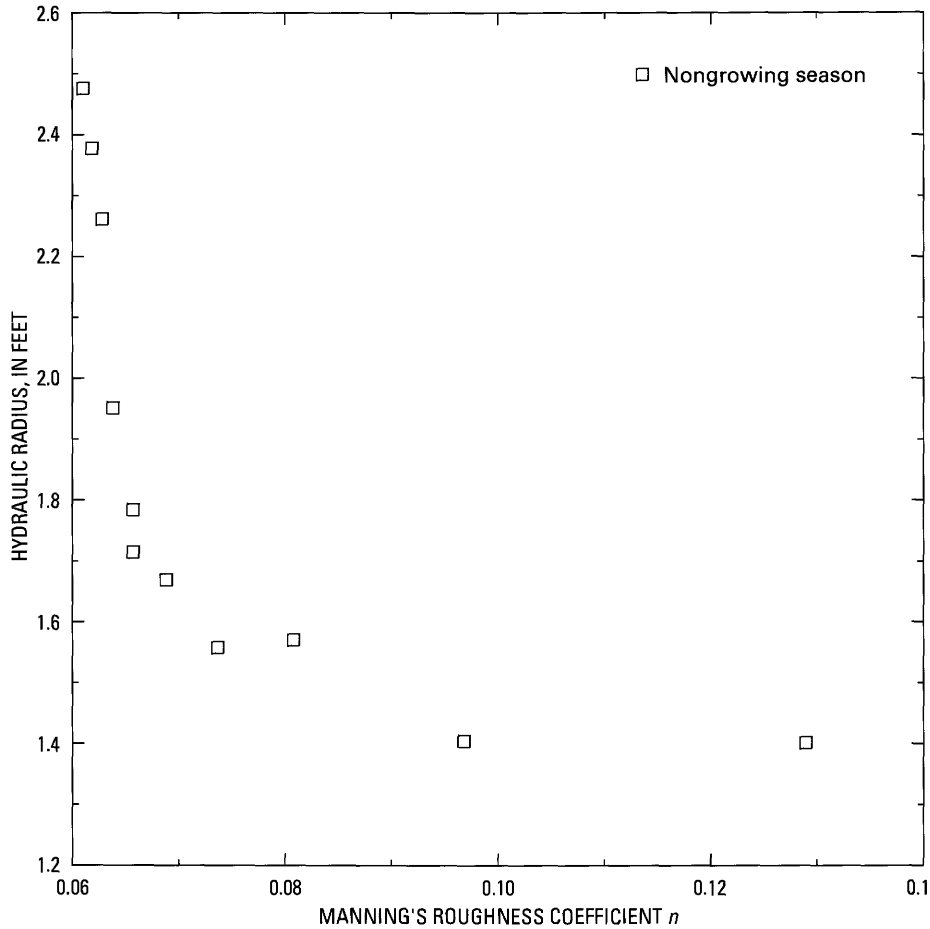


Figure 36. Relation between Manning's roughness coefficient and hydraulic radius at Indian River near Indian Lake, N.Y.

Table 17. Station description and summary of hydraulic data, Sacandaga River at Stewarts Bridge, near Hadley, N.Y.

Location.—Latitude 43°18'41" N., longitude 73°52'04" W., Saratoga County, on left bank 1.0 mi downstream from Stewarts Bridge, 1.1 mi west of Hadley, 1.4 mi upstream from mouth, and 1.5 mi downstream from Stewarts Bridge hydroelectric plant. A 3-section, 420-ft-long reach; section 1 is 340 ft downstream from gage.

USGS station-identification number.—01325000.

Drainage area.—1,055 mi^2.

Bed material.—Primarily rounded cobbles. Intermediate diameter d_{50} = 0.34 ft and d_{84} = 0.70 ft. Minimum diameter d_{50} = 0.23 ft.

Bank description.—Both banks have dense tree growth, one tree every 3 to 5 ft. Large trees from 2.5 to 3.0 ft in diameter are surrounded by many smaller trees from 0.5 to 1.0 ft in diameter. Little, if any, brush is growing among the trees. Vegetation indices: 2, nongrowing season; 2, growing season.

Remarks.—Flow is regulated by Great Sacandaga Lake. The velocity-head coefficients computed from discharge measurements made at this site range from 1.39 to 1.26 for discharges between 4,000 and 13,000 ft^3/s.

Summary of Hydraulic Data

[ft, feet; ft^2, square feet; ft/s, feet per second; ft^3/s, cubic feet per second]

Discharge (ft^3/s)	Average values for reach					Water-surface slope	Energy gradient	Percent wetted perimeter vegetated	Manning's *n*
	Area (ft^2)	Width (ft)	Hydraulic radius (ft)	Velocity (ft/s)	Froude number				
[1]3,870	1,320	273	4.83	2.93	0.23	0.00071	0.00072	0	0.039
[1]3,970	1,350	273	4.91	2.95	.23	.00076	.00076	0	.041
[1]4,130	1,370	273	4.99	3.02	.24	.00060	.00060	0	.036
[1]4,220	1,380	273	5.01	3.07	.24	.00067	.00067	0	.037
13,300	2,460	292	8.23	5.43	.33	.00174	.00150	6.0	.044

[1]The *n* value computed for this discharge and water-surface profile is affected by 11 to 13 percent flow-area expansion in the reach. The total water-surface fall is less than 0.33 ft.

Figure 37. Photographs of Sacandaga River at Stewarts Bridge, near Hadley, N.Y. Hydrographer at section 2 is holding a cross-section-identification card. *A*, At cross section 1, facing downstream toward right bank. *B*, At cross section 3, facing upstream along left bank.

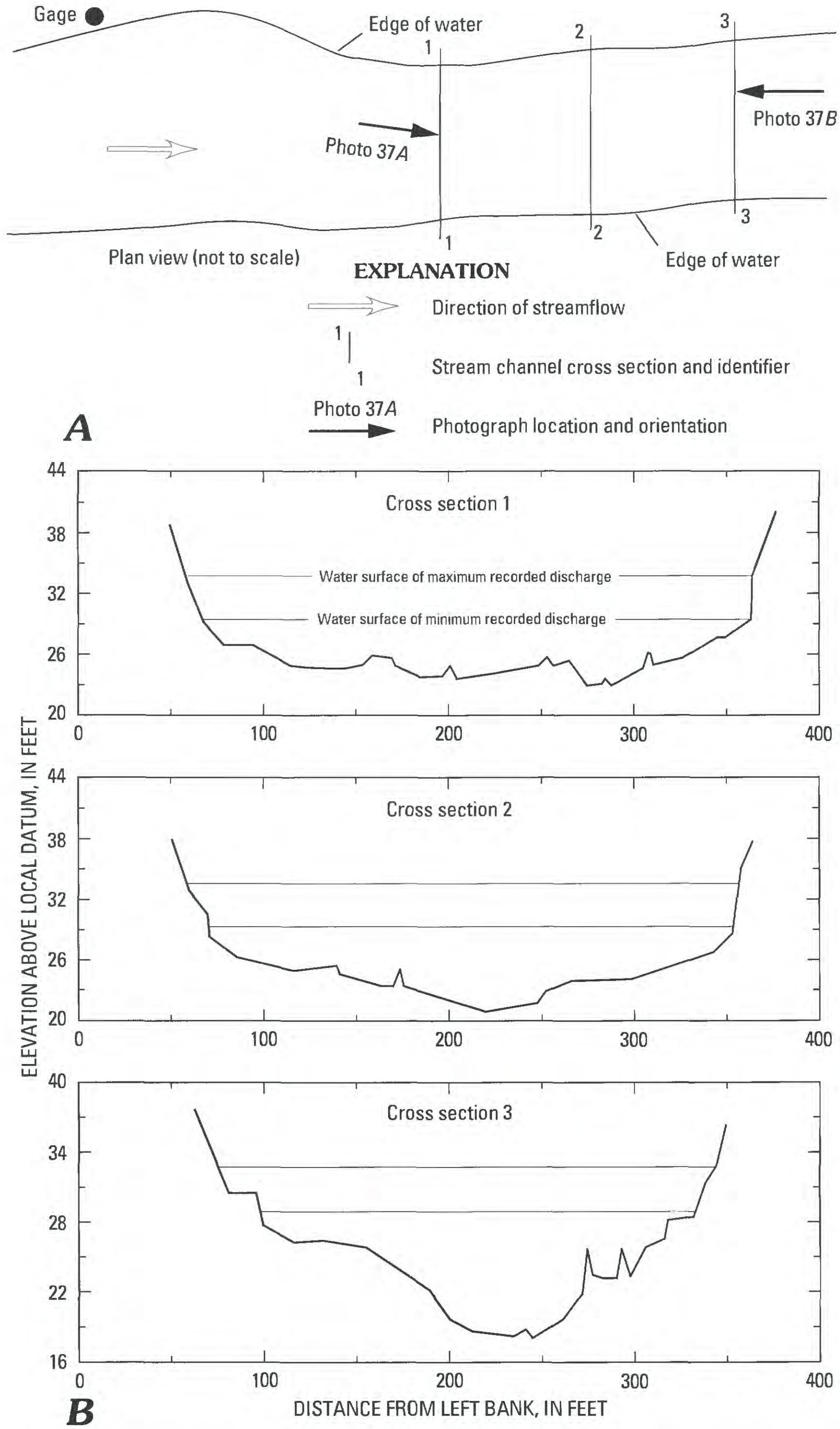


Figure 38. Plan view (*A*) and cross sections (*B*), Sacandaga River at Stewarts Bridge, near Hadley, N.Y. Photographs are shown in figure 37.

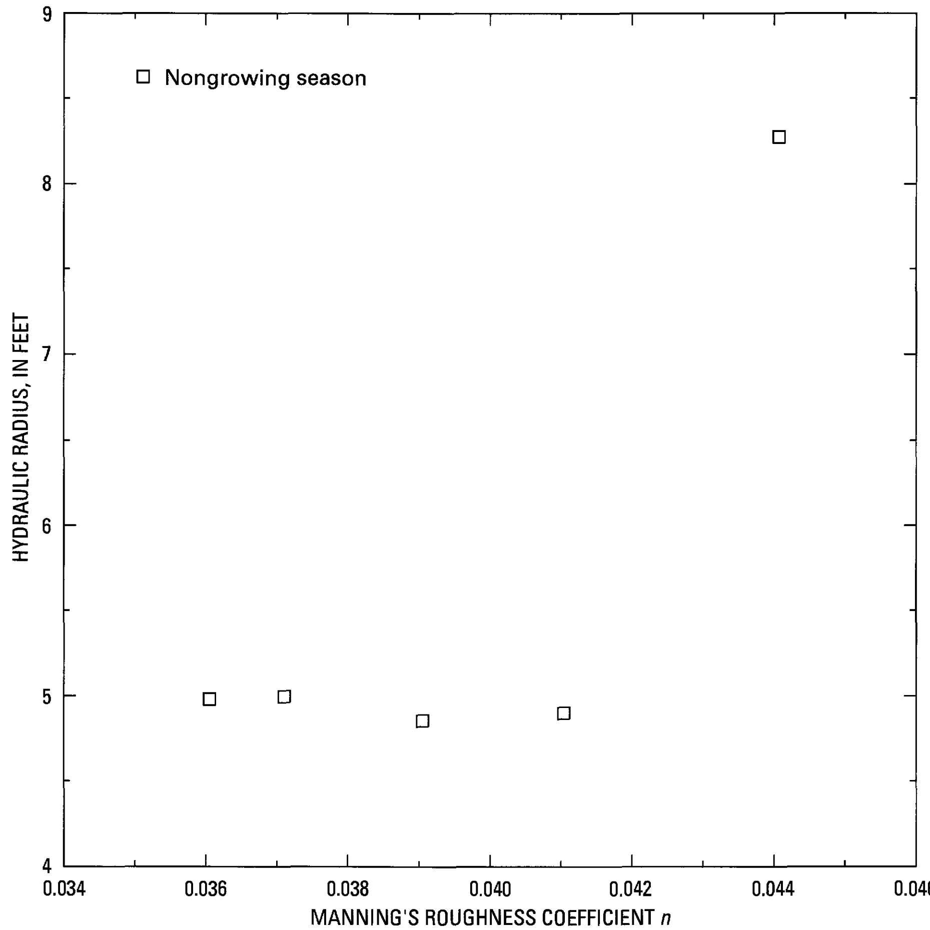


Figure 39. Relation between Manning's roughness coefficient and hydraulic radius at Sacandaga River at Stewarts Bridge, near Hadley, N.Y.

Table 18. Station description and summary of hydraulic data, Esopus Creek at Coldbrook, N.Y.

Location.—Latitude 42°00'51" N., longitude 74°16'16" W., Ulster County, on left bank at downstream side of bridge on Coldbrook Road in Coldbrook, 0.3 mi downstream from Little Beaver Kill, 1.5 mi upstream from Ashokan Reservoir, and 2.5 mi south of Mount Tremper. A 3-section, 412-ft-long reach; section 1 is at the gage.

USGS station-identification number.—01362500.

Drainage area.—192 mi^2.

Bed material.—Large cobbles and boulders as much as 8 ft in diameter. Intermediate diameter d_{50} = 1.1 ft and d_{84} = 3.0 ft. Minimum diameter d_{50} = 0.80 ft.

Bank description.—Both banks are vegetated with brush and trees. Large trees, greater than 1.5 ft in diameter, are interspersed among smaller ones, 0.5 to 1.5 ft in diameter, the resulting tree density is one tree every 5 ft. The brush is denser on the right bank than on the left bank. Vegetation indices: 3, nongrowing season; 4, growing season.

Previous n-value computation.—The roughness coefficient was computed for the flood of March 22, 1948, at two sites on this stream. The first site is just upstream of the present study site; the second is upstream of Route 28A, about 6 mi downstream of the gage. Ashokan Reservoir lies between these two sites. The data for these *n*-value computations, taken from Barnes (1967), are included in the following table.

Remarks.—The velocity-head coefficients computed from discharge measurements made at this site range from 1.12 to 1.29 for discharges between 2,000 and 32,000 ft^3/s.

Summary of Hydraulic Data

[ft, feet; ft^2, square feet; ft/s, feet per second; ft^3/s, cubic feet per second; —, no value presented]

Discharge (ft^3/s)	Average values for reach					Water-surface slope	Energy gradient	Percent wetted perimeter vegetated	Manning's *n*
	Area (ft^2)	Width (ft)	Hydraulic radius (ft)	Velocity (ft/s)	Froude number				
2,240	561	153	3.60	4.02	0.37	0.00328	0.00306	0	0.050
5,520	904	170	5.20	6.12	.47	.00374	.00339	0	.043
[1]6,140	985	174	5.56	6.24	.46	.00374	.00343	0	.044
[1]8,700	1,190	180	6.44	7.34	.50	.00391	.00358	2.7	.042
9,030	1,160	179	6.33	7.79	.54	.00405	.00363	2.2	.039
12,200	1,410	186	7.38	8.66	.56	.00415	.00378	5.7	.040
37,400	2,650	213	11.96	14.13	.71	.00459	.00434	18.9	.036
51,700	3,090	220	13.42	16.75	.79	.00500	.00437	21.7	.034
[2]13,900	1,460	178	8.12	9.46	.58	.00446	—	—	.043
[3]13,900	1,590	292	5.41	8.74	.66	.00340	—	—	.030

[1]The data used for this *n*-value calculation were collected during the growing season.
[2]From Barnes (1967). Site is at gage.
[3]From Barnes (1967). Site is about 6 mi downstream of gage.

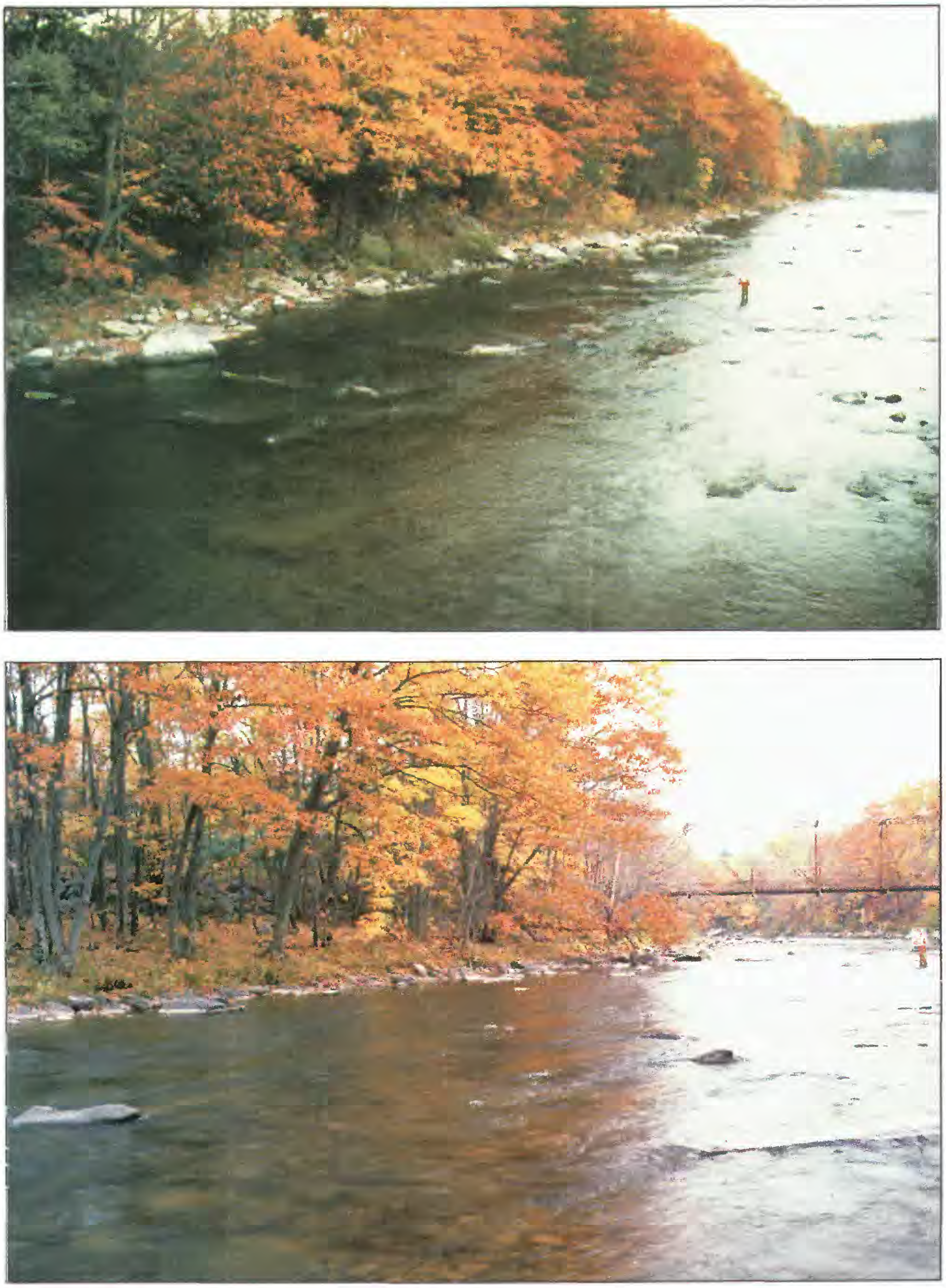


Figure 40. Photographs of Esopus Creek at Coldbrook, N.Y. Hydrographer is at section 2. *A*, At cross section 1, facing downstream toward left bank. *B*, At cross section 3, facing upstream toward right bank.

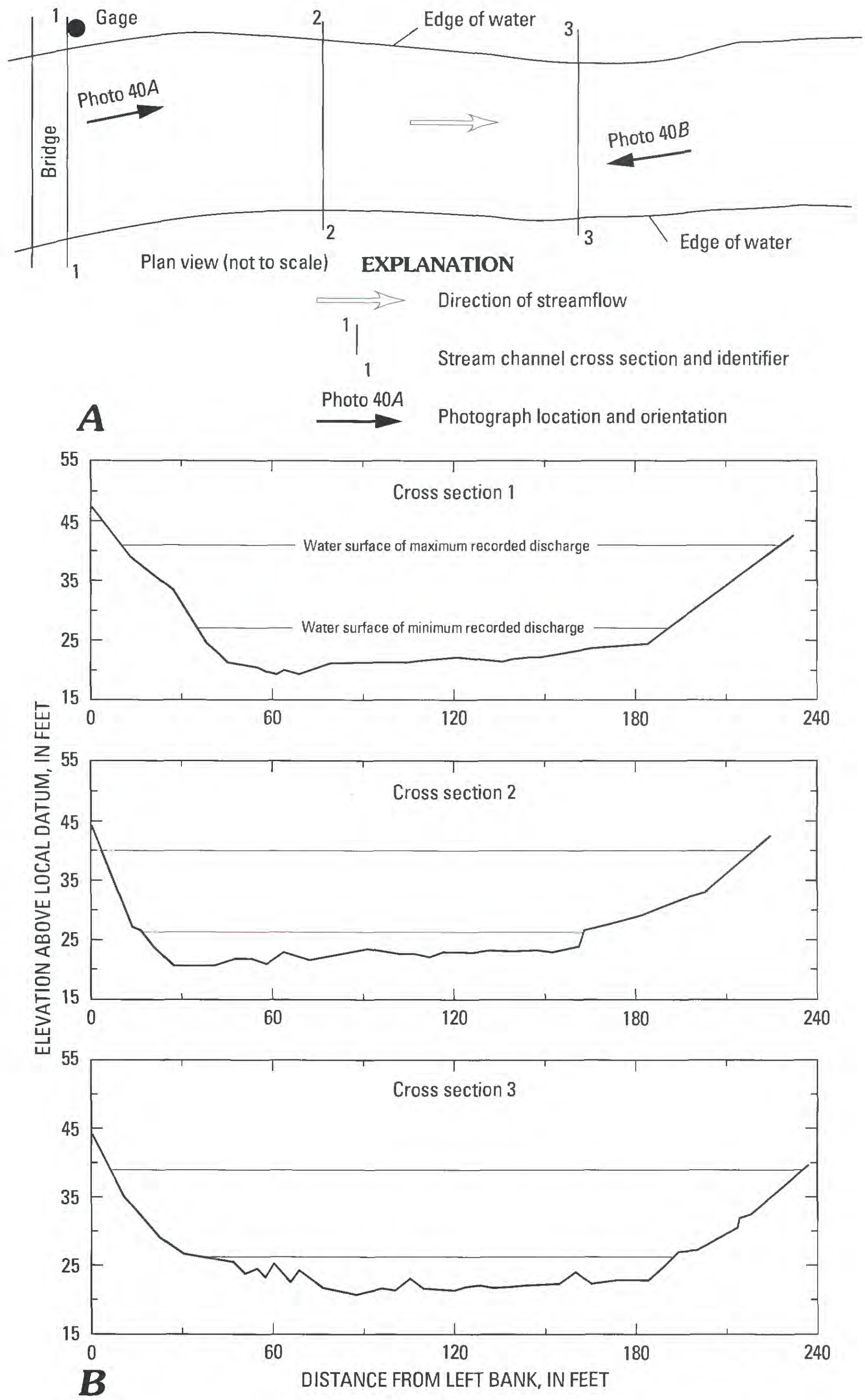


Figure 41. Plan view (*A*) and cross sections (*B*), Esopus Creek at Coldbrook, N.Y. Photographs are shown in figure 40.

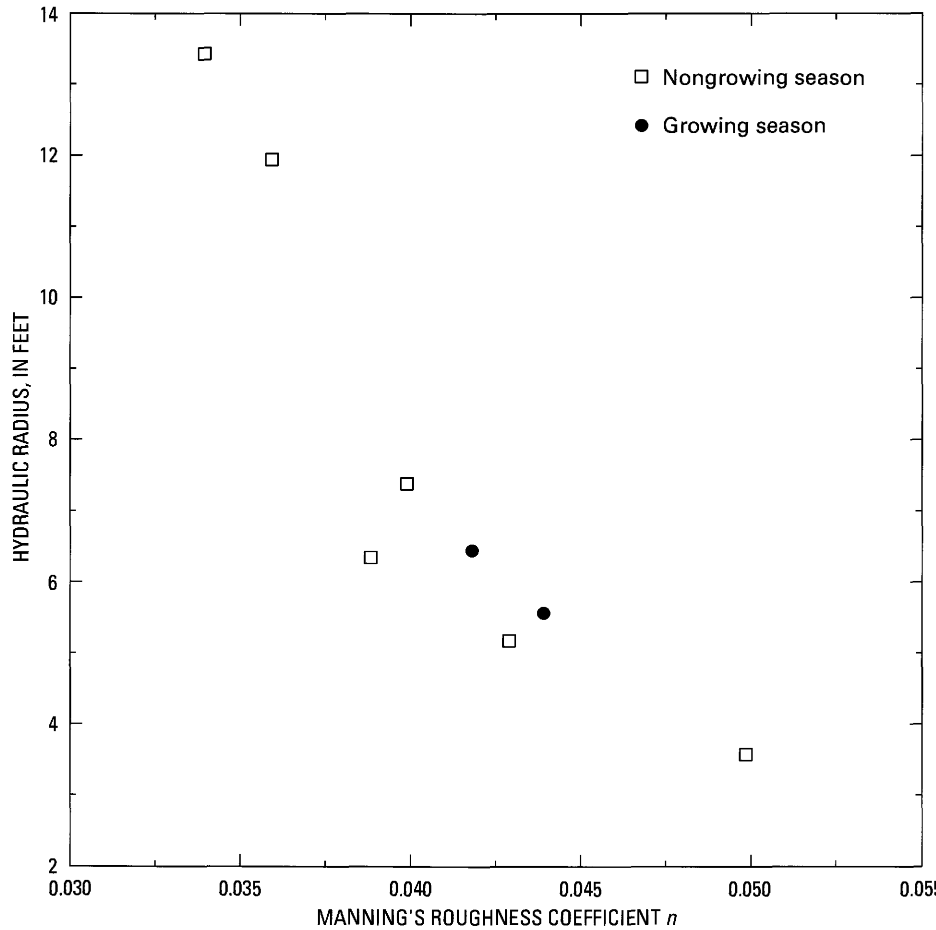


Figure 42. Relation between Manning's roughness coefficient and hydraulic radius at Esopus Creek at Coldbrook, N.Y.

Table 19. Station description and summary of hydraulic data, East Branch Delaware River at Margaretville, N.Y.

Location.—Latitude 42°08'41" N., longitude 74°39'14" W., Delaware County, on right bank at downstream side of bridge on Fair Street at intersection with Main Street at Margaretville, 0.2 mi upstream from unnamed tributary, and 1.6 mi downstream from Dry Brook. A 3-section, 354-ft-long reach; section 1 is 190 ft downstream from bridge on Fair Street.

USGS station-identification number.—01413500.

Drainage area.—163 mi^2.

Bed material.—Gravel and cobbles. Intermediate diameter d_{50} = 0.28 ft and d_{84} = 0.44 ft. Minimum diameter d_{50} = 0.09 ft.

Bank description.—Both banks have dense brush with a few sparsely spaced trees, mostly 1.0 to 1.5 ft in diameter. Vegetation indices: 1, nongrowing season; 2, growing season.

Summary of Hydraulic Data

[ft, feet; ft^2, square feet; ft/s, feet per second; ft^3/s, cubic feet per second]

Discharge (ft^3/s)	Average values for reach					Water-surface slope	Energy gradient	Percent wetted perimeter vegetated	Manning's *n*
	Area (ft^2)	Width (ft)	Hydraulic radius (ft)	Velocity (ft/s)	Froude number				
1,420	330	105	3.08	4.30	0.43	0.00209	0.00204	0.9	0.034
1,840	388	108	3.53	4.75	.44	.00212	.00203	3.6	.033
[1]1,990	451	109	4.05	4.41	.38	.00138	.00130	5.4	.031
2,100	417	110	3.75	5.03	.45	.00203	.00195	5.4	.032
[2]2,860	530	114	4.58	5.39	.44	.00209	.00196	8.6	.034
6,600	905	129	6.80	7.30	.49	.00240	.00198	20.3	.033

[1]Post-April 1987 flood; new channel geometry and stage-to-discharge relation.

[2]The data used for this *n*-value calculation were collected during the growing season.

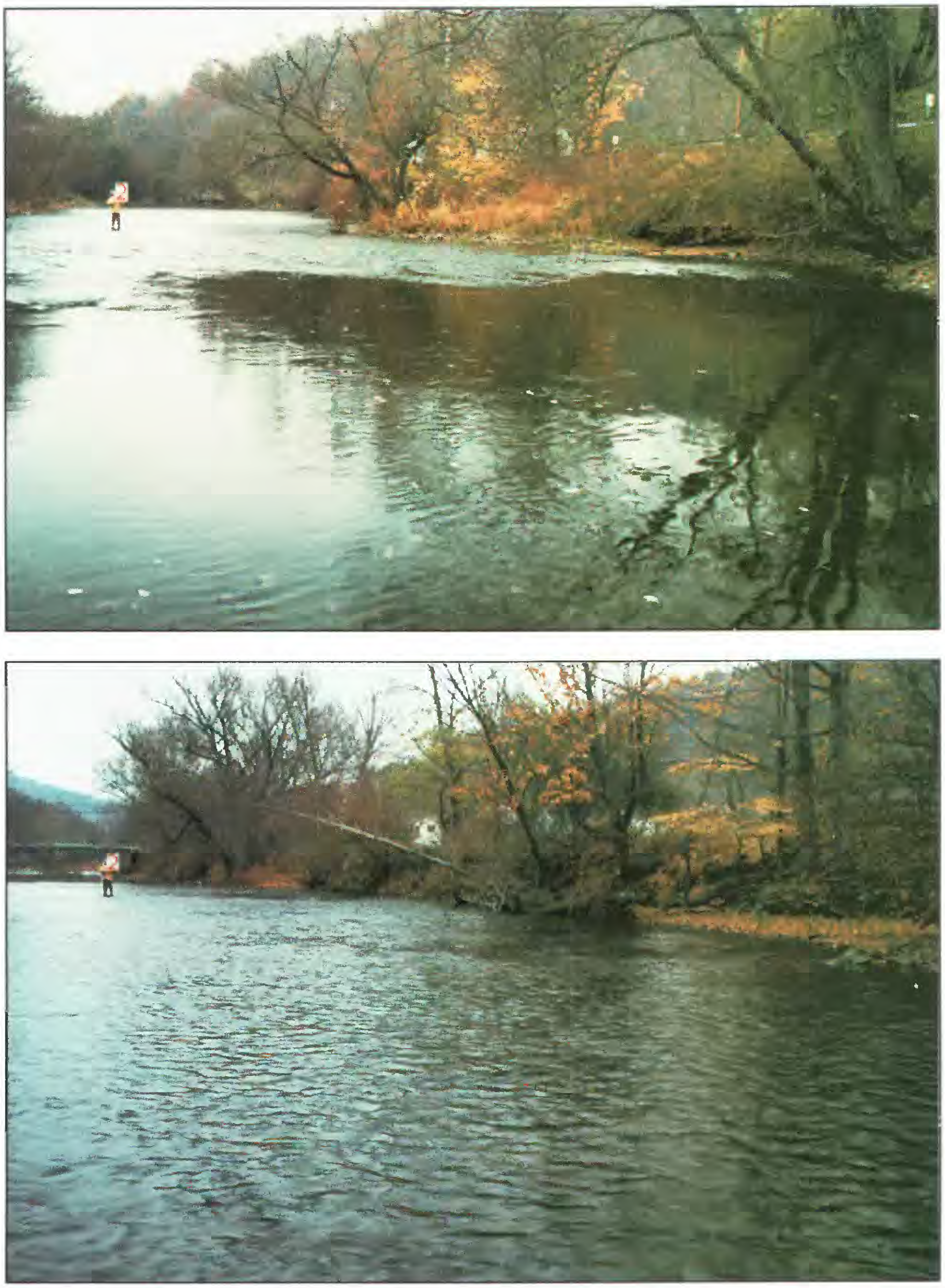


Figure 43. Photographs of East Branch Delaware River at Margaretville, N.Y. Hydrographer is at section 2. *A*, At cross section 1, facing downstream toward right bank. *B*, At cross section 3, facing upstream toward left bank.

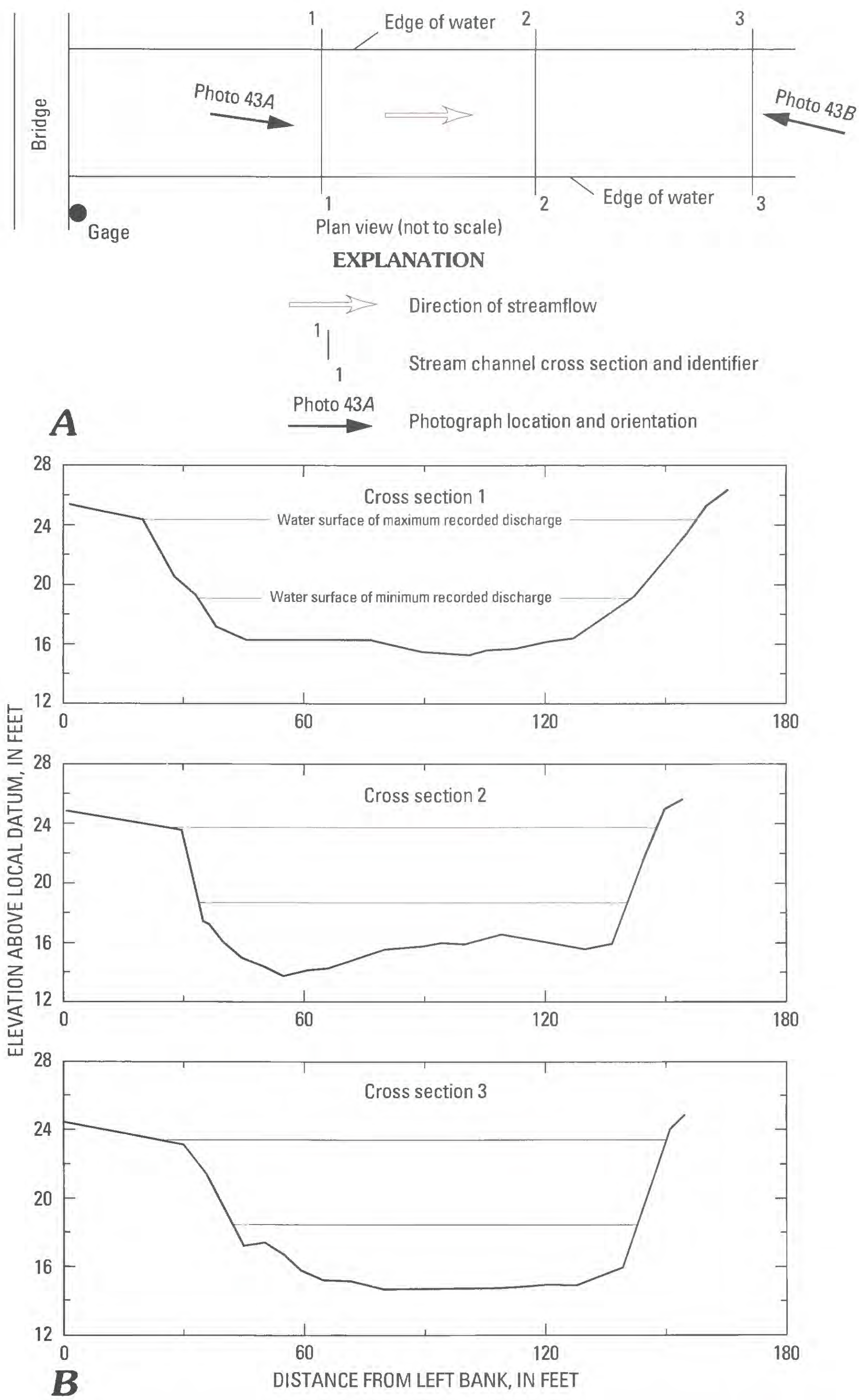


Figure 44. Plan view (*A*) and cross sections (*B*), East Branch Delaware River at Margaretville, N.Y. Photographs are shown in figure 43.

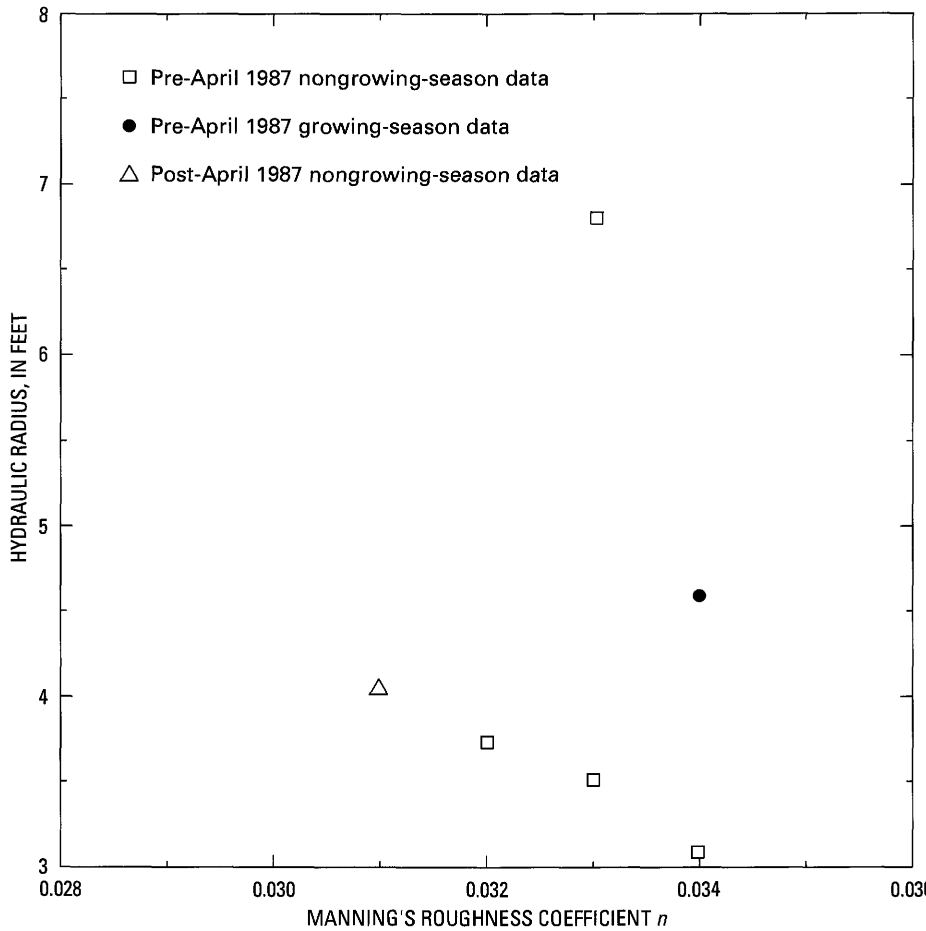


Figure 45. Relation between Manning's roughness coefficient and hydraulic radius at East Branch Delaware River at Margaretville, N.Y.

Table 20. Station description and summary of hydraulic data, Ouleout Creek at East Sidney, N.Y.

Location.—Latitude 42°20'00" N., longitude 75°14'07" W., Delaware County, on right bank 0.2 mi downstream from bridge on County Highway 44, 0.4 mi downstream from East Sidney Dam, at East Sidney, and 3.5 mi upstream from mouth. A 3-section, 345-ft-long reach; section 1 is at the gage.

USGS station-identification number.—01500000.

Drainage area.—103 mi^2.

Bed material.—Cobbles and small boulders, mostly flat. Intermediate diameter d_{50} = 0.41 ft and d_{84} = 1.43 ft. Minimum diameter d_{50} = 0.12 ft.

Bank description.—Both banks have tall summer grasses and scattered trees of varying diameters. Left bank is steep and has denser brush and fewer trees than the right bank. Hummocky grasses are in center of channel between cross sections 1 and 2. Vegetation indices: 1, nongrowing season; 2, growing season.

Remarks.—Flow is regulated by East Sidney Lake. The velocity-head coefficients computed from discharge measurements made at this site range from 1.19 to 1.30 for discharges between 900 and 1,700 ft^3/s.

Summary of Hydraulic Data

[ft, feet; ft^2, square feet; ft/s, feet per second; ft^3/s, cubic feet per second]

Discharge (ft^3/s)	Average values for reach: Area (ft^2)	Width (ft)	Hydraulic radius (ft)	Velocity (ft/s)	Froude number	Water-surface slope	Energy gradient	Percent wetted perimeter vegetated	Manning's *n*
Data collected during the nongrowing season									
966	213	77.3	2.64	4.99	.56	.00739	.00619	9.1	.043
1,060	223	78.8	2.72	5.17	.57	.00754	.00613	10.8	.043
1,100	222	78.6	2.71	5.45	.60	.00780	.00620	10.6	.041
1,190	242	81.3	2.80	5.34	.57	.00794	.00626	15.6	.044
1,420	264	85.1	2.97	5.86	.62	.00832	.00631	17.5	.041
1,450	272	86.4	3.02	5.84	.61	.00875	.00651	18.7	.043
[1]1,560	293	88.5	3.18	5.77	.59	.00855	.00644	20.7	.046
[1]1,660	303	89.6	3.24	6.02	.61	.00913	.00658	21.7	.045
1,680	297	88.4	3.22	6.18	.63	.00899	.00652	20.7	.043
[1]1,780	316	91.9	3.33	6.15	.65	.00913	.00656	23.1	.045
[1]1,880	323	92.5	3.38	6.39	.67	.00945	.00662	23.6	.044
Data collected during the growing season									
875	201	76.2	2.53	4.80	0.55	0.00713	0.00603	7.7	0.043
1,050	220	77.9	2.70	5.22	.58	.00725	.00600	9.8	.041
1,290	252	81.6	2.95	5.58	.59	.00806	.00637	11.8	.043
[1]1,610	299	88.9	3.22	5.89	.60	.00893	.00663	21.1	.046
[1]1,620	296	88.7	3.20	5.95	.60	.00870	.00642	20.9	.044
[1]1,750	314	91.7	3.32	6.07	.64	.00899	.00656	22.9	.045

[1]The *n* values computed for each subreach differ by 0.011 to 0.017.

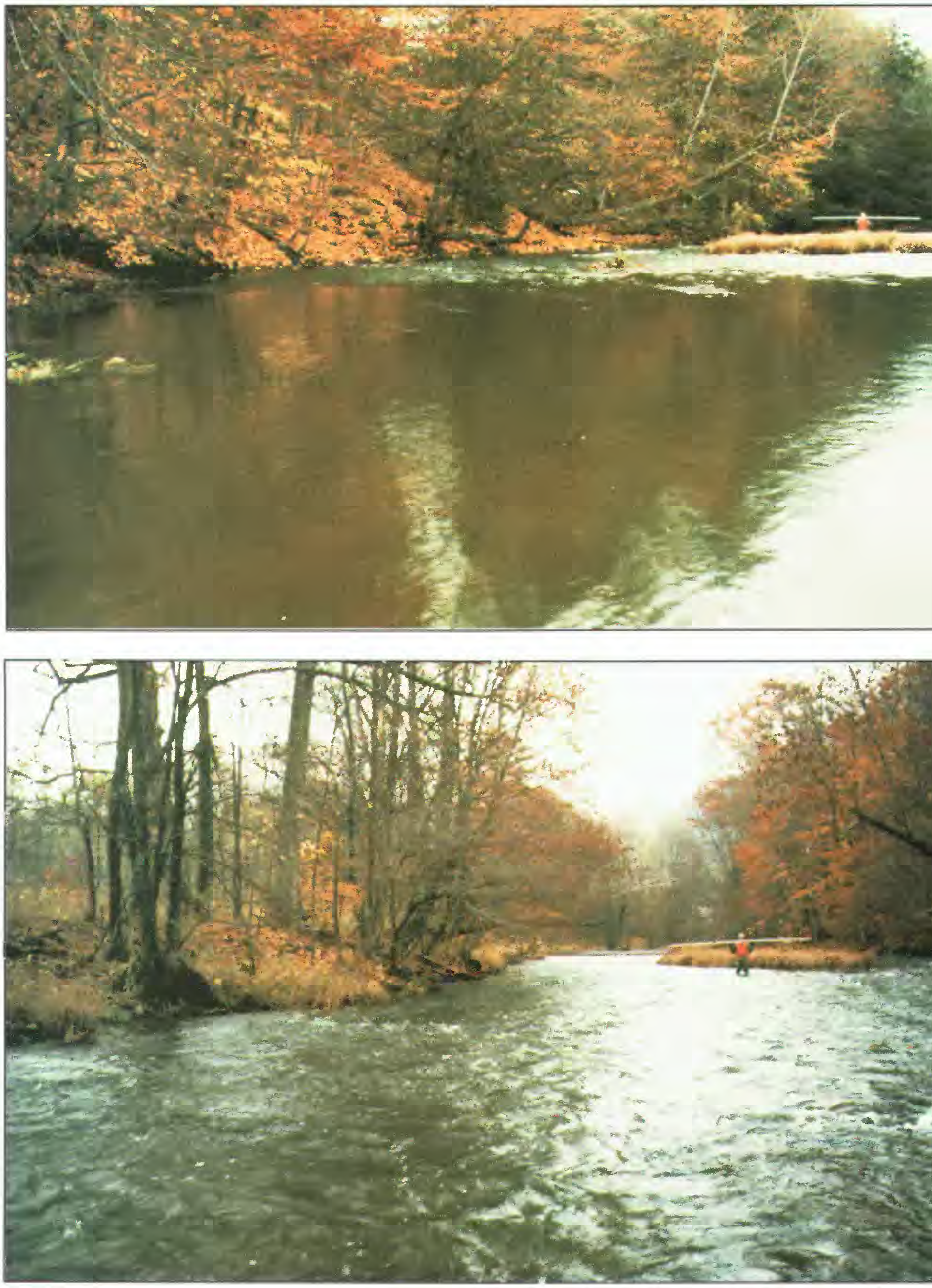


Figure 46. Photographs of Ouleout Creek at East Sidney, N.Y. Hydrographer at section 2 is holding a 15-ft rod at the approximate water-surface elevation of the maximum recorded discharge. *A*, At cross section 1, facing downstream toward left bank. *B*, Downstream from cross section 3, facing upstream toward right bank.

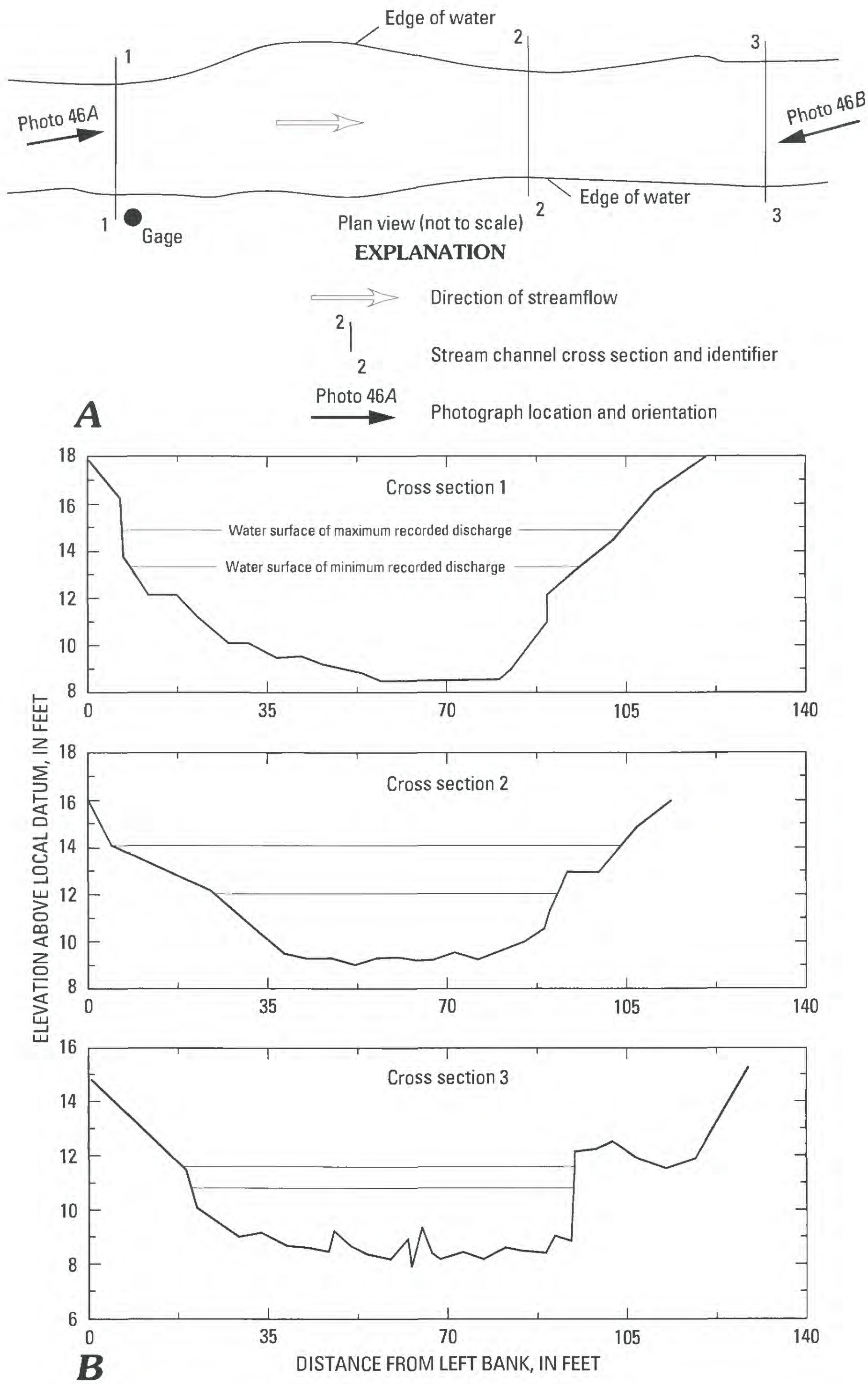


Figure 47. Plan view (*A*) and cross sections (*B*), Ouleout Creek at East Sidney, N.Y. Photographs are shown in figure 46.

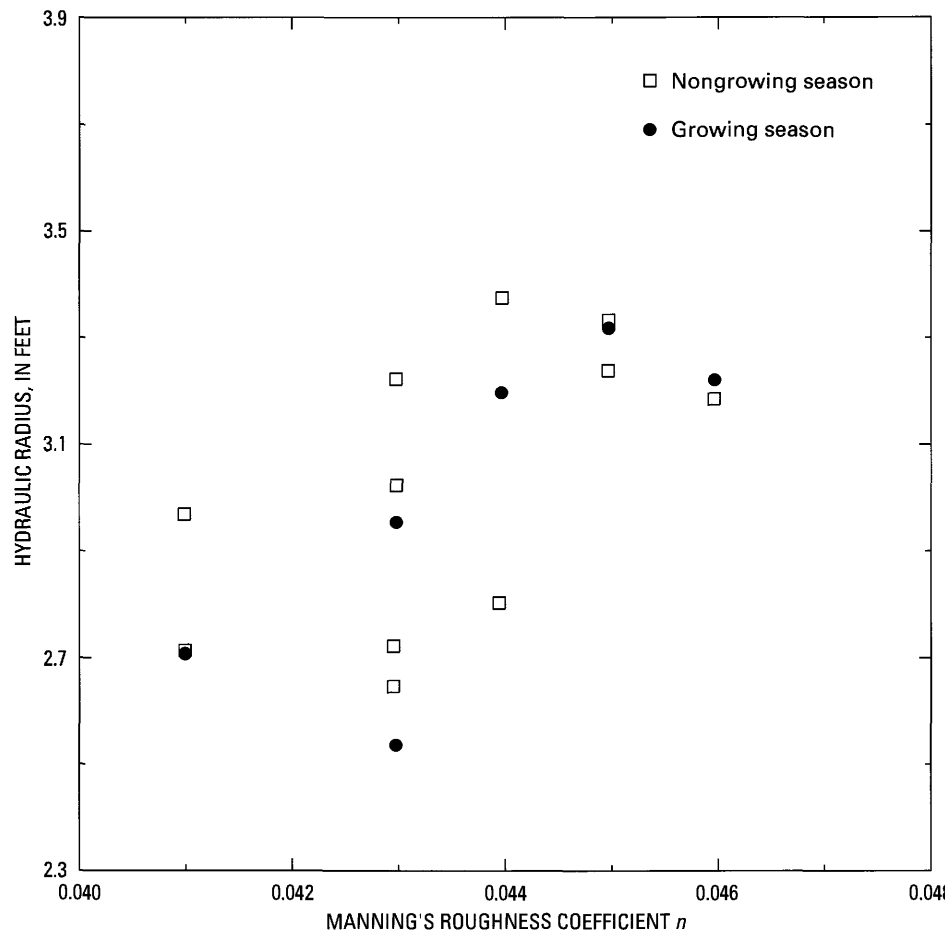


Figure 48. Relation between Manning's roughness coefficient and hydraulic radius at Ouleout Creek at East Sidney, N.Y.

Table 21. Station description and summary of hydraulic data, Susquehanna River at Unadilla, N.Y.

Location.—Latitude 42°19'17" N., longitude 75°19'01" W., Otsego County, on right bank 25 ft downstream from bridge on Bridge Street at Unadilla, 1.0 mi upstream from Carrs Creek, and 1.6 mi downstream from Ouleout Creek. A 2-section, 430-ft-long reach; section 1 is at the gage.

USGS station-identification number.—01500500.

Drainage area.—982 mi^2.

Bed material.—Cobbles, mostly flat. Intermediate diameter d_{50} = 0.42 ft and d_{84} = 0.74 ft. Minimum diameter d_{50} = 0.20 ft.

Bank description.—Both banks are steep and sparsely vegetated with brush and mature trees, 1.0 to 2.5 ft in diameter. Trees are spaced 20 to 50 ft apart on the left bank and 50 to 100 ft apart on the right bank. Vegetation indices: 1, nongrowing season; 2, growing season.

Remarks.—The velocity-head coefficients computed from discharge measurements made at this site range from 1.05 to 1.14 for discharges between 3,000 and 18,000 ft^3/s.

Summary of Hydraulic Data

[ft, feet; ft^2, square feet; ft/s, feet per second; ft^3/s, cubic feet per second]

Discharge (ft^3/s)	Average values for reach					Water-surface slope	Energy gradient	Percent wetted perimeter vegetated	Manning's *n*
	Area (ft^2)	Width (ft)	Hydraulic radius (ft)	Velocity (ft/s)	Froude number				
Data collected during the nongrowing season									
3,540	1,150	190	5.95	3.11	0.22	0.00053	0.00043	1.1	0.033
4,200	1,230	192	6.33	3.43	.24	.00058	.00046	2.1	.032
6,160	1,470	196	7.36	4.22	.27	.00072	.00054	5.0	.031
6,870	1,570	197	7.80	4.40	.28	.00077	.00057	5.0	.032
9,100	1,770	202	8.63	5.16	.31	.00091	.00065	7.8	.031
10,400	1,910	204	9.18	5.46	.31	.00105	.00076	8.7	.033
14,300	2,220	210	10.28	6.48	.35	.00142	.00100	11.6	.034
19,000	2,590	218	11.50	7.38	.38	.00151	.00100	15.2	.032
Data collected during the growing season									
3,720	1,170	190	6.06	3.20	.23	.00056	.00045	1.6	.033
4,210	1,240	192	6.38	3.41	.24	.00074	.00061	2.1	.037
4,320	1,240	192	6.38	3.49	.24	.00067	.00054	2.1	.034
4,450	1,270	192	6.48	3.54	.24	.00053	.00041	2.6	.030
5,880	1,470	196	7.36	4.02	.26	.00058	.00043	4.5	.029

Figure 49. Photographs of Susquehanna River at Unadilla, N.Y. *A*, At cross section 1, facing downstream toward left bank. Hydrographer at section 2 is holding cross-section-identification card (white square at left edge of water near center of picture). *B*, Downstream from cross section 2, facing upstream toward right bank.

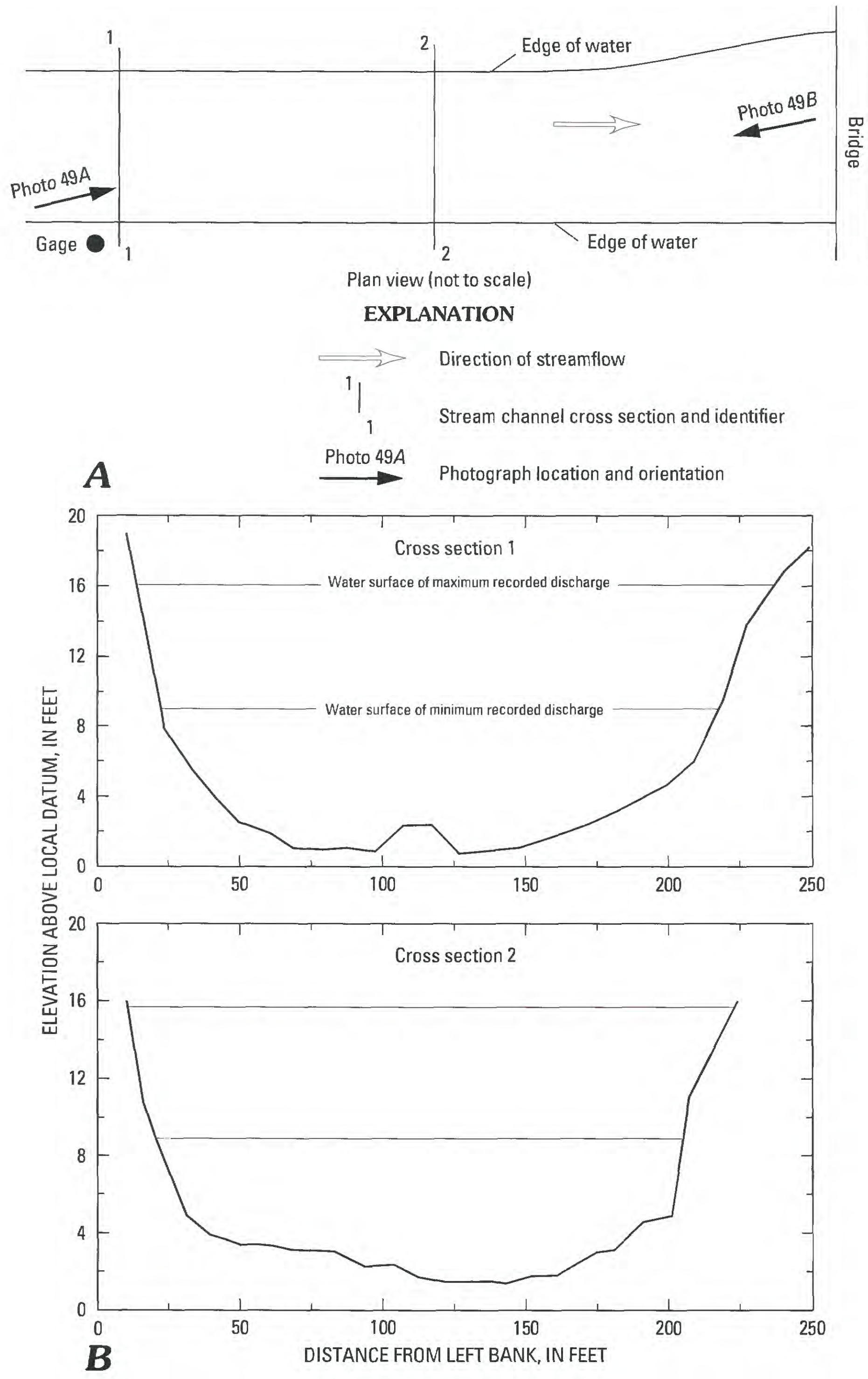


Figure 50. Plan view (*A*) and cross sections (*B*), Susquehanna River at Unadilla, N.Y. Photographs are shown in figure 49.

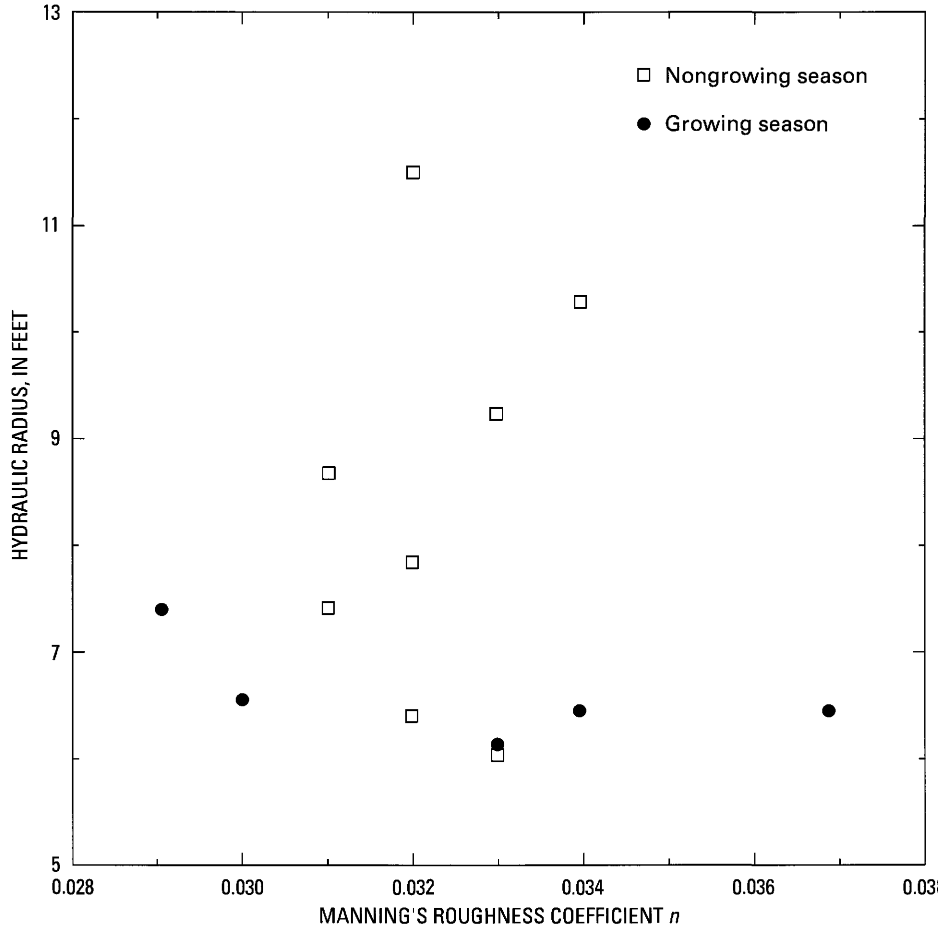


Figure 51. Relation between Manning's roughness coefficient and hydraulic radius at Susquehanna River at Unadilla, N.Y.

Table 22. Station description and summary of hydraulic data, Unadilla River at Rockdale, N.Y.

Location.—Latitude 42°22'40" N., longitude 75°24'23" W., Chenango County, on right bank 400 ft downstream from Chenango-Otsego County highway bridge at Rockdale, 0.7 mi downstream from Kent Brook. A 3-section, 559-ft-long reach is 0.8 mi downstream from bridge in Rockdale.

USGS station-identification number.—01502500.

Drainage area.—520 mi^2.

Bed material.—Cobbles, mostly flat. Intermediate diameter d_{50} = 0.35 ft and d_{84} = 0.55 ft. Minimum diameter d_{50} = 0.11 ft.

Bank description.—Both banks are steep and densely vegetated with brush, vines, and trees. Tree density on right bank is one tree about every 10 ft. Vegetation indices: 3, nongrowing season; 4, growing season.

Summary of Hydraulic Data

[ft, feet; ft^2, square feet; ft/s, feet per second; ft^3/s, cubic feet per second]

Discharge (ft^3/s)	Average values for reach: Area (ft^2)	Width (ft)	Hydraulic radius (ft)	Velocity (ft/s)	Froude number	Water-surface slope	Energy gradient	Percent wetted perimeter vegetated	Manning's *n*
Data collected during the nongrowing season									
1,430	501	148	3.45	2.90	0.28	0.00109	0.00096	0.7	0.034
1,650	530	148	3.63	3.15	.30	.00106	.00092	.7	.032
1,800	566	148	3.85	3.21	.29	.00097	.00085	1.3	.032
2,080	605	149	4.09	3.46	.31	.00106	.00093	2.0	.032
2,240	632	150	4.24	3.56	.31	.00107	.00095	2.0	.032
2,430	648	150	4.34	3.77	.32	.00104	.00091	2.6	.031
2,870	710	151	4.70	4.06	.33	.00102	.00091	3.2	.030
4,040	868	154	5.59	4.66	.35	.00091	.00085	5.7	.029
4,150	892	155	5.72	4.66	.34	.00098	.00092	5.7	.030
4,580	946	156	5.99	4.84	.35	.00088	.00084	6.9	.029
4,660	941	156	5.97	4.95	.36	.00098	.00093	6.9	.030
[1]6,170	1,150	157	7.11	5.38	.35	.00086	.00088	8.6	.030
[1]6,330	1,160	157	7.15	5.48	.36	.00080	.00083	8.6	.029
[1]6,370	1,200	158	7.36	5.33	.34	.00089	.00092	9.1	.032
[1]8,280	1,360	159	8.23	6.09	.37	.00073	.00080	10.8	.028
[1]13,000	1,700	162	9.94	7.67	.42	.00091	.00106	13.4	.029
Data collected during the growing season									
1,830	578	149	3.92	3.19	.29	.00091	.00081	1.3	.031
2,600	676	150	4.51	3.86	.32	.00098	.00087	2.6	.030
3,140	762	151	4.99	4.13	.33	.00093	.00084	3.9	.030
3,330	783	152	5.13	4.26	.33	.00093	.00085	5.7	.029
[1]7,540	1,290	159	7.88	5.83	.36	.00077	.00082	10.2	.029

[1]The left-bank overflow area is treated as ineffective-flow area for this *n*-value calculation. The data reflect this modification to the cross section. The computed *n* values are affected by 1 to 9 percent flow-area expansion in the reach.

Figure 52. Photographs of Unadilla River at Rockdale, N.Y. *A,* At cross section 1, facing downstream toward left bank. *B,* At cross section 3, facing upstream along right bank. Self-supported stadia rod is in center of picture.

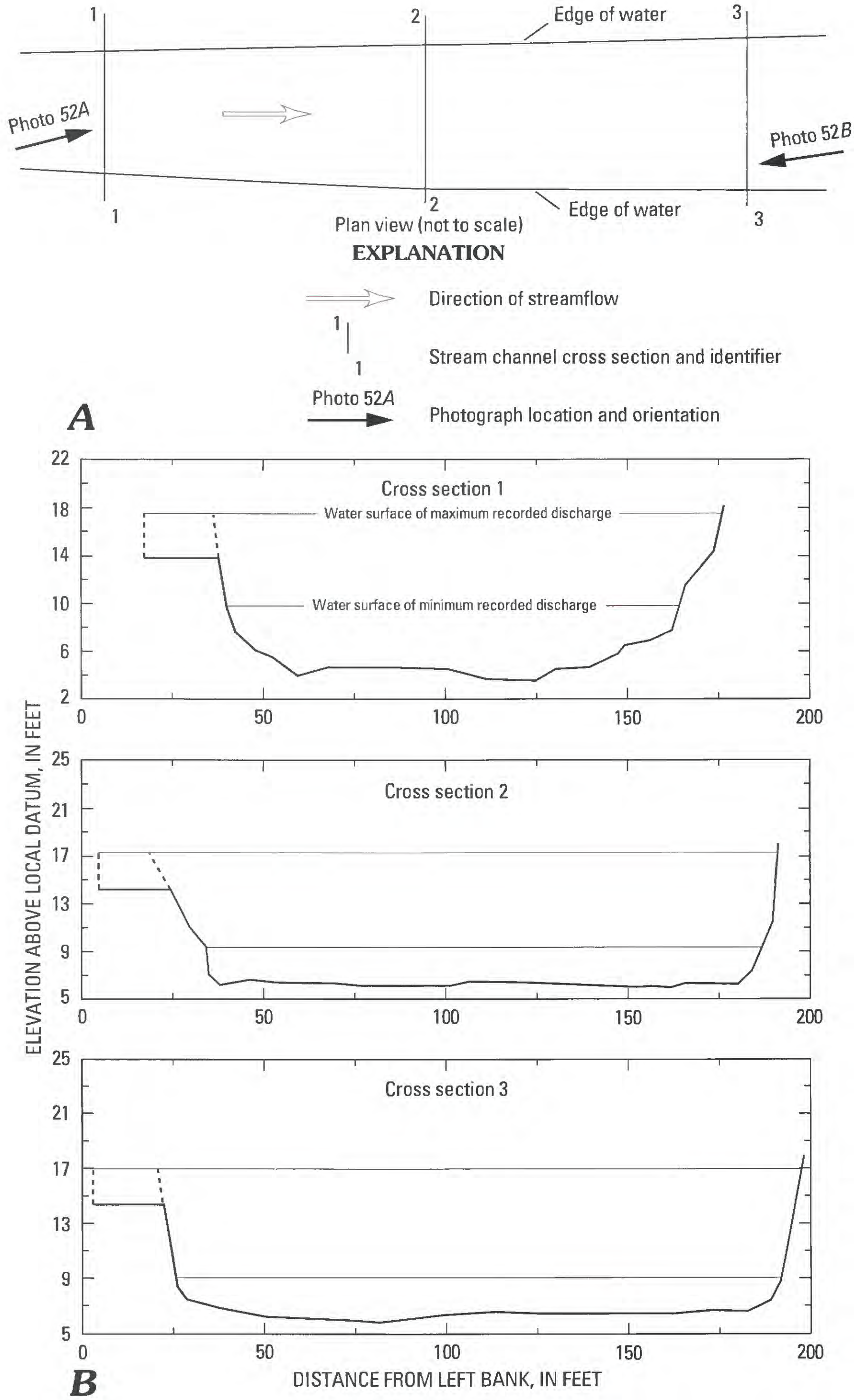


Figure 53. Plan view (*A*) and cross sections (*B*), Unadilla River at Rockdale, N.Y. Photographs are shown in figure 52.

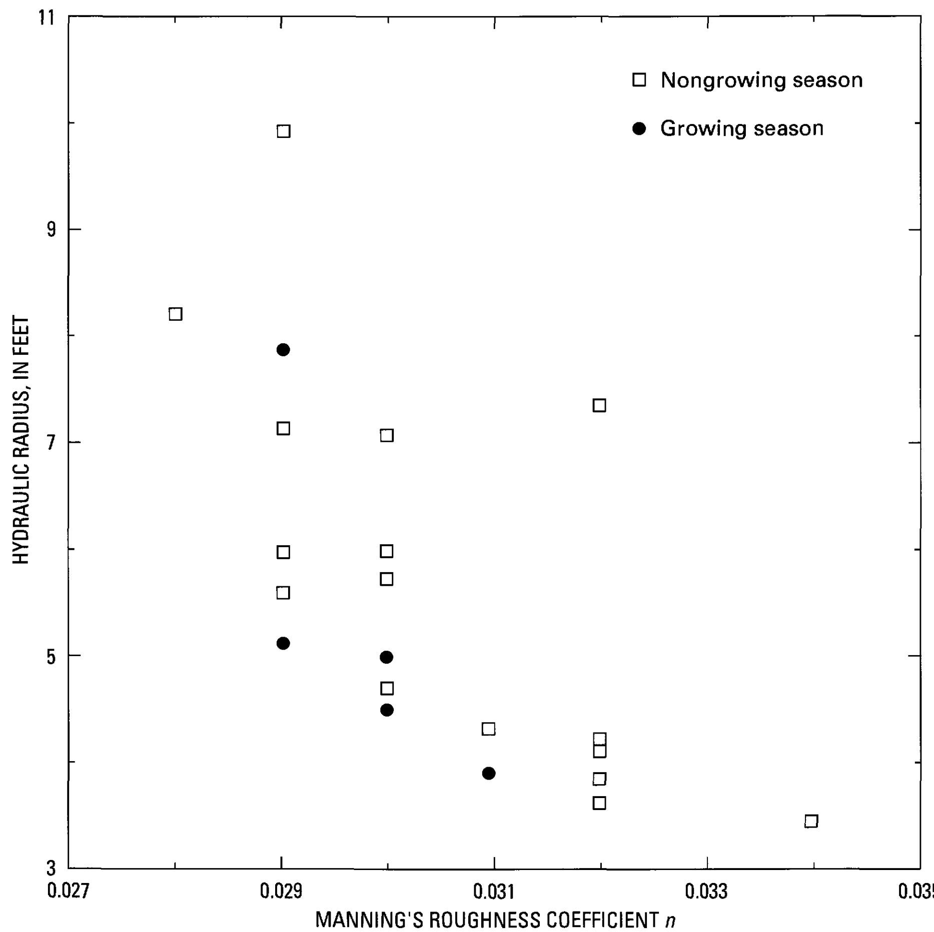


Figure 54. Relation between Manning's roughness coefficient and hydraulic radius at Unadilla River at Rockdale, N.Y.

Table 23. Station description and summary of hydraulic data, Tioughnioga River at Cortland, N.Y.

Location.—Latitude 42°36'10" N., longitude 76°09'35" W., Cortland County, on right bank at east end of Elm Street at Cortland, 0.4 mi downstream from confluence of East and West Branches. A 3-section, 1,150-ft-long reach; section 1 is 450 ft upstream from gage.

USGS station-identification number.—01509000.

Drainage area.—292 mi^2.

Bed material.—Gravel and small cobbles. Intermediate diameter d_{50} = 0.07 ft and d_{84} = 0.29 ft. Minimum diameter d_{50} = 0.04 ft.

Bank description.—Left bank has dense brush and scattered trees 20 to 50 ft apart. Right bank is grass lined and has a few small, bushy trees. Vegetation indices: 0.5, nongrowing season; 1.5, growing season.

Remarks.—The *n* values computed for flows less than about 4,000 ft^3/s are affected by 10 to 13 percent flow-area expansion in the reach; those for higher flows are affected by 6 to 9 percent flow-area expansion.

Summary of Hydraulic Data

[ft, feet; ft^2, square feet; ft/s, feet per second; ft^3/s, cubic feet per second]

Discharge (ft^3/s)	Average values for reach					Water-surface slope	Energy gradient	Percent wetted perimeter vegetated	Manning's *n*
	Area (ft^2)	Width (ft)	Hydraulic radius (ft)	Velocity (ft/s)	Froude number				
1,390	580	185	3.11	2.40	0.24	0.00057	0.00059	0.5	0.032
1,590	630	186	3.36	2.53	.24	.00057	.00058	1.6	.032
1,680	649	187	3.45	2.60	.25	.00057	.00058	1.6	.032
[1]1,920	706	188	3.72	2.73	.25	.00057	.00059	2.6	.032
1,990	729	189	3.82	2.74	.25	.00052	.00054	3.1	.031
2,290	794	190	4.12	2.89	.25	.00051	.00052	3.6	.030
2,330	801	190	4.16	2.92	.25	.00053	.00055	4.1	.031
2,750	890	193	4.55	3.10	.25	.00048	.00049	5.1	.029
2,750	869	192	4.46	3.17	.26	.00051	.00052	5.1	.029
2,810	904	193	4.61	3.12	.25	.00051	.00052	5.6	.030
2,820	909	194	4.64	3.11	.25	.00048	.00049	5.6	.030
3,590	1,060	198	5.29	3.39	.26	.00044	.00046	8.0	.029
4,170	1,160	201	5.69	3.61	.26	.00046	.00048	9.3	.029
4,320	1,180	201	5.79	3.65	.27	.00044	.00045	9.8	.028
5,640	1,380	215	6.32	4.09	.28	.00055	.00056	15.1	.029
[2]8,900	1,770	217	7.96	5.02	.31	.00048	.00049	17.0	.026

[1]The data used for this *n*-value calculation were collected during the growing season.

[2]The right-bank overflow area is treated as ineffective-flow area for this *n*-value calculation. The data reflect this modification to the cross sections.

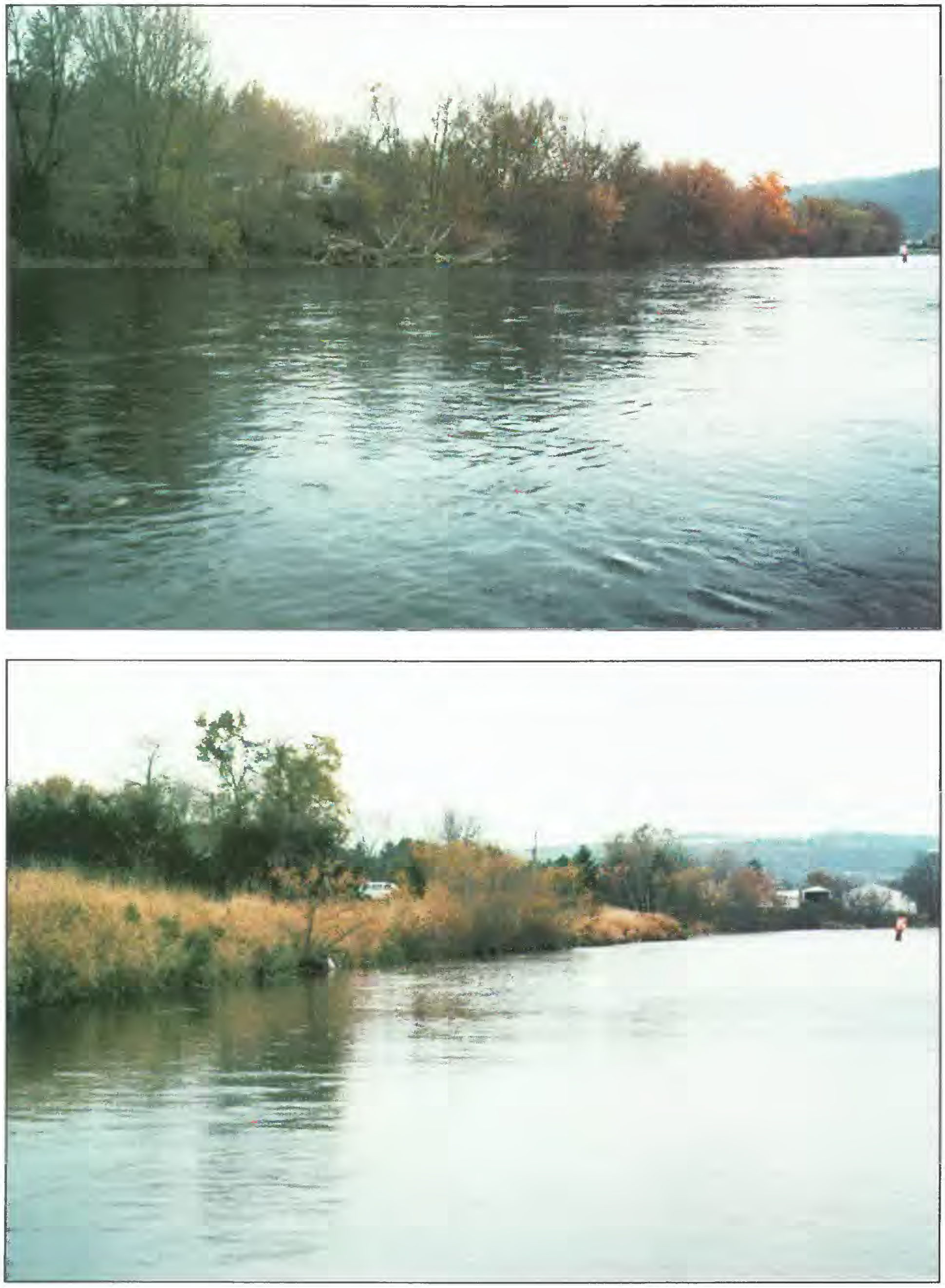


Figure 55. Photographs of Tioughnioga River at Cortland, N.Y. Hydrographer is at section 2. *A*, Downstream from cross section 1, facing downstream toward left bank. *B*, At cross section 3, facing upstream toward right bank.

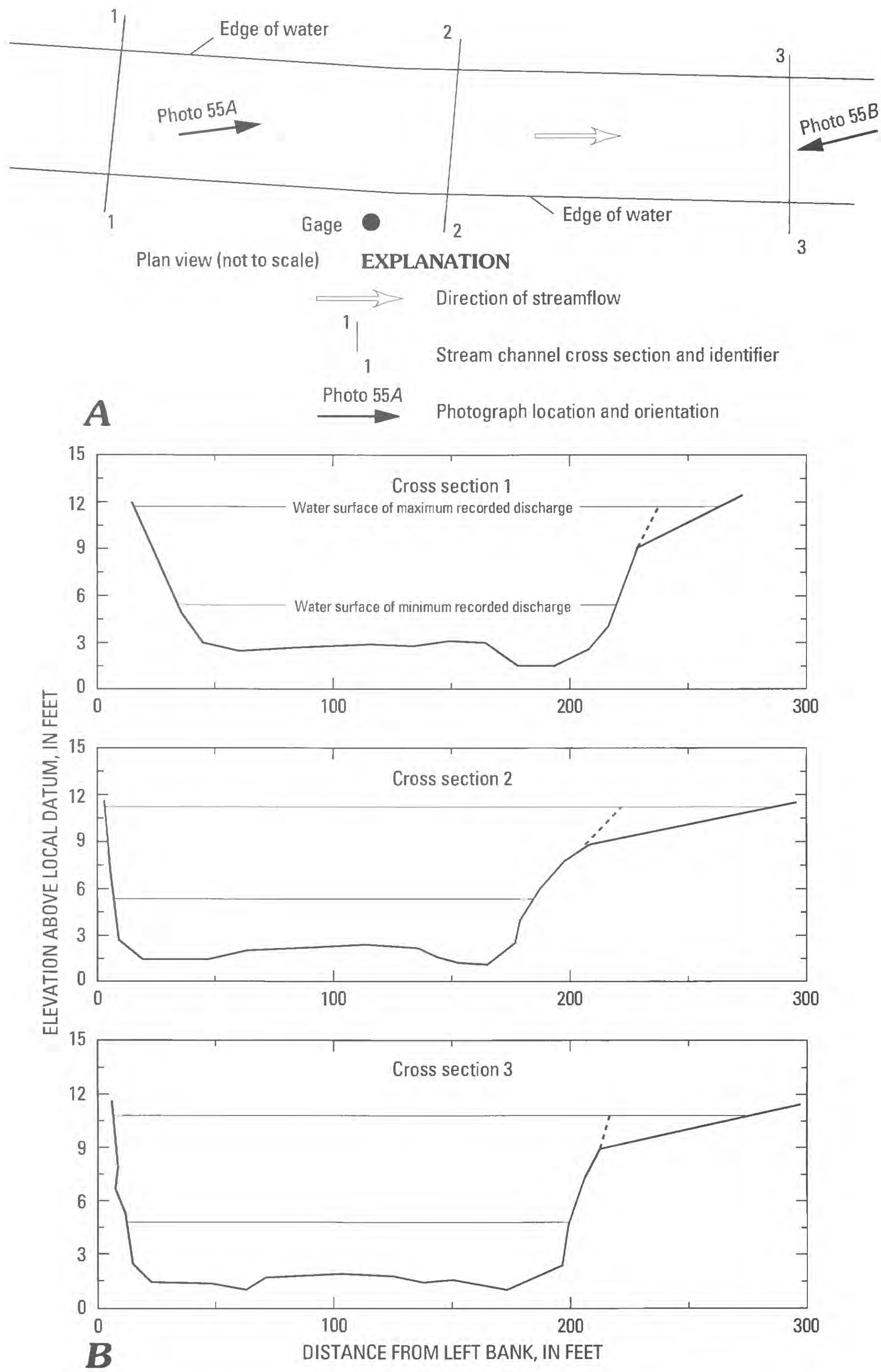


Figure 56. Plan view (*A*) and cross sections (*B*), Tioughnioga River at Cortland, N.Y. Photographs are shown in figure 55.

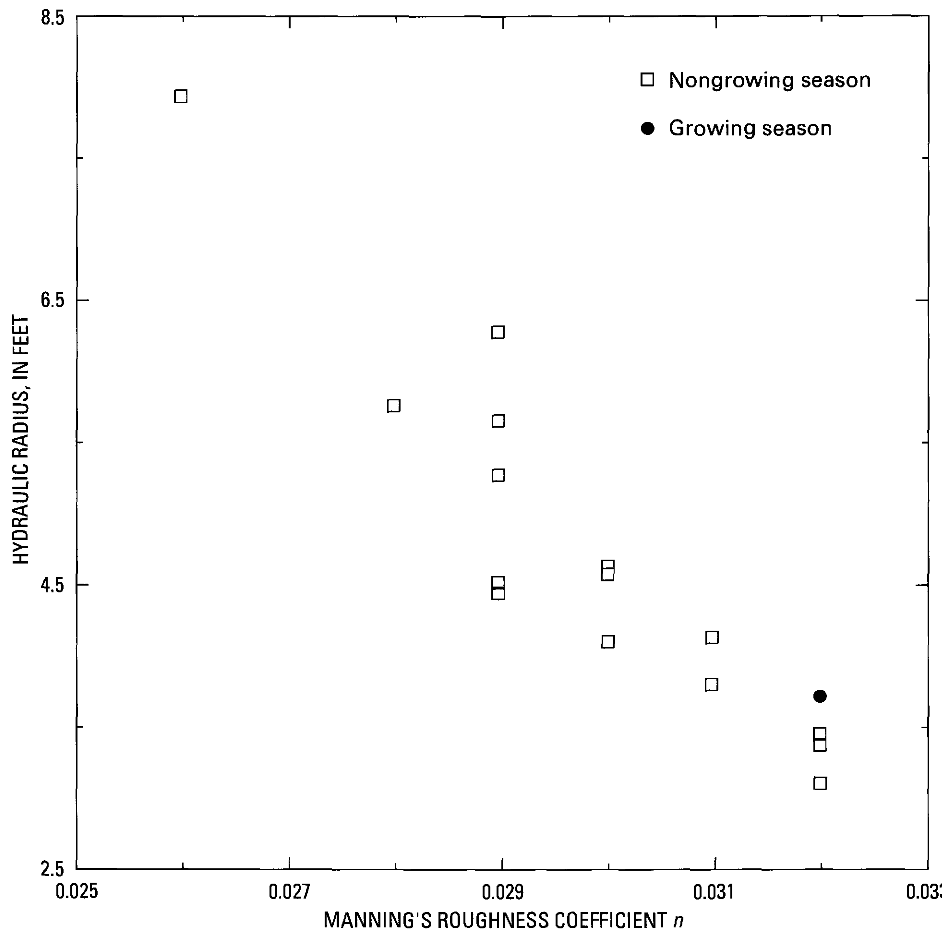


Figure 57. Relation between Manning's roughness coefficient and hydraulic radius at Tioughnioga River at Cortland, N.Y.

Table 24. Station description and summary of hydraulic data, Chenango River near Chenango Forks, N.Y.

Location.—Latitude 42°13'05" N., longitude 75°50'55" W., Broome County, on left bank in Chenango Valley State Park, and 1.2 mi downstream from Tioughnioga River and village of Chenango Forks. A 3-section, 1,340-ft-long reach; section 1 is 650 ft upstream from gage.

USGS station-identification number.—01512500.

Drainage area.—1,483 mi².

Bed material.—Cobbles, mostly flat. Intermediate diameter d_{50} = 0.37 ft and d_{84} = 0.60 ft. Minimum diameter d_{50} = 0.18 ft.

Bank description.—Both banks are steep, and lower parts are vegetated with grass, annual weeds, woody brush, and a few scattered trees. Upper parts have trees 0.5 to 2.0 ft in diameter and spaced about 10 ft apart. Vegetation indices: 1, nongrowing season; 2, growing season.

Remarks.—Floodflows are partly regulated by Whitney Point Lake. The velocity-head coefficients computed from discharge measurements made at this site range from 1.04 to 1.12 for discharges between 5,000 and 24,000 ft³/s.

Summary of Hydraulic Data

[ft, feet; ft², square feet; ft/s, feet per second; ft³/s, cubic feet per second]

Discharge (ft³/s)	Average values for reach: Area (ft²)	Width (ft)	Hydraulic radius (ft)	Velocity (ft/s)	Froude number	Water-surface slope	Energy gradient	Percent wetted perimeter vegetated	Manning's *n*
Data collected during the nongrowing season									
5,280	1,640	385	4.27	3.22	0.28	0.00073	0.00072	1.6	0.032
6,430	1,810	388	4.66	3.56	.29	.00081	.00079	2.6	.032
6,620	1,830	389	4.71	3.62	.29	.00081	.00079	2.6	.032
7,410	1,950	391	4.98	3.81	.30	.00086	.00083	3.3	.032
8,270	2,020	393	5.14	4.09	.32	.00089	.00087	3.8	.031
8,450	2,090	394	5.29	4.05	.31	.00087	.00085	4.0	.032
8,960	2,150	396	5.43	4.17	.32	.00094	.00091	4.5	.033
10,700	2,390	400	5.96	4.48	.32	.00093	.00090	5.5	.032
11,200	2,410	400	6.00	4.66	.33	.00093	.00090	5.5	.031
11,500	2,470	402	6.12	4.67	.33	.00094	.00091	5.9	.032
13,600	2,700	408	6.58	5.05	.35	.00097	.00093	7.3	.031
14,100	2,720	409	6.62	5.20	.36	.00099	.00095	7.5	.031
14,700	2,820	410	6.84	5.22	.35	.00097	.00093	8.0	.031
14,800	2,820	410	6.85	5.25	.35	.00097	.00093	8.0	.031
15,000	2,850	411	6.91	5.26	.35	.00090	.00087	8.0	.030
15,800	2,920	412	7.05	5.42	.36	.00096	.00092	8.2	.030
20,100	3,360	419	7.96	5.99	.37	.00101	.00097	10.2	.031
[1]26,500	3,910	429	9.06	6.77	.40	.00104	.00100	12.0	.030
Data collected during the growing season									
5,800	1,730	386	4.48	3.36	.28	.00078	.00077	2.1	.032
7,520	1,960	391	4.99	3.85	.30	.00089	.00087	3.3	.032
8,180	2,050	394	5.20	3.99	.31	.00089	.00087	3.8	.032
8,300	2,070	394	5.24	4.02	.31	.00084	.00082	4.0	.031
9,540	2,240	398	5.63	4.26	.32	.00087	.00085	4.8	.032

[1]The right-bank overflow area at cross section 1 is treated as ineffective-flow area for this *n*-value calculation. The data reflect this modification to the cross section.

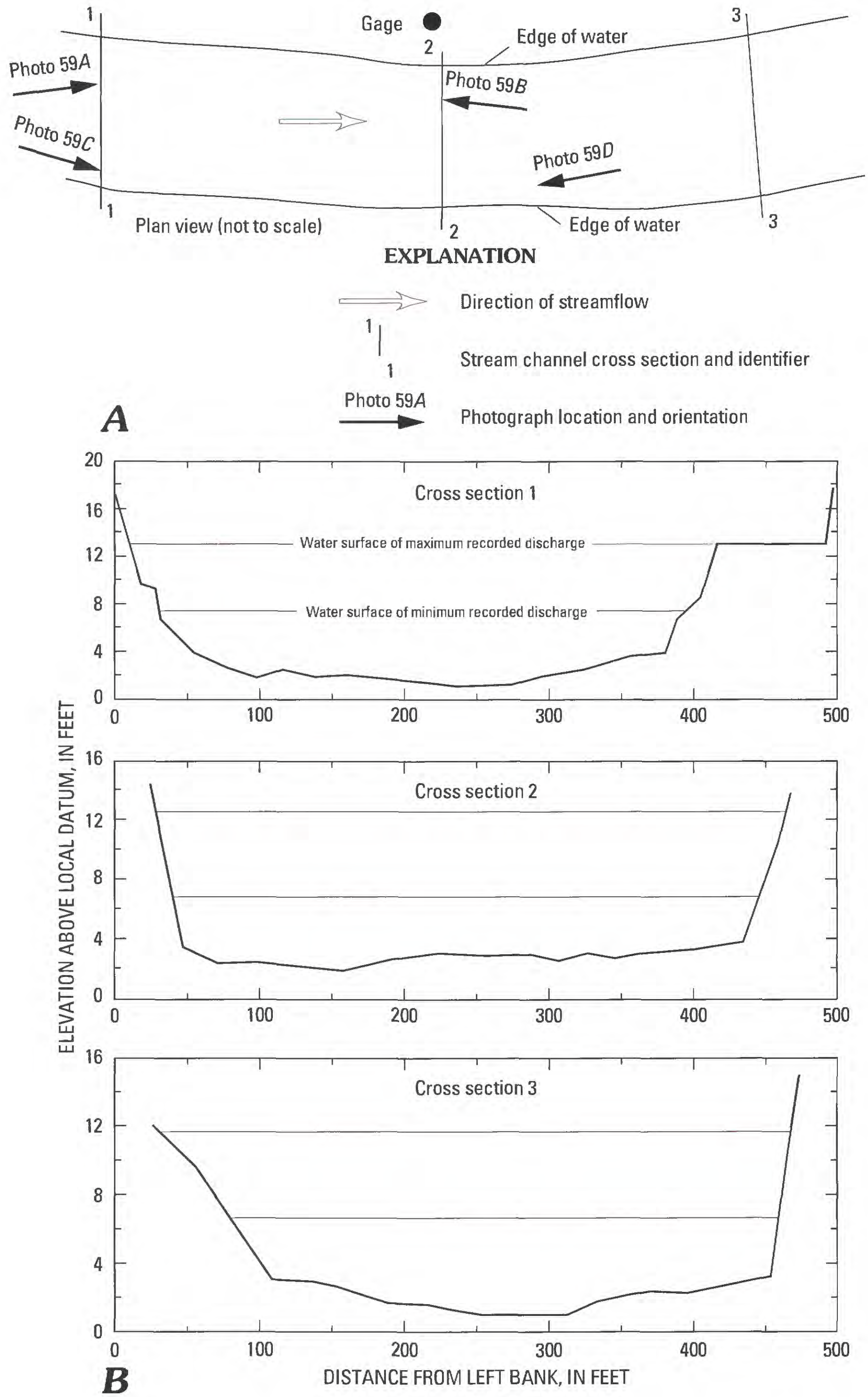


Figure 58. Plan view (*A*) and cross sections (*B*), Chenango River near Chenango Forks, N.Y. Photographs are shown in figure 59.

Figure 59. Photographs of Chenango River near Chenango Forks, N.Y. *A*, At cross section 1, facing downstream toward left bank during late fall. *B*, At cross section 2, facing upstream toward left bank during growing season. *C*, At cross section 1, facing downstream toward right bank during late fall. *D*, Downstream from cross section 2, facing upstream toward right bank during growing season. Self-supported 10-ft stadia rod is at section 2.

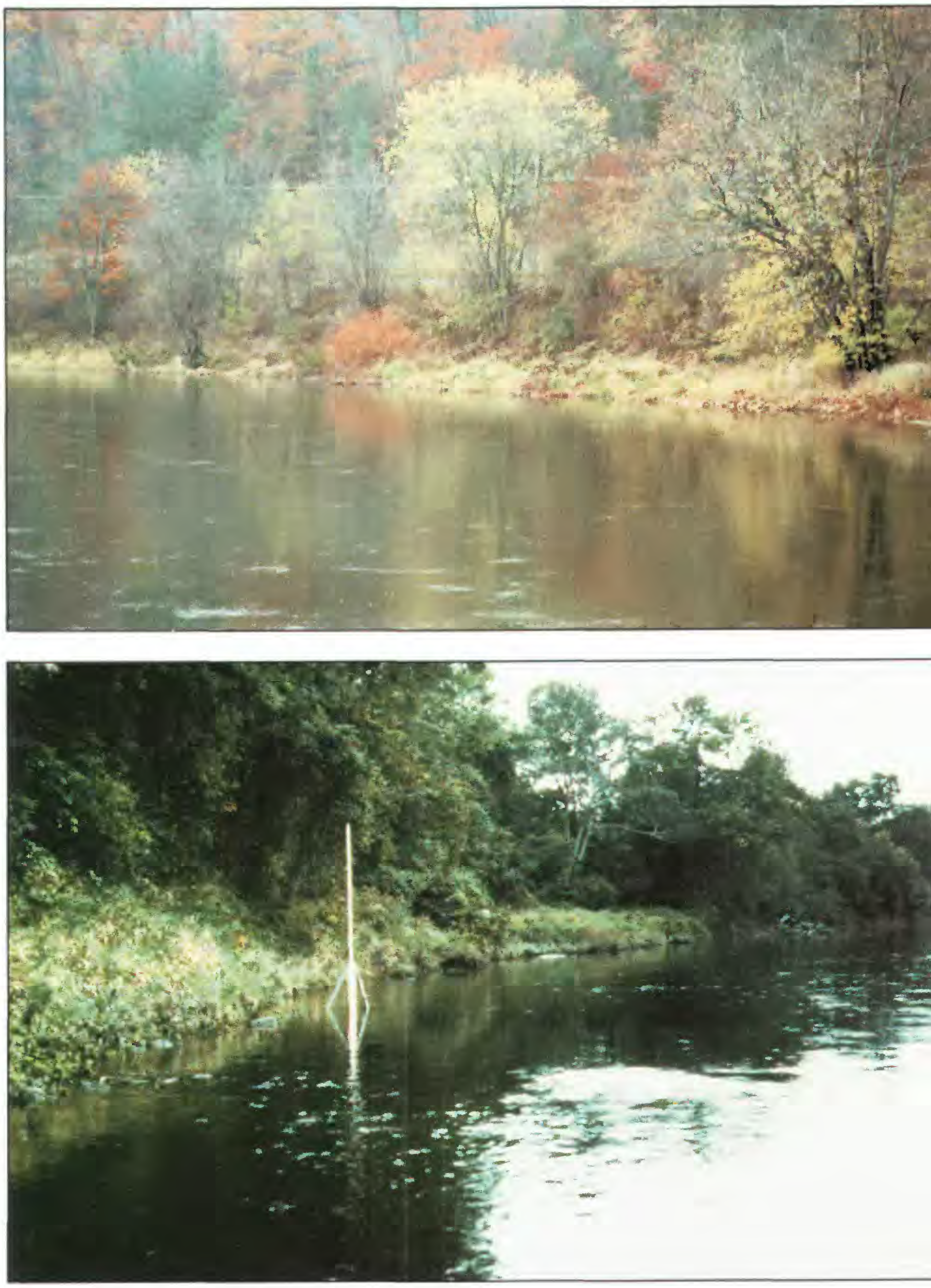


Figure 59. Continued.

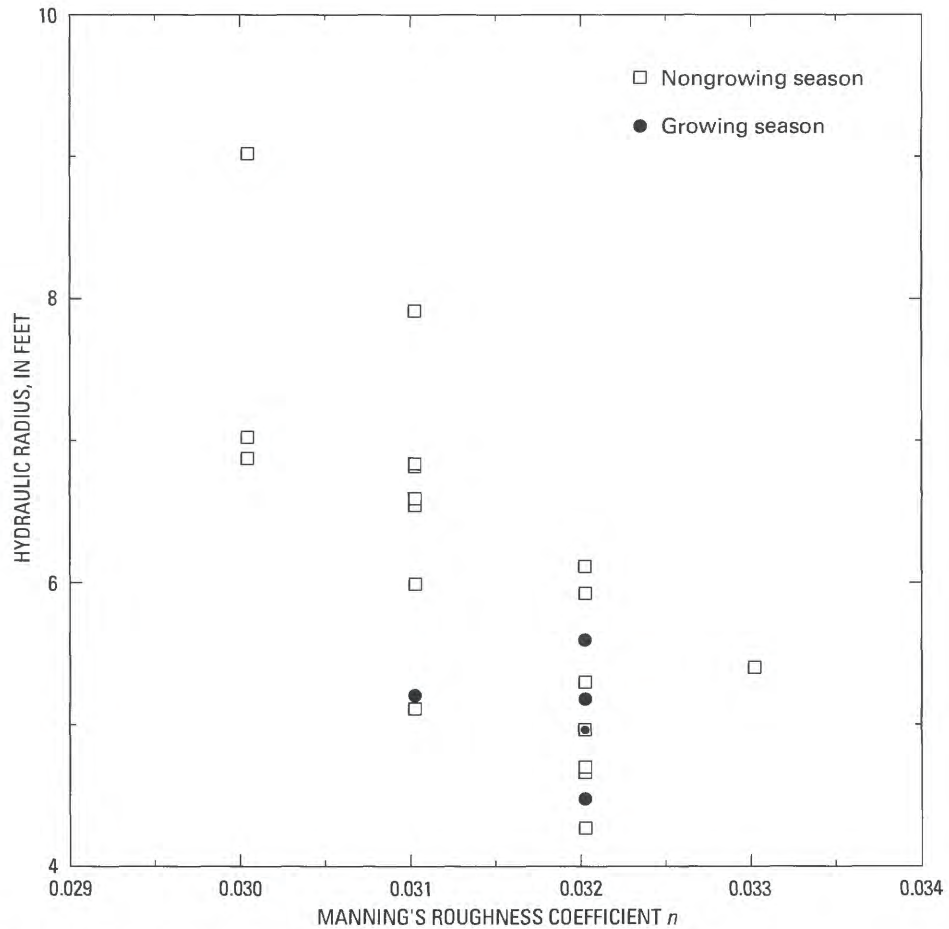


Figure 60. Relation between Manning's roughness coefficient and hydraulic radius at Chenango River near Chenango Forks, N.Y.

Table 25. Station description and summary of hydraulic data, Genesee River near Mount Morris, N.Y.

Location.—Latitude 42°46'00" N., longitude 77°50'21" W., Livingston County, on right bank 100 ft north of Jones Bridge Road, 0.8 mi downstream from Canaseraga Creek, 2.8 mi northeast of Mount Morris and 63.0 mi upstream from mouth. A 3-section, 1,000-ft-long reach; section 1 is 170 ft downstream from gage.

USGS station-identification number.—04227500.

Drainage area.—1,424 mi^2.

Bed material.—Gravel and some cobbles. Intermediate diameter d_{50} = 0.11 ft and d_{84} = 0.18 ft. Minimum diameter d_{50} = 0.06 ft.

Bank description.—Right bank is grass lined and has trees near top of bank. Left bank has grass, dense brush, trees, and overhanging branches from top of bank. Vegetation indices: 1, nongrowing season; 1, growing season.

Remarks.—Flow is regulated by Mount Morris Lake. The *n* values computed at this site are affected by 2 to 8 percent flow-area expansion in the reach. The velocity-head coefficients computed from discharge measurements made at this site range from 1.06 to 1.31 for discharges between 3,300 and 7,700 ft^3/s.

Summary of Hydraulic Data

[ft, feet; ft^2, square feet; ft/s, feet per second; ft^3/s, cubic feet per second]

Discharge (ft^3/s)	Average values for reach					Water-surface slope	Energy gradient	Percent wetted perimeter vegetated	Manning's *n*
	Area (ft^2)	Width (ft)	Hydraulic radius (ft)	Velocity (ft/s)	Froude number				
3,320	871	136	6.23	3.81	0.27	0.00048	0.00046	12.1	0.028
3,920	946	138	6.66	4.15	.28	.00041	.00039	13.4	.025
5,360	1,230	145	8.21	4.35	.26	.00041	.00039	18.0	.028
5,400	1,240	146	8.25	4.35	.26	.00037	.00035	18.5	.026
[1]5,600	1,240	146	8.24	4.52	.27	.00037	.00035	18.5	.025
6,720	1,450	151	9.23	4.64	.26	.00032	.00031	21.6	.025
[1]6,930	1,500	152	9.45	4.63	.26	.00032	.00031	22.6	.025
7,740	1,640	157	10.05	4.71	.26	.00032	.00031	25.0	.026

[1]The data used for this *n*-value calculation were collected during the growing season.

Figure 61. Photographs of Genesee River near Mount Morris, N.Y. *A*, Upstream from cross section 1, facing downstream toward left bank during late fall. Hydrographer at right edge of water at section 1 is holding a stadia rod extended 15 ft. *B*, At cross section 1, facing downstream and across the channel during growing season. *C*, Upstream from cross section 1, facing downstream toward right bank during late fall. Hydrographer at section 1 is holding a stadia rod extended 15 ft. *D*, At cross section 1 facing downstream along right bank during growing season. Self-supported stadia rod is extended 15 ft.

Figure 61. Continued.

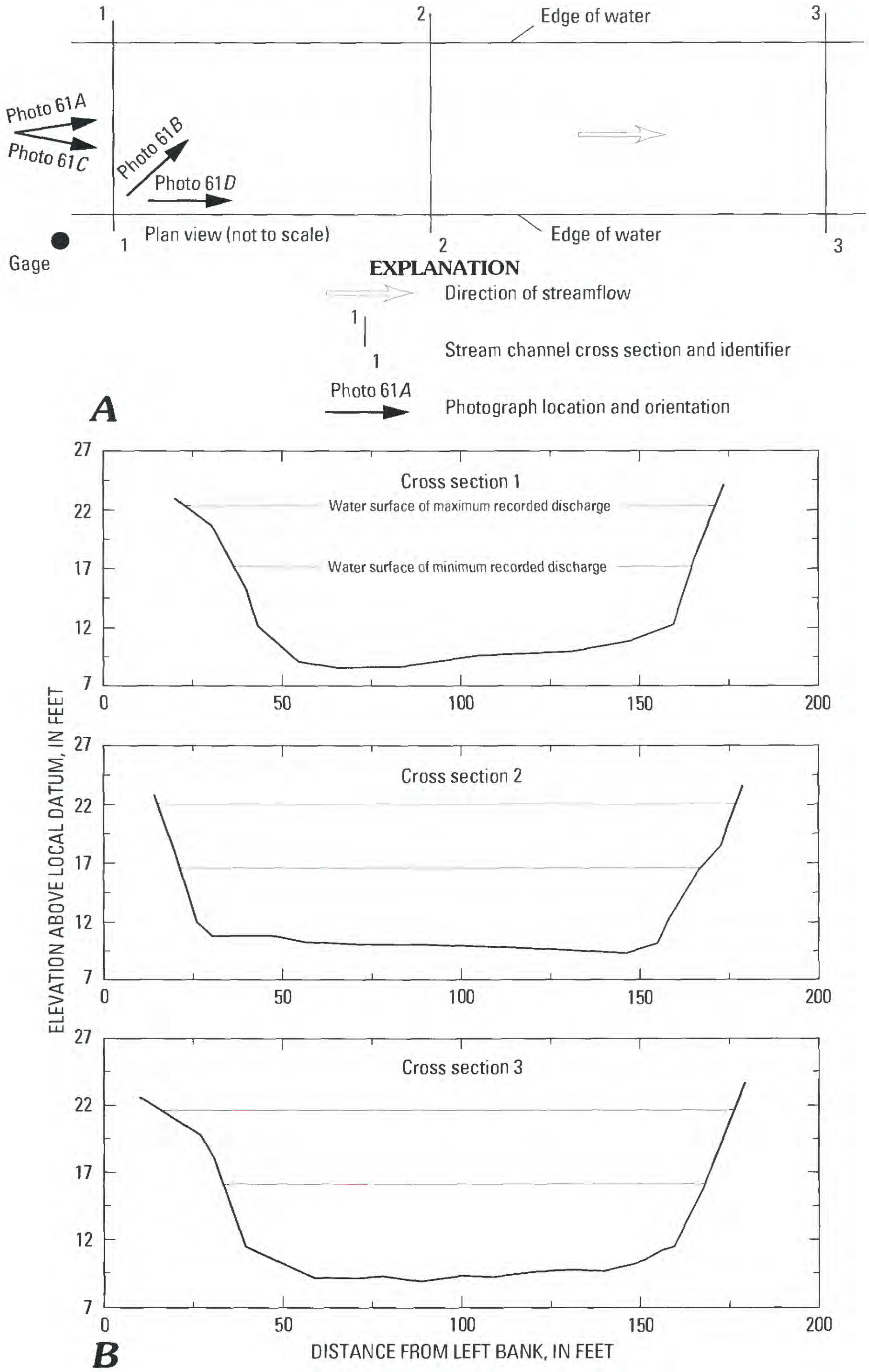


Figure 62. Plan view (*A*) and cross sections (*B*), Genesee River near Mount Morris, N.Y. Photographs are shown in figure 61.

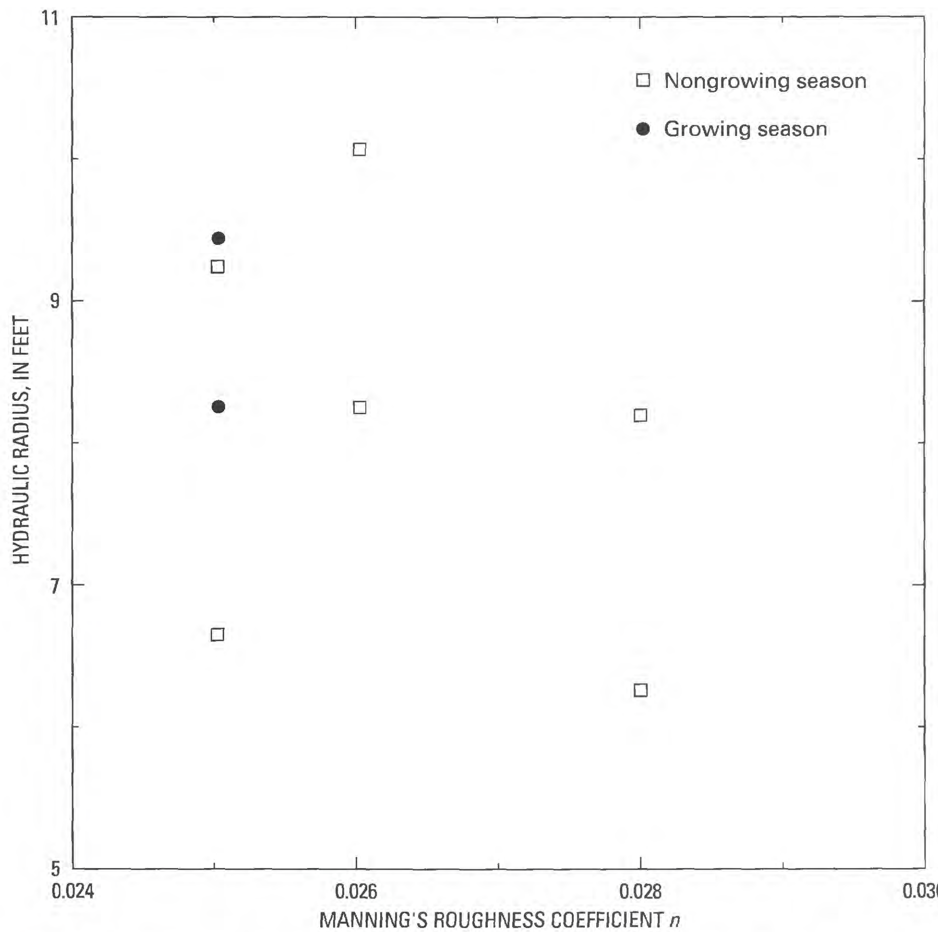


Figure 63. Relation between Manning's roughness coefficient and hydraulic radius at Genesee River near Mount Morris, N.Y.

Table 26. Station description and summary of hydraulic data, Trout River at Trout River, N.Y.

Location.—Latitude 44°59'23" N., longitude 74°17' 56" W., Franklin County, at bridge on county highway, 0.2 mi east of State Highway 30, at Trout River, 0.5 mi upstream from international boundary, 1.5 mi downstream from unnamed tributary, and 3.3 mi downstream from Little Trout River. A 3-section, 505-ft-long reach; section 1 is at the gage.

USGS station-identification number.—04270700.

Drainage area.—107 mi².

Bed material.—Primarily pitted and grooved bedrock, 25 percent of which is overlain by angular cobbles and gravel. Intermediate diameter d_{50} = about 0.15 ft and d_{84} = about 0.22 ft. Minimum diameter d_{50} not determined.

Bank description.—Both banks are vegetated with grass and annual plants along their lower parts and with trees, 0.5 to 1.5 ft in diameter, beyond. Trees are smaller and more densely spaced (about 20 ft apart) on right bank than on left. Vegetation indices: 0.5, nongrowing season; 1.5, growing season.

Summary of Hydraulic Data

[ft, feet; ft², square feet; ft/s, feet per second; ft³/s, cubic feet per second]

Discharge (ft³/s)	Average values for reach					Water-surface slope	Energy gradient	Percent wetted perimeter vegetated	Manning's *n*
	Area (ft²)	Width (ft)	Hydraulic radius (ft)	Velocity (ft/s)	Froude number				
[1]204	142	90.5	1.57	1.45	0.21	0.00160	0.00157	3.0	0.055
[2]606	226	95.7	2.32	2.71	.31	.00212	.00201	9.2	.044
[2]830	258	96.8	2.61	3.25	.35	.00234	.00218	10.4	.041
[3]3,300	523	104	4.83	6.34	.50	.00345	.00304	18.3	.037
[3]3,810	553	104	5.07	6.92	.53	.00396	.00340	19.1	.037

[1]The *n* values computed for the subreaches differ by 0.008.
[2]The *n* values computed for the subreaches differ by 0.013.
[3]The *n* values computed for the subreaches differ by 0.018.

Figure 64. Photographs of Trout River at Trout River, N.Y. *A*, At cross section 1, facing downstream toward left bank. Hydrographer is at section 2. *B*, At cross section 3, facing upstream toward right bank. Hydrographer at section 2 is standing at the approximate water-surface elevation of the maximum recorded discharge.

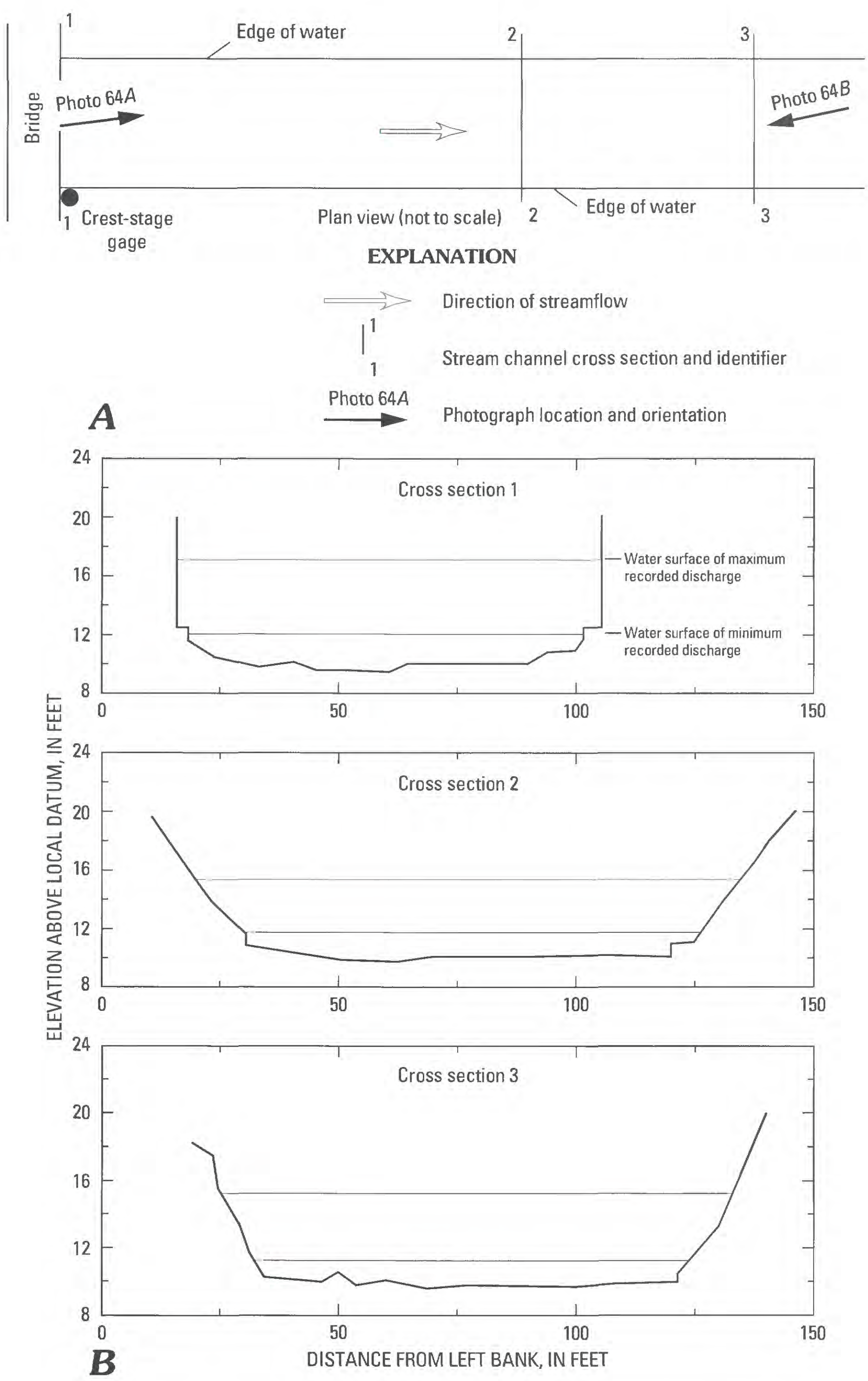


Figure 65. Plan view (*A*) and cross sections (*B*), Trout River at Trout River, N.Y. Photographs are shown in figure 64.

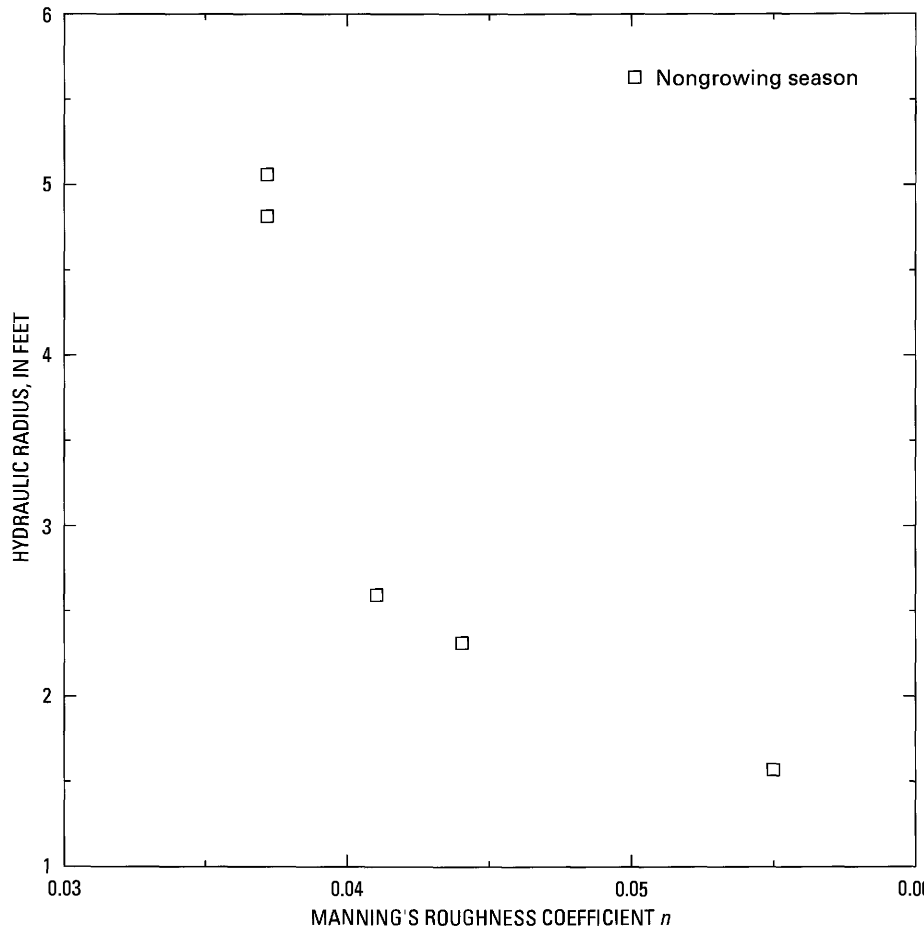


Figure 66. Relation between Manning's roughness coefficient and hydraulic radius at Trout River at Trout River, N.Y.

ANALYSIS OF ROUGHNESS-COEFFICIENT DATA

A total of 235 water-surface profiles were recorded at the 21 study sites, and the corresponding roughness coefficients were calculated. Of these, 36 profiles and calculations were considerably affected by flow-area expansion in the reach and (or) by a large variation in the *n* values computed for each subreach for a given water-surface profile and discharge. Although the actual magnitude of these computed *n* values might be questionable, the apparent relation between the *n* value and hydraulic radius and the analysis of the variation in the computed *n* values at a particular site are considered valid. (These profiles and *n*-value calculations are footnoted in the data tables in the preceding section.) An additional 72 profiles and their corresponding *n* values were substantially affected by streambank vegetation or by severe bank irregularities caused by scalloped banks with exposed tree roots. The *n* values computed for these profiles are analyzed in detail, and the indicated increments of roughness that are attributable to these factors are compared with the roughness-coefficient-adjustment values for vegetation and surface irregularities presented by Cowan (1956) and subsequently modified by Aldridge and Garrett (1973); results of the comparison are discussed in the section "Comparison of Observed and Published Adjustment Values." Many of the calculations for densely vegetated narrow channels indicate a large percentage of flow-area expansion. Unlike the previously discussed data, these computations are assumed to validly reflect the expected consequence of increased flow area that results from the increase in flow retardance from streambank vegetation. The remaining 127 profiles and their respective *n* values, plus 6 profiles and computed *n* values from the high-gradient channel, East Branch Ausable River at Au Sable Forks (which is also analyzed as a vegetation-affected site), were used in the other analyses, discussed in the following sections.

Relation Between Manning's Roughness Coefficient and Selected Variables

The degree of association between the roughness coefficient and the measured or computed hydraulic characteristics for the 21 study sites is identified by means of a correlation matrix (table 27). The four variables that show strong correlation with the roughness coefficient are hydraulic radius, slope, streambed-particle size, and relative smoothness. The relations among these variables are discussed in the following sections. Variables that have perfect or near-perfect correlation with each other are energy gradient and water-surface slope (0.99 correlation, table 27), hydraulic radius and mean depth (1.00), and stream-top width and wetted perimeter (1.00). These correlations imply that the variables within each pair can generally be substituted for each other without causing significant mathematical error in a linear regression analysis, given a uniform reach for the slope variables and a large channel for the other variables.

Hydraulic Radius

The basic roughness coefficient for a uniform channel should not vary with depth of flow if the ratio of mean depth (usually hydraulic radius) to size of roughness elements (usually the median value of the intermediate diameter of the streambed particles) is greater than 5 and less than 276 (Benson and Dalrymple, 1967). Channel width is assumed to be large relative to depth of flow, or bank materials are assumed to be the same as bed materials. This relation is substantiated by the hydraulic-data tabulations for each site. (See section, "Station Descriptions, Hydraulic Data, and Channel Photographs for the 21 Study Sites.") Low-gradient, wide channels (greater than 100 ft) with relative smoothness values (R/d_{50}) greater than 5 have nearly constant *n* values through their respective high-flow ranges (fig. 67). Although data plots indicate a slight inverse relation between *n* and *R*, the computed roughness coefficients for most of these sites differ by less than 0.005 from low-flow to bankfull conditions. Streambank vegetation has no measurable effect on roughness coefficients at these sites when less than 25 percent of the wetted perimeter is vegetated.

Channels with low relative smoothness (R/d_{50} less than or close to 5) generally are in mountain streams with high gradients and large median bed-particle sizes. The roughness coefficients for streams such as these decrease rapidly with increasing depth and approach an asymptotic value as bankfull flow is approached, as shown by Sargent (1979) and Jarrett (1984). Several of the sites studied show this relation (fig. 67) and had *n* values that differed by as much as 0.068 from low-flow to bankfull conditions, but most differed by 0.015 to 0.030. The *n* values computed for low-flow conditions, when flow depths are insufficient

Table 27. Correlation coefficients for selected hydraulic and streambed-particle-size characteristics for the 21 study sites in New York

[—, correlation coefficient for this pair of variables is given elsewhere in the table]

Variable	Untransformed data								
	R	T	S_f	S_w	d_{50}	d_{84}	R/d_{50}	R/d_{84}	n
Hydraulic radius, R	1.00	—	—	—	—	—	—	—	—
Top width of stream, T	.44	1.00	—	—	—	—	—	—	—
Energy gradient, S_f	–.50	–.50	1.00	—	—	—	—	—	—
Water-surface slope, S_w	–.50	–.52	.99	1.00	—	—	—	—	—
[1]Particle size, d_{50}	–.18	–.22	.80	.77	1.00	—	—	—	—
[1]Particle size, d_{84}	–.10	–.23	.69	.69	.90	1.00	—	—	—
Relative smoothness, R/d_{50}	.35	.04	–.49	–.50	–.64	–.55	1.00	—	—
Relative smoothness, R/d_{84}	.50	.07	–.51	–.51	–.58	–.57	.84	1.00	—
Manning's coefficient, n	–.50	–.40	.86	.83	.76	.60	–.46	–.48	1.00

	Log-transformed data						
	Log R	Log S_f	Log d_{50}	Log d_{84}	Log(R/d_{50})	Log(R/d_{84})	Log n
Log R	1.00	—	—	—	—	—	—
Log S_f	–.60	1.00	—	—	—	—	—
Log d_{50}	–.20	.73	1.00	—	—	—	—
Log d_{84}	–.24	.81	.91	1.00	—	—	—
Log (R/d_{50})	.62	–.87	–.89	–.84	1.00	—	—
Log (R/d_{84})	.66	–.91	–.79	–.89	.94	1.00	—
Log n	–.65	.86	.70	.75	–.86	–.89	1.00

[1]Computed from intermediate dimension of measured particles. See glossary for definitions.

to allow full development of the velocity profile, reflect the effect of energy-loss factors other than boundary-layer friction, which contribute substantially more to the roughness coefficient and produce larger n values than would be computed for higher flows. The pertinent points of this analysis, however, are the inverse relation between n and R and the magnitude of the change in the roughness coefficient from low-flow to bankfull conditions. The effect of streambank vegetation at these sites when less than 25 percent of the channel's wetted perimeter is vegetated is either reflected in the computed n value or is insignificant.

For narrow channels with dense streambank vegetation where typically more than 25 percent of the channel's wetted perimeter is vegetated and R/d_{50} is greater than 5, roughness coefficients generally increase with increasing depth of flow. An example is Scajaquada Creek at Buffalo (table 7), which has a dense growth of willow saplings at its low-water edge. Roughness coefficients at this site can vary substantially with both depth and season, ranging from 0.024 to 0.029 during the nongrowing season and from 0.027 to 0.033 during the growing season. On similar channels where R/d_{50} is less than 5, such as Tremper Kill near Andes (table 6), effects of streambank vegetation during the nongrowing season are indiscernible. Growing-season effects on the roughness coefficient can be substantial, however. These and other sites are discussed more fully in the analysis of "Streambank Vegetation."

Energy Gradient

Of all the hydraulic factors considered, the two that are most highly correlated with the roughness coefficient are energy gradient (friction slope) and water-surface slope. The correlation coefficient for the n value is slightly higher for energy gradient (0.86, table 27) than for water-surface slope (0.83). This close association indicates that hydraulic roughness increases with an increase in slope, as illustrated for high within-bank flows in figure 68. This observation agrees with Riggs' (1976) analysis of Barnes's (1967) data, Jarrett's (1984) findings on 21 streams in

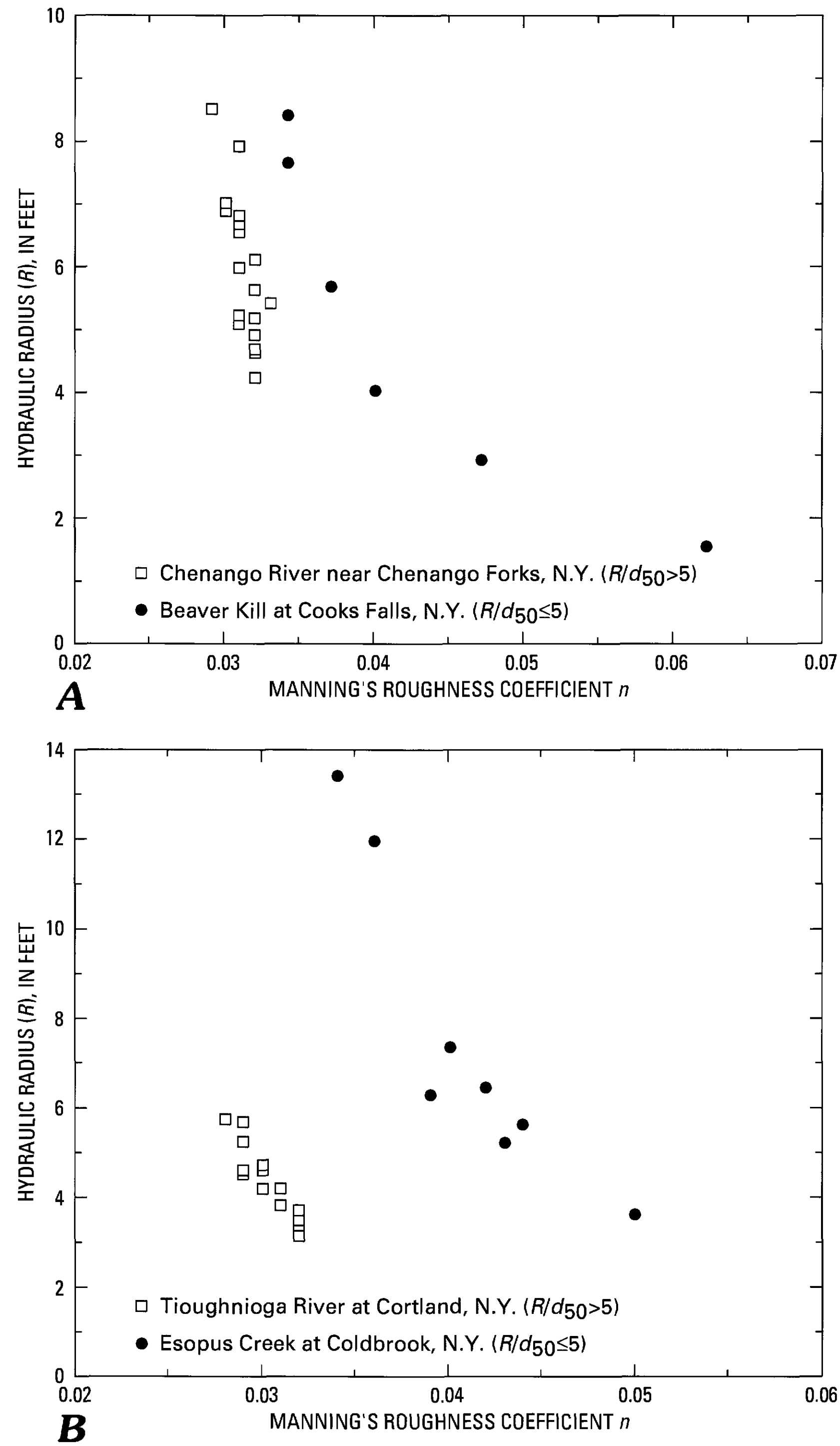


Figure 67. Relation between Manning's roughness coefficient and hydraulic radius for two channels where the ratio of hydraulic radius to the median particle size of streambed material (R/d_{50}) is greater than 5, and two channels where these values are equal to or less than 5. (Locations are shown in fig. 3.) *A*, Chenango River near Chenango Forks, N.Y., and Beaver Kill at Cooks Falls, N.Y. *B*, Tioughnioga River at Cortland, N.Y., and Esopus Creek at Coldbrook, N.Y.

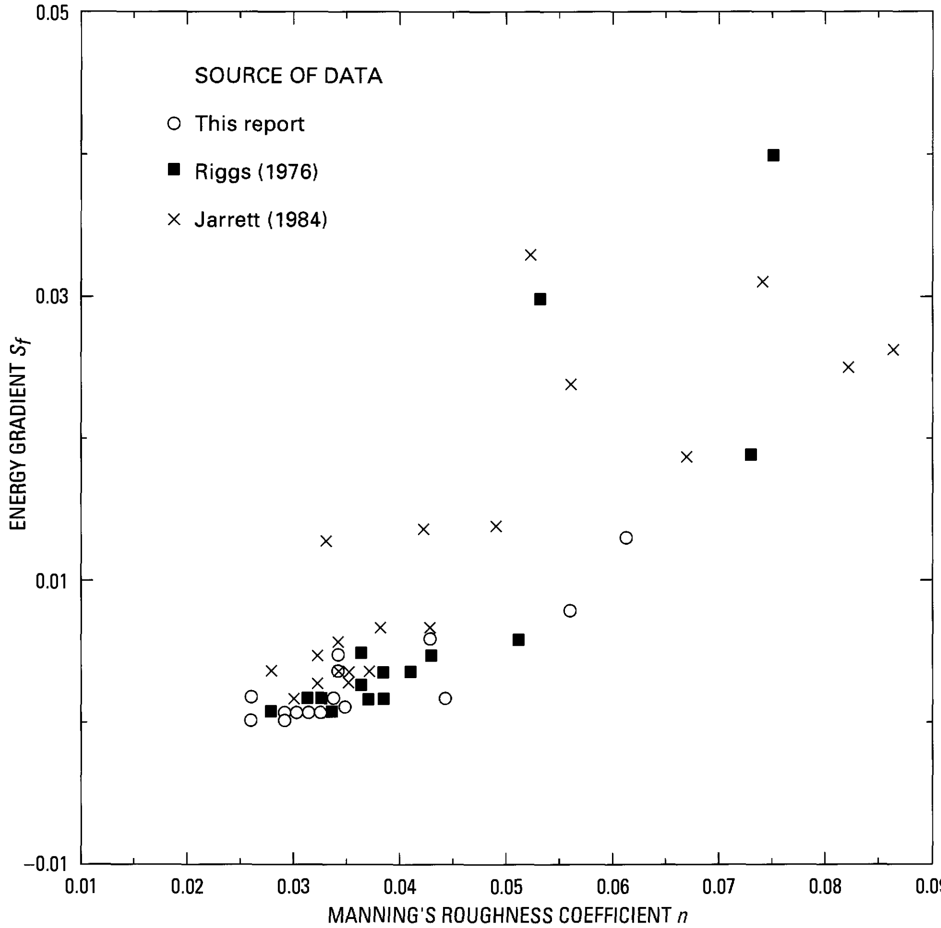


Figure 68. Relation between Manning's roughness coefficient and energy gradient for high within-bank flows.

Colorado, and Bray's (1979) conclusion that slope is a more reliable estimator of the n value than size of bed material.

Streambed-Particle Size and Relative Smoothness

Particle size of bed material is closely related to channel roughness and is commonly used as a beginning point for estimating a base n value for a reach. This minimum roughness is a function of the size, shape, spacing, and size distribution of the bed material (Bathurst, 1978). Although many of the study sites have additional roughness factors that contribute to the total channel roughness, the computed n values generally fall within the ranges defined by the bed-material size, as identified by Benson and Dalrymple (1967) (see table 1 of this report) for channels in the following categories: wide channels (more than 100 ft wide) with R/d_{50} greater than 5; stages at or near bankfull on wide channels with R/d_{50} less than 5; and bankfull stages on narrow channels with little or no streambank vegetation. The relation between the roughness coefficient and the median diameter (d_{50}) of the intermediate dimension of the bed particles for high within-bank flows is shown in figure 69. All other factors remaining constant, the hydraulic roughness of a channel will increase with an increase in bed-particle size.

The intermediate diameters d_{50} and d_{84}, the minimum diameter d_{50}, and a weighted diameter d_w were used to characterize the bed material in each reach and to identify any strong correlations with the roughness coefficient. The particle diameter d_w is based on the intermediate dimension of the particle and is defined by Limerinos (1970) as the sum of the three products obtained by multiplying d_{84} by 0.6, d_{50} by 0.3, and d_{16} by 0.1. The intermediate diameter d_{50} is most strongly correlated (0.76) with the roughness coefficient (table

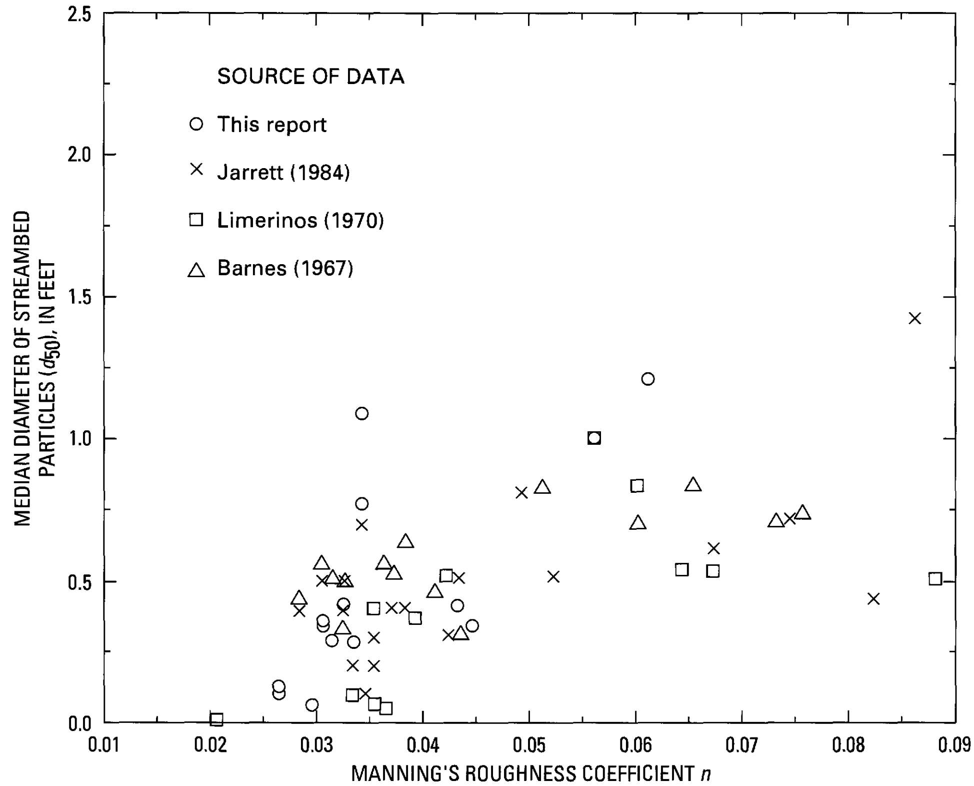


Figure 69. Relation between Manning's roughness coefficient and streambed-particle size (intermediate diameter d_{50}) for high within-bank flows.

27). The weighted d_w values are less than, but closely correlated with, the d_{84} values.

Several researchers (Boyer, 1954; Bathurst, 1978; Colosimo and others, 1988) have used a ratio of flow depth to a specific particle-size diameter to define relative smoothness for channels with predominantly large grained bed material. In this study, relative smoothness was computed from the hydraulic radius and each of the above-mentioned particle-size diameters; the relative smoothness based on the minimum diameter d_{50} was correlated most highly (–0.52) with the roughness coefficient. When the variables are logarithmically transformed, this correlation improves (–0.88) and is just slightly less than the correlation between the log-transformed n value and the log-transformed relative smoothness based on the intermediate diameter d_{84} (–0.89). Shown in figure 70 are the relations between the roughness coefficient and relative smoothness values based on the intermediate particle-size diameters for wide channels (more than 100 ft wide) and narrow channels with no measurable roughness effect from streambank vegetation.

The relation between bed particle-size distribution and the roughness coefficient was checked through application of the particle-size data for the intermediate dimension. Two values that characterize the particle-size distribution were computed: d_{84}/d_{50} and $(d_{16} + d_{50} + d_{84})/3(d_{50})$. No consistent relation was identifiable between the roughness coefficient and either of these values for particle-size distribution.

Streambank Vegetation

Vegetation growing within the streambanks, including the low-water channel, retards flow by increasing turbulence and reducing channel capacity. Although reduced channel capacity is not an energy-loss factor, it is often incorporated along with turbulence into the roughness coefficient. Available data on roughness-adjustment values to correct for vegetation (table 4) are primarily applicable to channels where vegetation is uniformly distributed across a channel section and for channels less than 100 ft wide. Narrower channels generally require larger adjustments for vegetation, and wide channels with no substantial

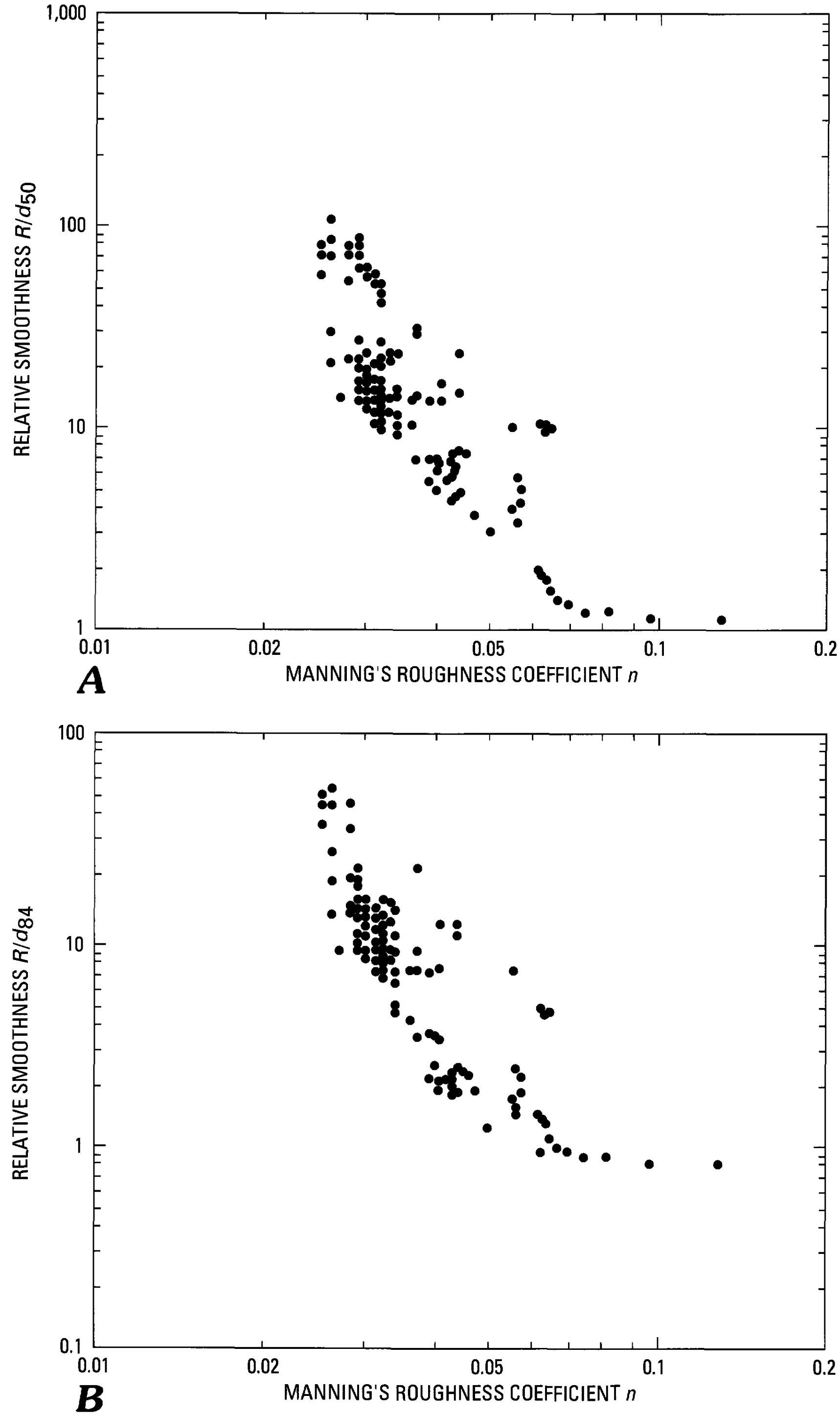


Figure 70. Relation between Manning's roughness coefficient and relative smoothness values, R/d_{50} (*A*) and R/d_{84} (*B*), based on the intermediate particle-size diameters for wide channels (more than 100 ft wide) and narrow channels with no measurable roughness effect from streambank vegetation.

Table 28. Description and index of streambank vegetation of study sites in New York

[Descriptions pertain to the general vegetation conditions of the inundated part of the reach]

Vegetation index number	Qualifying term	Description
0	Sparse	All seasons: Short or mowed grass or submerged long grass and soft-stemmed plants that are bent with the flow. A few scattered trees of any diameter. Nongrowing season: Also corresponds to vegetation described for growing season for index number 1.
1	—	Growing season: Rigid grasses and soft-stemmed plants not yet submerged; scattered woody brush, and only a few trees (any diameter) spaced more than 50 ft apart. Passage by foot or sighting with surveying equipment unobstructed by vegetation. Nongrowing season: Corresponds to vegetation described for growing season for index number 2.
2	Moderate	Growing season: Moderately dense woody brush and scattered trees (any diameter) spaced between 20 and 50 ft apart. Grasses and soft-stemmed plants may be mixed among the brush. Passage by foot or survey sighting occasionally obstructed by vegetation. Nongrowing season: Corresponds to vegetation described for growing season for index number 3.
3	—	Growing season: Similar to vegetation described for index number 2 but more woody brush or a greater density of trees (1 every 10 to 20 ft). Large-diameter trees (greater than 1.5 ft) interspersed among smaller diameter trees (0.5 to 1.0 ft).
4	Dense	All seasons: High density of mixed-diameter trees spaced less than 5 ft apart interspersed among dense woody shrubs, willow saplings, and (or) vines. Passage by foot or survey sighting impossible along banks.

channel-bottom vegetation would require negligible adjustments, if any. Few studies have dealt with the incremental roughness effects of streambank vegetation alone.

Streambank vegetation at the 21 study sites ranged from maintained (mowed) grass to various combinations and densities of trees and brush. Three of the sites had vegetated low-overflow areas, and one had grass growing on a gravel bar over a very small part of its channel bottom. The streambank-vegetation descriptions were categorized (table 28), and a vegetation index, which represents the type and relative density of streambank vegetation, was developed. This index represents the average vegetation conditions of the inundated part of both banks and can change with flow depth and season. A low value (0 to 1) denotes sparse vegetation and minimal flow retardance; a high index (4) signifies dense vegetation and a potentially large effect on the roughness coefficient. The vegetation indices for bankfull flows at the study sites are presented in the data tables in the section, "Station Descriptions, Hydraulic Data, and Channel Photographs for the 21 Study Sites." Table 28, although not all-inclusive, describes the vegetation characteristics of the study sites, which are representative of conditions in most streams in the northeastern United States.

Comparison of the computed roughness coefficients for two sites that are similar in all ways but one, or for the same site under different conditions, can be used to evaluate the effect of the differing characteristics on the n value. This method was used by Ramser (1929), who documented the effects on the roughness coefficient of dredging, channelization, and the removal of channel vegetation and other obstructions. Cowan (1956) used Ramser's data to compute the values for roughness-coefficient adjustment which are presented in table 4. This technique was used in the analysis of the effects of streambank vegetation on the roughness coefficient at the study sites; the results are presented in table 29.

Data tabulations (table 29) and graphs of R versus n values (presented in the section, "Station Descriptions, Hydraulic Data, and Channel Photographs for the 21 Study Sites") indicate that bank vegetation has no measurable effect on the roughness coefficient of streams that are wider than 100 ft and that have wetted perimeters less than 25 percent vegetated. Study sites that meet this criterion have average stream widths that range from about 100 to 429 ft, wetted perimeters that are from 0 to 25 percent vegetated, and hydraulic radii that increase by 3.4 to 9.8 ft in the range of flows recorded. That the *n* values computed for these sites are nearly constant or decrease with increasing flow depth (fig. 67) indicates that the effect of streambank vegetation on the total *n* value is undetectable. At study sites where stream widths are less than 63 ft, vegetation (brush, grass, and trees) that covers more than 25 percent of the wetted perimeter causes the computed roughness coefficient to increase by as much as 0.005 during the nongrowing season and by an additional 0.002 to 0.012 during the growing season (table 29). The largest adjustment values represent reaches with high vegetation density, narrow channels, or low but greater-than-zero percentages of vegetation submergence (that is, the ratio of depth of inundation to height of vegetation). The values for streambank-vegetation adjustment for one site (East Branch Ausable River at Au Sable Forks), where the top width is about 200 ft and the wetted perimeter is more than 30 percent vegetated, appear to range from 0.005 to 0.009. The relation between the percentage of wetted perimeter that is vegetated and the indicated value of the roughness-coefficient adjustment for streambank vegetation is shown in figure 71. Overall, the analyses of the channels affected by vegetation indicate that the percentage of wetted perimeter that is vegetated can be used as an indicator of energy losses that are attributable to streambank vegetation. The magnitude of the vegetation effect can be estimated from evaluation of such factors as energy gradient, stream-top width, season, and type, density, and percent of submergence of vegetation. The wide scatter of the data in figure 71 reflects the wide variability of these factors among the study sites.

Details of the analyses of vegetation effects on the roughness coefficients at nine sites are discussed in the following paragraphs. Sites are presented in order of largest to smallest vegetation effect, the narrow channels (less than 100 ft wide) being discussed first. Two sites, Onondaga Creek at Dorwin Avenue, Syracuse, and Tioughnioga River at Itaska, where streambank vegetation has no apparent effect on the computed roughness coefficient, are presented for comparison with the vegetation-affected sites. Data graphs and photographs of each site in the section "Station Descriptions, Hydraulic Data, and Channel Photographs for the 21 Study Sites" can be viewed for clarification of the analyses and channel descriptions given in the text.

Tremper Kill near Andes is vegetated on the right bank with grass, soft-stemmed annual plants, and a few large trees; the left bank is steep and has hemlock trees growing above the level of the highest flow recorded during the study period (fig. 4). The average top widths of the channel for the recorded water-surface profiles are from 37 to 53 ft, and the wetted perimeters are from 24 to 48 percent vegetated (table 6). Streambank vegetation during the nongrowing season had no discernible effect on the computed *n* values at this site (fig. 6), probably because the large-scale bed material and the irregular left bank with exposed tree roots create major flow impediments that mask the effect of the vegetation on the right bank. Also, as noted in table 27, water-surface slope and energy gradient are strongly correlated with the roughness coefficient. In high-gradient channels such as this one, slope can exert a controlling effect on the *n* value that obscures the effect of streambank vegetation, at least during the nongrowing season. The summer growth, which replaces dead and broken grasses with taller and more resistive plants, has a noticeable effect on the *n* values, however (fig. 6). The maximum adjustment to the roughness coefficient for growing conditions (0.012) corresponds to a water-surface elevation just above that of the low-flow channel—the point at which flows encounter resistance from bamboo-like stalks and tufts of grasses. The channel's computed *n* value for a flow with a hydraulic radius of 1.49 ft during the nongrowing season is 0.054, and that for a flow with a similar hydraulic radius (1.40 ft) during the growing season is 0.066 (table 29). The difference between these two values, 0.012, is attributed to the increased streamflow resistance from the streambank vegetation present during the growing season. Similarly, the computed roughness coefficient for a flow with a hydraulic radius of 2.84 ft during the nongrowing season is 0.052 and that for a flow with a hydraulic radius of 2.76 ft during the growing season is 0.057. The difference, 0.005, is also attributed to growing-season vegetation. The decrease in the adjustment to the roughness coefficient that is attributed to streambank vegetation as flow depth increases probably reflects the decrease in the energy losses as the vegetation becomes submerged and bends with the flow.

Scajaquada Creek at Buffalo is a flood-control channel lined with vetch and grasses along most of its

Table 29. Incremental effects of streambank vegetation on the roughness coefficient

[Locations are shown in fig. 3. Numbers in parentheses indicate an apparent value. Blank spaces indicate no pertinent data]

Site number and name	Width (feet)	Hydraulic radius (feet)	Energy gradient	Percent wetted perimeter vegetated	Estimated base *n* value	Computed *n* value		Adjustment values for streambank vegetation	
						Nongrowing season	Growing season	Nongrowing season	Growing season
Sites where streambank vegetation has a measurable or apparent effect on the computed roughness coefficient									
1. Tremper Kill	41.5	1.49	0.01068	32.7		0.054			
near Andes	41.0	1.40	.01057	31.7			0.066		0.012
	47.6	2.34	.01061	42.1		.054			
	46.3	2.21	.01045	40.5			.058		.004
	53.2	2.84	.01205	48.2		.052			
	52.2	2.76	.01097	47.2			.057		.005
2. Scajaquada	54.2	3.02	.00043	27.9		.024			
Creek at Buffalo	63.2	3.94	.00055	38.5		.029		0.005	
	50.5	2.62	.00055	22.5			.027		
	55.6	3.16	.00072	29.7			.033		.006
	54.2	3.02	.00043	27.9		.024			
	54.6	3.06	.00072	28.4			.032		.008
	55.2	3.13	.00053	29.3		.026			
	55.6	3.16	.00072	29.7			.033		.007
	57.4	3.36	.00048	32.1		.026			
	57.3	3.35	.00060	31.9			.030		.004
	62.5	3.87	.00055	37.7		.029			
	60.3	3.66	.00056	35.5			.029		.000
3. Moordener Kill	38.6	1.57	.00130	10.9		.031			
at Castleton-on-	46.6	2.63	.00147	27.4		.034		(.003)	
Hudson	42.3	2.16	.00145	19.5			.035		
	43.5	2.33	.00158	21.9		.032			.003
	45.9	2.60	.00166	26.5			.038		
	46.6	2.63	.00147	27.4		.034			(.004)
4. Canisteo River	37.4	2.78	.00308	36.1		.034			
at Arkport	37.5	2.80	.00301	36.2		.031		.000	
	38.6	2.92	.00316	38.0			.034		[1](.003)
	38.8	2.95	.00306	38.4			.033		[1](.002)
5. Mill Brook near	38.1	1.14	.00990	0		.062			
Dunraven	43.0	1.37	.01095	[2]13.1		.057		.000	
	43.4	1.38	.01015	[2]15.6			.069		[1,3](.012)
	62.7	3.66	.01080	[2]42.0		.035		(.000)	
6. East Branch	188	3.73	.00835	33.7	[4]0.051	.056		(.005)	
Ausable River at	209	4.18	.00818	40.4	[4].050		.055		(.005)
Au Sable Forks	213	4.42	.00831	41.2	[4].050	.057		(.007)	
	230	5.85	.00815	45.4	[4].047	.056		(.009)	

Table 29. Incremental effects of streambank vegetation on the roughness coefficient—Continued

Site number and name	Width (feet)	Hydraulic radius (feet)	Energy gradient	Percent wetted perimeter vegetated	Estimated base *n* value	Computed *n* value		Adjustment values for streambank vegetation	
						Nongrowing season	Growing season	Nongrowing season	Growing season
Sites where streambank vegetation has a measurable or apparent effect on the computed roughness coefficient—Continued									
7. Beaver Kill at Cooks Falls	199	4.11	0.00397	0.5	[5]0.040	0.040		0.000	
	208	5.50	.00432	[2]5.2	[5].036	.041		[3].005	
	209	5.68	.00445	[2]5.7	[5].035	.040		[3].005	
	210	5.81	.00424	[2]6.1	[5].035		0.039		[3]0.004
	210	5.80	.00428	[2]6.1	[5].035	.037		[3].002	
	222	8.39	.00474	11.9		.034		(.000)	
Selected sites where streambank vegetation has no apparent effect on the computed roughness coefficient									
8. Onondaga Creek at Dorwin Ave., Syracuse	65.4	1.90	0.00152	5.1		0.027			
	85.2	4.10	.00145	[6]27.8		.026		0.000	
9. Tioughnioga River at Itaska	211	1.65	.00050	0			0.030		
	265	4.23	.00108	[2]17.6		.031		[3](.001)	
	272	4.90	.00114	[2]19.4		.032			
	287	6.66	.00125	[2]32.5		.032		(.000)	
13. Esopus Creek at Coldbrook	153	3.60	.00306	0		.050			
	220	13.42	.00437	21.7		.034		(.000)	
14. East Branch Delaware River at Margaretville	105	3.08	.00204	.9		.034			
	129	6.80	.00198	20.3		.033		(.000)	
16. Susquehanna River at Unadilla	190	5.95	.00043	1.1		.033			
	218	11.50	.00100	15.2		.032		(.000)	
17. Unadilla River at Rockdale	148	3.45	.00096	.7		.034			
	162	9.94	.00106	13.4		.029		(.000)	
18. Tioughnioga River at Cortland	185	3.11	.00059	.5		.032			
	217	7.96	.00049	17.0		.026		(.000)	
19. Chenango River near Chenango Forks	385	4.27	.00072	1.6		.032			
	429	9.06	.00100	12.0		.030		(.000)	
20. Genesee River near Mount Morris	136	6.23	.00046	12.1		.028			
	157	10.05	.00031	25.0		.026		(.000)	

[1]This adjustment value is considered an approximation because the large flow-area expansion in the reach introduces uncertainty into the *n*-value calculation.

[2]This percentage of wetted perimeter that is vegetated takes into account a low-bank area in addition to the channel-side banks.

[3]This adjustment value reflects the effect of vegetation covering a low-bank area in addition to the channel-side banks.

[4]Base *n* value estimated from equation 4 (Jarrett, 1984).

[5]Base *n* value estimated by graphical interpolation.

[6]The vegetated part of the wetted perimeter at this site is covered by mowed grass, which has no discernible effect on the *n* value.

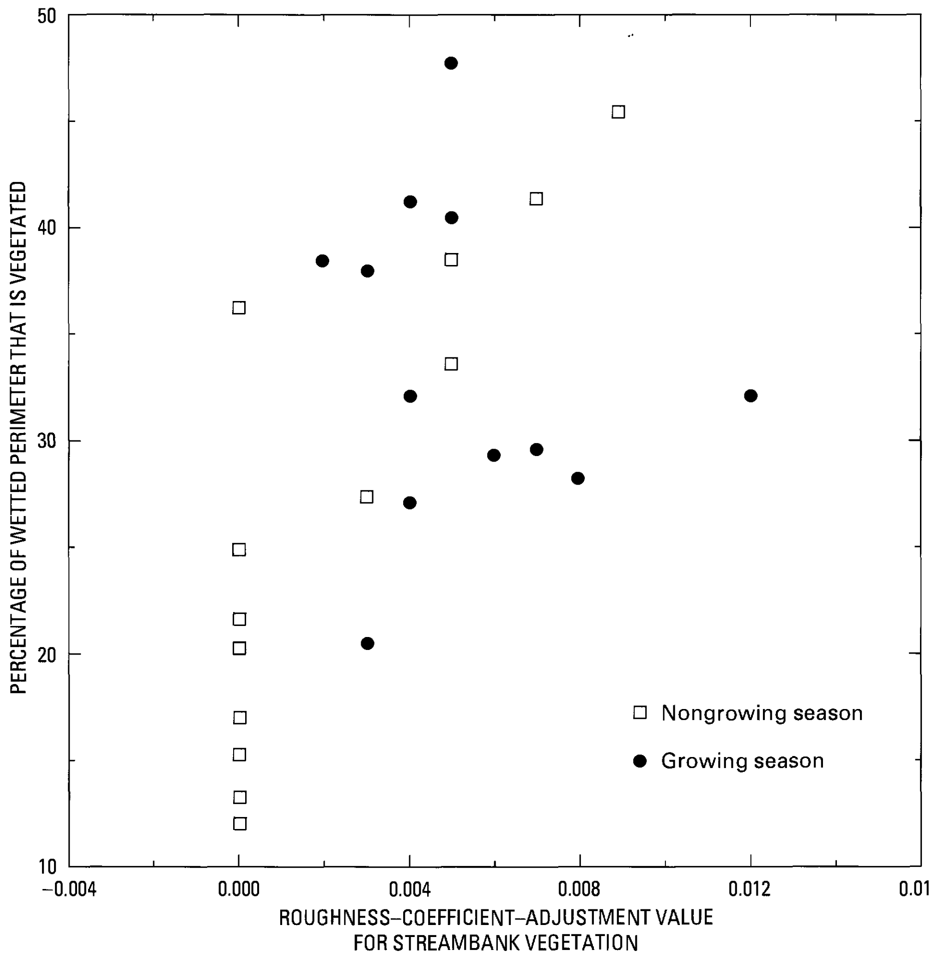


Figure 71. Relation between percentage of wetted perimeter that is vegetated and roughness-coefficient-adjustment value for streambank vegetation during nongrowing and growing seasons.

banks (fig. 8). The average top widths of the channel for the recorded water-surface profiles range from 50 to 63 ft. The wetted perimeters are from 22 to 38 percent vegetated (table 7). A dense growth of willow saplings and grasses at the low-water edge has a substantial effect on the roughness coefficient. During the nongrowing season, the computed n value increased as water levels rose above the low-water channel and the flow encroached on the vegetation (fig. 9). At the depth at which vegetation was completely submerged and covered about 35 percent of the wetted perimeter of the stream channel, the computed n value ceased to increase and remained constant (0.029) at slightly higher flows. The maximum adjustment to the roughness coefficient for the bank vegetation during the nongrowing season, 0.005 (table 29), is the difference between the minimum and maximum n values computed from data collected during that season. During the growing season, the n value increased quickly with increasing flow and reached a maximum of 0.033 (fig. 9) when the depth was about three-fourths the height of the vegetation (75 percent submergence). At higher flows, where flexible vegetation bends and thus provides less resistance, the n value decreased until the vegetation was completely submerged, at which point it was the same as for nongrowing conditions. The maximum adjustment to the roughness coefficient for the growing-season vegetation is 0.008 (table 29). This is the difference between the growing- and nongrowing-season n values computed for flows with hydraulic radii (R) of 3.06 ft (n = 0.032) and 3.02 ft (n = 0.024), respectively; this difference decreases to 0.007 for an average R of 3.14 ft, to 0.004 for an average R of 3.36 ft, and to 0.000 as R approaches 3.7 ft.

Moordener Kill at Castleton-on-Hudson is vegetated with a few 2- to 3-ft-diameter trees and dense brush and vines (fig. 10), the summertime density of which is about twice that of the nongrowing season. The average top widths of the channel for the recorded water-surface profiles are from 37 to 47 ft, and the percentage of the wetted perimeter that is vegetated ranges from 7 to 27 percent (table 8). The computed roughness coefficients appear to be affected by streambank vegetation during the nongrowing season (fig. 12). The channel's computed n value for a flow having a hydraulic radius (R) of 1.57 ft is 0.031; as the depth increases to bankfull (R = 2.63 ft) and the percentage of wetted perimeter of the channel that is vegetated increases from 11 to 27 percent, the computed n value increases to 0.034 (table 8). This increase in the roughness coefficient, 0.003 (table 29), is attributed to the increased streamflow resistance as an increasing percentage of flow is impeded by streambank vegetation during the nongrowing season. Data for two n-value calculations that were collected during the late fall before snow accumulation appear to reflect the same effect of streambank vegetation as data collected during the growing season. Two comparisons of nongrowing-season n values with growing-season n values can be made with these data (table 29). The channel's computed n value for the flow having a hydraulic radius of 2.16 ft during the growing season is 0.035, and that for a flow having a slightly greater hydraulic radius (2.33 ft) during the nongrowing season is 0.032. Similarly, the computed n value for a growing-season flow with a hydraulic radius of 2.60 ft is 0.038, and that for a nongrowing-season flow with a hydraulic radius of 2.63 ft is 0.034. These differences, 0.003 and 0.004 (table 29), can be attributed to the increased flow resistance from summer growth.

Canisteo River at Arkport is the outflow channel for a reservoir 0.2 mi upstream. Flows in this channel, therefore, are highly regulated. The banks are covered with brush and a few trees that range from 0.5 to 2.0 ft in diameter. The left bank has denser brush than the right bank, and both banks have exposed tree roots (fig. 14). The average top widths of this channel for the recorded water-surface profiles range from 30 to 39 ft, and the wetted perimeters are from 18 to 40 percent vegetated (table 9). Most of the n-value calculations are affected by significant flow-area expansion. Nothing conclusive can be stated as to the effect of streambank vegetation during the nongrowing season, and comparison of n values for the growing versus nongrowing seasons is also inconclusive (fig. 15). For example, the computed n values for a medium flow of 489 ft³/s during the growing and nongrowing seasons are both 0.032, whereas two n values computed for the nongrowing season for a discharge of 517 ft³/s differ by 0.003 (table 9). At the highest discharges, which show the least effect of flow-area expansion, the computed n value increases from 0.031 (for R = 2.80 ft) during the nongrowing season to 0.033 or 0.034 (for $R \approx 2.94$ ft) during the growing season (table 29). The lack of increase for a medium-flow n-value during the growing season could be due to an insufficient increase in seasonal vegetation density at medium stages to cause a noticeable increase in the roughness coefficient, whereas at higher flows, this increase in vegetation density has a measurable effect.

Mill Brook near Dunraven has average top widths between 38 and 63 ft (table 10) and a low overflow area on the left bank that is vegetated by hummocky grasses (fig. 16). During the nongrowing season, the grass hummocks have little or no effect, as shown by the decrease in the n value from 0.062 (R = 1.14 ft) for the low-water channel to 0.057 (R = 1.37 ft) for a water level that covers most of this vegetation (table 29). This decrease could reflect the trend in the n-value-to-depth relation that is expected on this high-gradient channel; as such, the grass hummocks would be considered additional bed-roughness elements of a wider low-water channel. The growing-season effect of this grassy area is shown by the n-value increase to 0.069 for a similar hydraulic radius (R = 1.38 ft). This increase (0.012, table 29) is considered an approximation, however, because the large flow-area expansion in the reach introduces uncertainty into the n-value calculation. The percentage of the wetted perimeter that is vegetated when water covers this area ranges from 13 to 16 percent—less than at most other study sites at which streambank vegetation has some effect on the total roughness coefficient. This discrepancy probably occurs because the low, grassy area functions more as an extension of the low-water channel than as a part of the streambank.

Onondaga Creek at Dorwin Avenue, Syracuse, is a maintained (mowed) grass-lined flood-control channel with rock riprap along the lower part of the right bank (fig. 25). This site is slightly larger than those described previously, and average top widths of the channel for the recorded flows range from 65 to 85 ft (table 13). The computed roughness coefficients for this channel, whose wetted perimeters are from 5 to 28 percent vegetated with short grass, do not show any definite effect from streambank vegetation (table 29). This is probably because the effect of cut grass, which has an approximate n value of 0.030 (Chow, 1959, p. 113), is similar to that of the bed material, whose computed n values range from 0.026 to 0.029.

East Branch Ausable River at Au Sable Forks is about 200 ft wide during high flows and is much larger than the previously discussed sites. It is similar to the other sites, however, in that 30 to 45 percent of its wetted perimeter (depending on the flow depth) is vegetated with dense brush, grass, and trees 0.5 to 1.5 ft in diameter (fig. 19). The coarse bed material (cobble and boulder), high-energy gradient of 0.008, and low relative smoothness give large roughness coefficients (0.056, table 11) that would be expected to decrease with increasing stage. This does not occur, however; the computed n values remain relatively constant with increasing flow depth, probably because the expected decrease in streamflow resistance is offset by the increase in percentage of the wetted perimeter that is affected by vegetation. Jarrett's (1984) n-value estimation equation (eq. 4) for high-gradient channels with large bed material should be applicable to this site. This equation gives n-value estimates between 0.051 and 0.047 for the recorded discharges. If the above assumption is correct, then the differences between these estimated n values and those computed from the field data would indicate n-value adjustments of 0.005 to 0.009 for streambank vegetation at this site (table 29).

Beaver Kill at Cooks Falls is a wide (174 to 222 ft), high-gradient channel whose data show the expected inverse relation between the roughness coefficient and flow depth (fig. 24, table 12). The low right bank is densely vegetated with woody brush, willow saplings, and grasses (fig. 22) that affect this relation. As flows of 5,000 to 8,000 ft^3/s begin to encroach upon this area, the computed n value stops decreasing. The n values for flows with hydraulic radii of 4.11 and 5.50 ft are 0.040 and 0.041, respectively (table 29). As the vegetation becomes submerged and bends, providing less resistance to the flow, the computed n value decreases quickly from 0.040 at $R = 5.68$ ft to 0.039 and 0.037 at $R \approx 5.80$ ft. At higher flows, the n value decreases to 0.034 and appears to complete the n-to-R trend indicated by the data from the lower flows. Graphical interpolation between the data extremes allows selection of base n values. The differences between these base n values and the computed values range from 0.002 to 0.005 (table 29) and indicate the increment of roughness that is attributable to the dense vegetation on the low right bank.

Tioughnioga River at Itaska is another wide channel (211 to 287 ft wide) with a wetted perimeter that is more than 25 percent vegetated at high flows, but unlike East Branch Ausable River at Au Sable Forks and Beaver Kill at Cooks Falls, no additional roughness effect from vegetation can be assumed. The computed n values have a low-water value of 0.030, then alternate between 0.031 and 0.032 at greater flow depths (table 14), and are essentially constant through the recorded flow range. Even though the flow passes through a low, vegetated overflow area on the right bank (fig. 28), no increase in the n value on this low-gradient, cobble channel is discernible during the non-growing season (table 29). As at Mill Brook near Dunraven, this vegetated overflow area is more an extension of the low-water channel (along with a corresponding change in bed roughness) than a part of the streambank. No data are available from which to identify any additive effect to the roughness coefficient from vegetation during the growing season.

Photographic Comparisons Among the Study Sites

The underlying premise of aids to roughness-coefficient estimation that rely on the comparison of photographs for estimating a roughness coefficient at a site of interest is that channels with similar hydraulic characteristics will have similar energy losses and, hence, similar n values. Often channels that appear similar upon visual inspection actually have unnoticeable differences that could substantially affect the roughness coefficient. A prime example of this situation is the inability to accurately estimate channel or water-surface slopes from a photograph; however, slope can have a controlling influence on the n value (fig. 68; also Riggs,1976; Bray, 1979; Jarrett, 1984). Channel characteristics, such as bed material and channel vegetation, are easier than slope to see from a photograph, but estimating their contribution to energy losses from a photograph can still be difficult. To illustrate this point, additional photographs have been included in the section, "Station Descriptions, Hydraulic Data, and Channel Photographs for the 21 Study Sites." These photographs show seasonal changes in vegetation at selected sites and, with the n-value data presented, can be used to evaluate the effect of these changes on the roughness coefficient at a particular site as well as the effect of differences among sites.

The following examples illustrate the applicability and limitation of photographic comparisons as an aid to n-value-estimation. (1) The causes of seasonal variation in the roughness coefficient can be seen from the photographs for Tremper Kill near Andes (fig. 4) and Scajaquada Creek at Buffalo (fig. 8). In both cases, the condition of the vegetation in the springtime nongrowing season, following months of snow-cover compaction, produces less flow resistance than the same vegetation during the growing season and the presnow, late fall season. (2) Scajaquada Creek at Buffalo and Onondaga Creek at Dorwin Avenue, Syracuse, are both "maintained" channels, but the fact that the banks of the former site are not mowed all the way to the low-water edge (fig. 8), and have a dense swath of vegetation on both sides of the channel, results in a substantial increase in the roughness coefficient as flow depth increases (fig. 9). Onondaga Creek is slightly wider than Scajaquada Creek, but its banks are periodically mowed to the water's edge (fig. 25). This practice prevents the growth of woody plants; therefore, vegetation has no discernible effect on the roughness coefficient. (3) Regardless of vegetation density, channel stream-top width exerts a strong influence over streambank-vegetation effects on the roughness coefficient. Many wide channels, such as Tioughnioga River at Itaska (fig. 28), Susquehanna River at Unadilla (fig. 49), and Unadilla River at Rockdale (fig. 52), have vegetation conditions similar to those found at the above-mentioned narrow-channel sites, but the streambank vegetation at these sites has no discernible effect on the roughness coefficients. (4) Likewise, seasonal variation in vegetation on the banks of wide channels, such as Chenango River near Chenango Forks (fig. 59) and Genesee River near Mount Morris (fig. 61), is similar to the vegetation conditions on narrow channels, yet the effect of summertime growth of streambank vegetation on the roughness coefficients at the wide-channel sites is undetectable.

In light of these comparisons, the following cautions are offered. When attempting to assess the effect that streambank vegetation has or does not have on the roughness coefficient, one must consider vegetation density and seasonal conditions in relation to the overall size of the channel. As previously pointed out, the percentage of wetted perimeter that is vegetated, which is closely related to channel stream-top width in temperate climatic zones, can be used as an indicator of streambank-vegetation effects on the roughness coefficient. As channel width increases from site to site, the percentage of wetted perimeter that is vegetated generally decreases and remains less than 25; thus no effect from streambank vegetation is expected. Also, photographic comparison as a method of n-value selection should seldom be used alone, without consideration of other available information, and the hydraulic data from the site of interest should be checked to confirm the similarity that is perceived from the photograph.

Comparison of Observed and Published Adjustment Values

Ramser (1929) collected data and computed roughness coefficients for drainage channels before and after dredging or straightening and during growing- and nongrowing-season conditions. Cowan (1956) used Ramser's data to compute roughness-coefficient adjustment values for five primary factors of energy loss for open-channel flows. The vegetation-adjustment values for the roughness coefficients computed for the study sites (table 29) are generally less than those presented by Cowan (1956). From the descriptions of vegetation given in Cowan's table (this report, table 4), adjustment values for the vegetation at the study sites would range from 0.010 to 0.025 during the nongrowing season and from 0.025 to 0.050 during the growing season. In contrast, the indicated adjustments for the vegetation-affected study sites were only as high as 0.005 during the nongrowing season and, for the most extreme combination of vegetation conditions, only as high as 0.017 during the growing season. This discrepancy is not surprising because the study channels affected by vegetation (excluding East Branch Ausable River) with widths of 30 to 63 ft are close in size to most of the larger channels whose data were used to calculate Cowan's adjustment values. Also, many of the vegetation conditions described by Cowan apply to the entire cross section of the channel and are not limited to the streambanks alone. Therefore the most appropriate adjustment values for the study sites would be those close to or less than Cowan's minimum values. Where possible, new examples of channel conditions for streambank vegetation, based on the results of the data presented in this report, have been included with Cowan's data in table 4.

Kayaderosseras Creek near West Milton had higher energy losses than sites with similar hydraulic characteristics and particle sizes (see table 15). In addition to bed roughness, this channel has highly irregular banks and changes abruptly from wide, deep, smooth, and semicircular to a narrower, shallower, and less regular shape (fig. 32*B*). Trees projecting from the right bank cause erosion upstream and downstream of the projections (fig. 31). This scalloping effect, plus exposed tree roots, adds greatly to the energy losses of this 80-ft-wide channel. The Cowan (1956) procedure to estimate the *n* value can approximate the increments of roughness, as quantified by the computed *n* values, that can be attributed to bank irregularities and to variations in channel size and shape. A base *n* value of 0.050 was estimated for this reach of Kayaderosseras Creek from the similarities and differences between the study site and the data presented in table 1 (Aldridge and Garrett, 1973) for cobble channels; table 2 (Chow, 1959) for "minor mountain streams" with gravel, cobbles, and boulders; and Barnes (1967, p. 66 and 186). Both of Barnes' (1967) sites have more sand- and gravel-bed material, lower water-surface slopes, and greater depths than Kayaderosseras Creek.

If 0.050 is assumed as a reasonable base *n* value for high within-bank flows at this site (discharges between 1,000 and 1,200 ft^3/s), and if an adjustment value of 0.001 is applicable for the change in channel size and shape, the remaining increment of roughness (computed by subtracting 0.051 from the computed *n* values in table 15) could be attributed to streambank irregularities. These adjustment values, 0.005 to 0.012, fall within the range of adjustment values for moderate to severe cross-section irregularities given in table 4.

EVALUATION OF ROUGHNESS-COEFFICIENT EXPLANATORY VARIABLES

Multiple-regression techniques were used to ascertain the ability of all pertinent variables to explain the variation found in the roughness coefficients. The entire data set, that is, 133 profiles as identified in the section, "Analysis of Roughness-Coefficient Data," was initially used in the following analyses of energy gradient, hydraulic radius, and relative smoothness. Because the study sites encompass a wide range of hydraulic characteristics that determine the relation between the *n* value and flow depth, these data were subsequently divided into hydraulically similar groups on the basis of high and low ranges of several variables. These subsets were reevaluated for their ability to estimate their respective computed roughness coefficients. Only the data from the seven study sites where streambank vegetation had a measurable or apparent effect on the roughness coefficient were used in the analysis of the type and density of vegetation. Finally, several published *n*-value equations were assessed as to their ability to estimate the *n* values calculated for the study sites.

Identification of Pertinent Variables

The variables most highly correlated with the *n* value are energy gradient and relative smoothness (table 27, log-transformed values). These variables, along with hydraulic radius, are evaluated individually and in combination with each other in the following paragraphs. The type and density of streambank vegetation at the study sites are considered as explanatory variables for the increment of roughness that can be attributed to this flow-retarding factor.

Energy Gradient

At a significance level of 0.05, the most statistically significant untransformed variable is energy gradient, S_f. This term, which has a high correlation with the *n* value (0.86, table 27), can explain 74 percent of the observed variability in the roughness coefficients. The close degree of association between these two variables agrees with the results of other researchers (Riggs, 1976; Jarrett, 1984). The relation between the log-transformed values of these variables is similar to that developed by Bray (1979) between *n* and water-surface slope, S_w (eq. 3). This is not surprising because Bray's data are similar to those collected at most of the low-gradient (slopes less than 0.002) study sites. Because Bray's equation (eq. 3) is based on high within-bank flows on gravel-bed rivers and on a data set that is larger (67 sites) than that compiled in this study, it should yield consistent and reliable estimates of the roughness coefficient for channels with similar hydraulic and particle-size characteristics. No new equation of similar form is presented here.

Hydraulic Radius and Relative Smoothness

Hydraulic radius, by itself, was not statistically significant (at an 0.05 significance level) in explaining the variation of the roughness coefficients at the study sites because the relation between hydraulic radius and the n value was inconsistent, as discussed previously in the section, "Relation Between Manning's Roughness Coefficient and Selected Variables." The log-transformed relative smoothness, R/d_{84}, which was highly correlated with the log-transformed n value (−0.89, table 27), can explain 80 percent of the observed variation in the roughness coefficient, however. A regression equation that defines this close degree of association does not appear to be an improvement over Bray's equation (eq. 3) for estimating roughness coefficients.

Energy Gradient and Relative Smoothness

The combination of variables that best explains the variation found in the roughness coefficients is the combination of log-transformed values of energy gradient and relative smoothness, R/d_{84}. Regression analysis indicates that these variables together can explain 81 percent of the observed variation in the n values. This is not substantially better than the degree of explanation provided by the log-transformed R/d_{84} alone, however.

Type and Density of Streambank Vegetation

The collection of n-value data from channels affected by vegetation indicated the possibility of developing an equation to estimate the increment of the total hydraulic roughness that could be attributed to streambank vegetation. In addition to the percentage of wetted perimeter that is covered by vegetation, a dummy variable for season (0 = dormant and 1 = growing season) and a vegetation-index value that incorporates the type and relative density of streambank vegetation (table 28) were considered as explanatory variables. The vegetation-index value ranged from 0 for banks with mowed grass to 4 for banks with dense woody brush, vines, and trees. The vegetation and hydraulic data from the seven sites where streambank vegetation had a measurable or apparent effect on the roughness coefficient (table 29) are too sparse to give all-conclusive results, but the analysis indicates that the percentage of wetted perimeter that is vegetated can be used as an indicator of energy losses that are attributable to streambank vegetation.

Grouping of Data

The diversity of the data and the apparent inclusion of two or more major categories of factors controlling the n value led to attempts to further explain the variation found in the roughness coefficients by grouping sites or data with similar characteristics. Two factors that showed either poor or no linear relation to the roughness coefficient were top width of stream and the ratio of hydraulic radius to top width (R/T). The data from the 133 profiles that were used in the preceding analyses were divided on the basis of high and low ranges in these terms; 100 ft for stream top width and 0.035 for R/T were arbitrarily chosen as the dividing points. The data also were grouped by energy-gradient values, and 0.002 was used as the dividing point. This value was used to separate the data into high- and low-gradient profiles and corresponds with Jarrett's (1984) slope criterion. Finally, in accordance with the relative submergence criteria of Bathurst and others (1981), the data were divided into large- and small-scale roughness categories on the basis of R/d_{84} and R/d_{50} ratios. Large-scale roughness refers to bed material with a particle size the same order of magnitude as the depth of flow. Small-scale roughness refers to bed material of small particle size in relation to the depth of flow. No combination of the above groupings of data yielded an overall improvement in the development of an n-value estimation equation derived from data from this study alone.

Assessment of Published Equations

As mentioned previously, Benson and Dalrymple (1967) state that the n-value relations for channels with an R/d_{50} ratio greater than 5 differ from those for channels with a ratio less than 5. Bathurst (1978) points out that the flow resistance of large-scale roughness, in which the size of the sediment is of the same order of magnitude as the depth of flow, is dependent on the sum of the form drags of the individual roughness elements, whereas the flow resistance of small-scale roughness is described by boundary-layer theory, wherein the roughness elements on the streambed function collectively as one surface to apply a frictional shear on the flow. Bathurst and others (1981) summarize past studies that show that flow-resistance processes differ among channels with differing ratios of flow depth to particle size (depth/d_{50}) and recommend that a power-law resistance equation be used to estimate n values for channels with large-scale roughness (depth/d_{50} less than 2), and different semilogarithmic equations be used for channels with small-scale (depth/d_{50} greater than 7.5) and intermediate roughness. Griffiths (1981) proposes separate equations for gravel channels with rigid and mobile beds. A channel bed is considered mobile if the product of $36.09RS_w$, where R is hydraulic radius, in feet, and S_w is water-surface slope, is greater than the channel's median bed-particle size; otherwise, the channel bed is considered rigid. Therefore, no single resistance equation can consistently and accurately estimate n values for all channels. In addition, researchers who have defined field-based relations between the roughness coefficient and variables such as water-surface slope, energy gradient, bed-particle size, and hydraulic radius (Limerinos, 1970; Bray, 1979; Griffiths, 1981; Jarrett, 1984) were subject to the geographic limitations of their respective research areas or purposely selected sites with ideal channel characteristics. As a result, the application of the equations that have been developed from these and other studies is limited to flows and channels that are similar to those from which the various equations were derived.

Twelve published n-value equations were assessed for their ability to estimate the computed n values from the study sites. Though not inclusive of all n-value equations that have been developed, they are representative of the many forms that have been proposed and take into account the many relevant and measurable explanatory variables that have been shown by other investigators to explain a large percentage of the stream-to-stream and within-stream variations in the roughness coefficient. The estimative abilities of these equations are indicated in table 30 by (1) the range of differences between the n values computed from the study-site data by equation 15 and those estimated by each equation, and (2) the mean absolute error of these differences. The closest n-value estimates for high within-bank flows and their respective equations are given in table 31. High within-bank flows were selected as a way to standardize the comparison of the equations. Results for lower flows in the same channels could be quite different from those for the high flows selected.

No one equation was capable of accurately estimating n values for all stages on all channels. For the 133 n-value calculations that are included in the general analysis of the data, equation 3 (Bray, 1979) gives the closest estimates of the computed n values; the mean absolute error is 0.002 (table 30). The differences between the computed n values and those estimated by equation 3 range from –0.011 to 0.023. Table 31 shows that equation 3 most closely estimates n values for gravel and small-cobble channels (median particle size 0.06 to 0.5 ft and R/d_{50} greater than 5). In addition to equation 3, equations 6 and 7 (Strickler, 1923; and D.C. Froehlich, U.S. Geological Survey, written commun., 1978, respectively) frequently estimated the computed n values for high within-bank flows on cobble channels within 0.002 (table 31). This accuracy is less consistent than that shown by the estimates from equation 3, however. Equation 6 has a mean absolute error of 0.004 but tends to underestimate the computed n values, as the range in differences (0.000 to 0.039) indicates. The range in differences for estimates by equation 7 (–0.005 to 0.016) is smaller than the ranges for equations 3 and 6, but the mean absolute error (0.006) is higher.

The apparent accuracy of Bray's (1979) equation, as indicated by the data presented in table 31, does not imply that this equation is the best general n-value equation for all streams, first, because the similarity of more than half of the study sites to those used by Bray (1979) in the development of his equation is coincidental, and second, because this equation is limited to high within-bank flows on gravel-bed channels. This analysis does indicate that Bray's equation can give reliable n-value estimates for channels with hydraulic characteristics that are similar to those of the sites used in the development of equation 3, however.

Equation 4 (Jarrett, 1984) is the only equation that is based on data from high-gradient channels. For the 40 n-value calculations for channels in which friction slope exceeds 0.002 and R/d_{50} is less than or only slightly greater than 5, the mean absolute error for equation 4 is 0.008. Equations 6 and 18 in table 30 (Strickler, 1923, and Henderson, 1966, respectively) accurately estimated the computed n values for high within-bank flows at Esopus Creek at Coldbrook and Beaver Kill at Cooks Falls (table 31), but these equations cannot reproduce the decrease in the roughness coefficient with increasing flow depth that occurs in this type of channel. The negative exponent on the hydraulic-radius variable of equation 4 ensures an inverse relation between the n value and flow depth.

The flow-retarding effect of streambank vegetation on wide channels with a wetted perimeter that is less than 25 percent vegetated appears to be reasonably quantified in the roughness coefficients estimated

Table 30. Differences between n values computed from study-site data and those estimated from published n-value equations

[—, no value presented]

Investigator	Equation[1]	Range of differences[2]	Mean absolute error	Equation number
	Gravel- and (or) cobble-bed channels[3]			
Bray (1979)[4]	$n = 0.104S_w^{0.177}$	–0.011 to 0.023	0.002	3
	$n = 0.048d_{50}^{0.179}$	–0.012 to 0.027	.007	16
	$n = \dfrac{0.0927R^{1/6}}{0.248 + 2.36\log(R/d_{50})}$	–0.012 to 0.007	.007	17
Strickler (1923)[5]	$n = 0.034d_{50}^{1/6}$	0.000 to 0.039	.004	6
Henderson (1966)	$n = 0.031d_{75}^{1/6}$	0.000 to 0.039	.005	18
Limerinos (1970)	$n = \dfrac{0.0926R^{1/6}}{1.16 + 2.0\log(R/d_{84})}$	–0.012 to 0.005	.007	2
	$n = \dfrac{0.0926R^{1/6}}{0.35 + 2.0\log(R/d_{50})}$	–0.016 to 0.002	.010	19
Froehlich (1978)[4]	$n = 0.245R^{0.14}(R/d_{50})^{-0.44}(R/T)^{0.30}$	–0.005 to 0.016	.006	7
Griffiths (1981)[4]	$n = \dfrac{0.0927R^{1/6}}{0.760 + 1.98\log(R/d_{50})}$	–0.011 to 0.012	.007	20
	$n = 0.104R^{1/6}(R/d_{50})^{-0.297}(R/P)^{0.103}$	–0.015 to 0.014	.008	21
Sauer (1990)[6]	$n = 0.11S_w^{0.18}R^{0.08}$	–0.016 to 0.020	.005	5
	High-gradient channels[7]			
Jarrett (1984)	$n = 0.39S_f^{0.38}R^{-0.16}$	–0.007 to 0.062	0.008	4
	Vegetated channels[8]			
Bray (1979)	Equation 3	–0.011 to 0.019	—	3
Strickler (1923)	Equation 6	0.001 to 0.034	—	6
Froehlich (1978)[4]	Equation 7	–0.019 to 0.017	—	7
Sauer (1990)[6]	Equation 5	–0.016 to 0.016	—	5

[1] All length dimensions are in feet. S_w is slope of water surface, S_f is energy gradient, T is top width of stream, and P is wetted perimeter. Other variables are as previously defined.

[2] A negative difference indicates an overestimation of the computed n value by the equation. A positive difference indicates an underestimation.

[3] Based on 96 n-value computations from channels with intermediate diameter d_{84} less than 1.0 ft.

[4] D.C. Froehlich (U.S. Geological Survey, written commun., 1978), as published in Jobson and Froehlich (1988).

[5] As published in Henderson (1966).

[6] V.B. Sauer (U.S. Geological Survey, written commun., 1990).

[7] Based on 40 n-value computations from channels with friction slope greater than 0.002.

[8] Based on 40 n-value computations from channels with more than 25 percent of their wetted perimeters vegetated.

Table 31. Best estimates of *n* values computed from study-site data by selected published equations for high within-bank flows

[Locations are shown in fig. 3. ft^3/s, cubic feet per second; —, no value presented]

Site number and name	Discharge (ft^3/s)	Computed *n* value	Two best estimates of computed *n* values			
			n value	Equation[1]	*n* value	Equation[1]
Gravel- and(or) cobble-bed channels						
8. Onondaga Creek at Dorwin Ave., Syracuse	1,890	0.026	0.026	7	0.024	6
9. Tioughnioga River at Itaska	10,100	.031	.032	3	.028	6
	10,900	.032	.032		.028	
12. Sacandaga River at Stewarts Bridge	13,300	.044	.042	2	.041	5
14. East Branch Delaware River at Margaretville	2,860	.034	.034	7	.035	3
	6,600	.033	.033		.036	
16. Susquehanna River at Unadilla	14,300	.034	.034	7	.033	3
	19,000	.032	.033		.033	
17. Unadilla River at Rockdale	4,580	.029	.029	6	.030	3
	4,660	.030	.029		.031	
18. Tioughnioga River at Cortland	4,320	.028	.029	19	.026	3
	5,640	.029	.029		.028	
19. Chenango River near Chenango Forks	20,100	.031	.031	3	.029	6
	26,500	.030	.031		.029	
20. Genesee River near Mount Morris	6,930	.025	.025	3	.024	6
	7,740	.026	.025		.024	
High-gradient channels						
7. Beaver Kill at Cooks Falls	19,800	0.034	0.033	[2]6	0.037	4
	23,900	.034	.033		.036	
11. Indian River near Indian Lake	718	.062	.065	4	—	—
	794	.061	.065		—	—
13. Esopus Creek at Coldbrook	37,400	.036	.035	[2]6	.033	4
	51,700	.034	.035		.033	
15. Ouleout Creek at East Sidney	1,450	.043	.043	7	.045	20
	1,680	.043	.043		.044	
Vegetated channels						
1. Tremper Kill near Andes	1,040	0.052	0.054	5	0.048	3
	[3]832	.057	.057	20	.060	4
2. Scajaquada Creek at Buffalo	759	.029	.029	16	.030	2
	[3]656	.029	.029	16	.030	2
3. Moordener Kill at Castleton-on-Hudson	409	.034	.033	3	.037	5
	[3]374	.038	.038	5	.034	3
4. Canisteo River at Arkport	576	.031	.028	6	.036	4
	[3]671	.033	.037	4	.037	3
6. East Branch Ausable River at Au Sable Forks	10,800	.056	.056	20	.053	5
	[3]5,720	.055	.057	21	.052	5

[1]Equations are given in table 30.

[2]A second equation (eq. 18), similar in form to equation 6, gives *n*-value estimates (0.036 for Esopus Creek and 0.033 for Beaver Kill) with a similar degree of accuracy.

[3]Data used for this *n*-value calculation were collected during the growing season.

by the previously discussed equations. For channels in which vegetation covers more than 25 percent of the wetted perimeter, no single equation estimates the computed n values with consistent accuracy. On narrow channels (less than 50 ft wide) with densely vegetated streambanks, equation 5 (V.B. Sauer, U.S. Geological Survey, written commun., 1990) yielded more accurate n values than any other equation, presumably because it is based on roughness coefficients that account for the effect of vegetation as well as other flow-retarding factors. The positive exponent on the hydraulic-radius term of this equation ensures an increasing n value with increasing stage, as is expected for densely vegetated narrow streams. This equation cannot account for the varied vegetation types and densities that are found in stream channels, however, and therefore, is not expected to yield consistently accurate n-value estimates. On high-gradient vegetated channels, energy gradient appears to have a greater effect on the roughness coefficient than vegetation. For this type of channel, equation 4 (Jarrett, 1984) is again given preference for estimating n values. The foregoing statements concerning the ability of equations to estimate roughness coefficients for narrow, densely vegetated channels are based on a limited data set and serve only as generalizations and guides; therefore, judgment based on experience is necessary to determine their applicability to a particular situation.

Transferability of Study-Site Data

Even though no new n-value-estimation equation based on the study data alone has been proposed as an aid in estimating roughness coefficients at unstudied sites of interest, the New York study-site data are applicable to any other sites with similar hydraulic characteristics. As with other roughness-coefficient data and reports, the data collected from the study sites and presented in this report are transferable to other sites of interest subject to the limitations of the data. Though the computed n values represent a wide range of hydraulic conditions (table 5), they do not cover all combinations of hydraulic conditions that are implied by these ranges. Some hydraulic characteristics are closely related; one would expect to find large bed particles in a high-gradient channel, for example. Other hydraulic characteristics, such as streambank vegetation, channel size, and cross-sectional shape, can vary independently of any other factor and produce a wide diversity of roughness conditions. With this caution in mind, an engineer or hydrologist can use the computed n values, along with the photographs and hydraulic data, to obtain an accurate estimate of the roughness coefficient at a site of interest.

For this purpose, the data can be divided into the three main categories that were identified in the discussion of the relation between Manning's roughness coefficient and hydraulic radius in the section, "Analysis of Roughness-Coefficient Data." These groups are described as follows: (1) wide, low-gradient channels with median streambed-particle sizes between 0.07 and 0.42 ft and relative smoothness values (R/d_{50}) that are generally greater than 5; (2) high-gradient channels with median streambed-particle sizes between 0.45 and 1.20 ft and relative smoothness values that are generally equal to or less than 5; and (3) narrow channels with dense streambank vegetation where typically more than 25 percent of the channel's wetted perimeter is vegetated. On the basis of the New York study-site data, a channel is wide if its stream-top width is more than 100 ft; it is narrow if its width is less than 63 ft. A more precise demarcation point between wide and narrow channels is impossible because the data set is limited in this range. Low- and high-gradient channels have been arbitrarily defined as those with energy gradients less than and greater than 0.002, respectively. Study sites that meet the criteria described for the first category are as follows:

- Tioughnioga River at Itaska
- Sacandaga River at Stewarts Bridge, near Hadley
- East Branch Delaware River at Margaretville
- Susquehanna River at Unadilla
- Unadilla River at Rockdale
- Tioughnioga River at Cortland
- Chenango River near Chenango Forks
- Genesee River near Mount Morris

Category 2 study sites are

- Tremper Kill near Andes
- Mill Brook near Dunraven
- East Branch Ausable River at Au Sable Forks
- Beaver Kill at Cooks Falls
- Indian River near Indian Lake
- Esopus Creek at Coldbrook
- Trout River at Trout River

Category 3 study sites are

- Tremper Kill near Andes
- Scajaquada Creek at Buffalo
- Moordener Kill at Castleton-on-Hudson

Canisteo River at Arkport

Mill Brook near Dunraven

The study sites not listed above are those that, because of site-specific conditions, do not fit into these general categories. These sites are

Onondaga Creek at Dorwin Avenue, Syracuse

Kayaderosseras Creek near West Milton

Ouleout Creek at East Sidney

The first of the remaining sites would be considered a low-gradient channel; the last two are high-gradient sites. Coincidentally, all three sites have stream-top widths between 65 and 99 ft, which places them within the intermediate-width range between the defined values for "wide" and "narrow" channels.

These groupings define the general channel characteristics that dominate the relation between the *n* value and hydraulic radius. Once this relation is identified, the hydraulic data and photographs of the study sites that conform to this type of relation can be consulted, and additional similarities with the site of interest can be noted. The three uncategorized sites can be used in the same way that other photographic comparisons are used. On the basis of the similarities between the site of interest and the study site that most closely approximates the hydraulic characteristics of the site of interest, an *n* value is either selected directly or selected as a first approximation that is later adjusted for differences between the two sites. A more complete outline of this process of selecting an *n* value is given in the following section.

PROCEDURE FOR ESTIMATING ROUGHNESS COEFFICIENTS FOR NATURAL STREAM CHANNELS

The procedure outlined in this section (modified from Jarrett, 1985) is intended to enable the user to systematically evaluate the factors that affect hydraulic roughness in natural channels with coarse-grained bed material. Experience and sound engineering judgment also are needed to properly evaluate the interaction of factors that affect roughness.

The steps outlined below refer to a single discharge or depth of flow. If *n* values are to encompass a range of flow depths, the procedure would be repeated for selected depths to account for the changes. A roughness-evaluation form (fig. 72) and photographs of the stream are useful as documentation of stream-roughness coefficients. Ideally, the *n* value would be evaluated by different methods of estimation, then compared with field-selected *n* values.

1. Determine the extent of the reach in which roughness appears uniform and to which roughness coefficients are to apply. If channel roughness is not uniform throughout the reach, *n* values need to be assigned for average conditions. Use evidence of scour or deposition to determine whether the channel is stable, unstable, or a combination of both. Verify that present conditions are representative of those being considered.
2. Decide whether and where the cross section will be subdivided to provide uniform flow conditions within each section. Subdivide the cross section to obtain basic channel shapes (rectangular, trapezoidal, semicircular, or triangular) and complete or nearly complete wetted perimeters. Generally, the section is subdivided on the basis of geometry into a channel and left and right overbank areas. The point of subdivision between the main channel and the overbank areas is made at the point where overbank flow first occurs, not at the low-water edge, even on streams where the roughness in the low-water channel differs from that on the banks or is the same in the channel and overbank areas. The overbank areas could require further subdivision to reflect distinct changes in roughness that is uniform along the reach (such as for vegetation). Davidian (1984) presents guidelines for subdivision of a cross section and discusses the errors that result from improper methods.
3. Define the type and size of bed material in each section of the channel, and compute the stream width, hydraulic radius, energy gradient (friction slope) and (or) water-surface slope, and percentage of wetted perimeter that is vegetated. Select an initial roughness coefficient by referring to one or more of the methods described below. Close agreement among *n* values obtained by differing methods will add confidence to the accuracy of the chosen value. Certain general relations exist among the above-mentioned variables, and deviations from these relations should be identified. For example, median bed-material size is strongly correlated with slope. Where this relation is weak or absent, as in a low-gradient, bouldery channel, hydraulic judgment must be used to evaluate the effect of this anomaly on the roughness coefficient. In this example, slope

ROUGHNESS COEFFICIENT EVALUATION

Stream and location: .... Date: ....
....
....

Reach length: ....

Reach description: ....
....
....

Width: .... Hydraulic radius: .... Water-surface slope/energy gradient: ....
Bed material: ....
....

Intermediate diameter d_{50}: .... d_{84}: .... R/d_{50}: ....

Vegetation description: ....
....
....

Percentage of wetted perimeter that is vegetated: ....

Channel computation of n value:

Factor	Value	Remarks/Reference

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

....
....
....

Calculation of composite n value: weighted by wetted perimeter or area.
....

Figure 72. Sample roughness-coefficient-evaluation form (modified from Jarrett, 1985, fig. 14*A*).

would probably have a stronger effect on the *n* value than particle size; therefore, an *n* value smaller than one based on particle size alone would be the more appropriate value.

a. *Refer to roughness-coefficient values in tables 1, 2, 3, or tables in the references mentioned in the section, "Published Coefficients."* Most tabulated values reflect idealized bankfull conditions. Departures from these conditions will require *n*-value adjustments. Note whether the values in the tables reflect boundary friction from the bed and bank materials alone or include other flow-retarding factors. If a range of roughness coefficients is given, use low *n* values for wide channels.

b. *Compare the channel with photographs given by Ramser (1929), Scobey (1939), Chow (1959), Barnes (1967), Aldridge and Garrett (1973), and this report.* Note that the computed or estimated *n* values presented therein are site- and flow-specific. Any deviation in depth of flow, width, area, water-surface slope, vegetation type or density, and channel curvature from that in an illustrated site requires evaluation of the differences and appropriate modification of the selected *n* value. Bankfull roughness coefficients selected for uniform channels with particle-size and hydraulic characteristics similar to sites for which *n* values are published will contain less error and require less adjustment than those for sites that do not conform to these criteria.

c. *Apply equations 2 through 7 where applicable.* A user of these equations must be aware of the limitations and assumptions that apply to each. (See section, "Equations," for details.) Generally, an equation used to estimate roughness coefficients can be reliably applied to a site whose characteristics fall within the ranges of characteristics of the sites used in the equation's development. The more a site of interest exceeds the limitations or violates the assumptions on which an equation is based, the less reliable will be the results. For such sites, comparison of *n* values selected by alternative methods would be advisable.

4. Obtain from table 4 the adjustment factors that apply to the reach. Consider upstream and downstream conditions that could cause disturbance or backwater in the reach being studied. Be certain not to add an adjustment for factors that are already represented in the initially selected *n* value. (The distinction between a base *n* value and an initially selected *n* value is important. A base *n* value reflects the roughness due to bed and bank material only [see glossary], whereas the initially selected *n* value could include other roughness-contributing factors.) Chow's (1959) base values (table 1) apply to the smoothest condition possible for a given bed material. The values of Benson and Dalrymple (1967), reproduced in table 1, are for a straight, uniform channel of the indicated material and are closer to actual field values than those of Chow. Aldridge and Garrett (1973) suggest that, if Chow's base values are used, the adjustment values in table 4 should be used directly. If base values are taken from Benson and Dalrymple (1967) or computed from equation 2 (Limerinos, 1970), the adjustment values should be from one-half to three-fourths as large as those given in table 4. Roughness coefficients that are computed from equations 3, 4, and 5 (Bray, 1979; Jarrett, 1984; V.B. Sauer, U.S. Geological Survey, written commun., 1990, respectively), or selected from a photo-comparison source, or obtained from a table of *n* values that represent roughness factors such as vegetation, meandering, or irregular channel features might require little or no adjustment; only a severe channel condition as described in table 4 would require further adjustment. For this condition, Jarrett (1985) suggests that the adjustment to the *n* value calculated by equation 4 be about half the corresponding maximum value in table 4. Use equation 8 to compute a final roughness coefficient. The value obtained is the overall *n* value for the channel unless a composite *n* value needs to be computed (step 5).

5. If roughness is not uniform across the channel or within a subdivided section, a composite *n* value must be computed. First, an *n* value is selected (step 3), adjusted for flow-retarding factors, if necessary (step 4), and then weighted by a channel or flow characteristic. Chow (1959) explains the procedure for calculating a composite *n* value by weighting the different roughness coefficients by the applicable part of the wetted perimeter of the channel. The sum of the products of roughness coefficient and wetted perimeter for each segment of a channel, divided by the total wetted

perimeter, produces a composite *n* value. Where depth varies considerably or where dense brush occupies a large and distinct segment of the channel, Aldridge and Garrett (1973) suggest using flow area to weight the different roughness coefficients. A composite *n* value might not be required, depending on the method used to select an initial *n* value. If this initial estimate is a true base *n* value, then a composite *n* should be computed, but if this initial estimate is obtained by a method that already accounts for the variation in roughness within a channel or subdivided section, the initial *n* value is already a composite value and requires no further computation or adjustment.

6. If sand is a major constituent of the bed material, the flow regime must be checked. Reliable *n*-value estimates are possible only for upper regime flows. Consult the section, "Published Coefficients," for references and guidance in estimating *n* values for such sites.
7. If roughness coefficients for overbank areas must be calculated, refer to Arcement and Schneider (1989), who present guidelines for selecting *n* values for densely vegetated natural flood plains; Chow (1959), who presents tabulated *n* values for natural and agricultural overbank areas; Hejl (1977), who describes a method for determining *n* values for flooded urban areas; or Jarrett (1985), who gives explanations and examples of roughness-coefficient selection for each of these overbank conditions.

SUMMARY AND CONCLUSIONS

Manning's roughness coefficients are presented for a wide range of discharges and water-surface profiles at 21 sites that are representative of streams found in New York State excluding Long Island. Crest-stage gages were used to record water-surface profiles. Sites were selected to meet the following criteria:

1. A U.S. Geological Survey streamflow-gaging station with relatively stable stage-to-discharge relation is nearby;
2. Channels are relatively straight and uniform, and overbank flows are absent or minimal;
3. Particle size and size distribution of bed material are the major flow-resisting factors (no sand-bed channels were included in this study); and
4. Channels are relatively free of all other flow-retarding factors except streambank vegetation.

The hydraulic and particle-size data collected at these sites are diverse and do not constitute a single *n*-value population. On coarse-grained channels, the relation between the computed roughness coefficient and flow depth varied among the sites in a predictable manner, depending on energy gradient, relative smoothness (ratio of hydraulic radius to median streambed-particle size), stream-top width, and channel-vegetation density. On low-gradient, wide channels with large relative smoothness, the computed *n* values remained relatively constant with increasing flow depth. The *n* values for most of these sites varied by less than 0.005 from low-flow to bankfull conditions. On high-gradient channels with low relative smoothness, the computed roughness coefficient decreased with increasing depth. Study sites in this category had *n* values that varied by as much as 0.068, but generally by 0.015 to 0.030 from low-flow to bankfull conditions. On narrow low-gradient channels with dense streambank vegetation, the *n* value is expected to increase with increasing depth at least to the point of vegetation submergence.

The presence of the incremental roughness effect of streambank vegetation can be evaluated by the percentage of wetted perimeter that is vegetated. No measurable effect of bank vegetation is found on channels with widths greater than about 100 ft and wetted perimeters that are less than 25 percent vegetated. For wide channels with wetted perimeters that are 25 to 50 percent vegetated, bank vegetation appears to have a small additive effect on the roughness coefficient. On narrow channels in which the wetted perimeter typically is more than 25 percent vegetated, the effect of streambank vegetation can be substantial. The magnitude of the energy-loss effect of streambank vegetation depends on the season and on the type, density, and percent submergence of the vegetation. The energy gradient of a narrow channel can have a controlling effect on the *n* value that can obscure the effect of streambank vegetation, especially on high-gradient channels during the nongrowing season. Additive *n*-value adjustments for bank vegetation are incorporated into a table of adjustment values for five major flow-retarding factors.

Several published equations were assessed for their ability to estimate the roughness coefficients computed for the study sites. The study-site data were divided into hydraulically similar groups that met the limitations of the data set used to develop each equation. No one equation was capable of estimating accurately n values for all stages on all channels. An equation based on water-surface slope alone provides the best estimates of the computed n values for high within-bank flows on low-gradient, gravel and small-cobble channels and requires no adjustment for streambank vegetation in wide channels. An equation based on energy gradient and an inverse function of hydraulic radius can duplicate the expected relation between the n value and flow depth on high-gradient channels with bed material of large cobbles and boulders. For wide channels of this type, the effect of streambank vegetation on the n value appears to be incorporated into the computed value. No equation is consistently accurate in estimating roughness coefficients for densely vegetated narrow channels, primarily because no equation has been specifically developed for this purpose and because the wide diversity of vegetation densities and types among stream channels precludes consistently accurate results from a single equation.

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