In cooperation with the
Maine Atlantic Salmon Commission and
U.S. Fish and Wildlife Service

Hydraulic-Geometry Relations for Rivers in Coastal and Central Maine

Scientific Investigations Report 2004-5042

U.S. Department of the Interior
U.S. Geological Survey

Cover Photograph: Piscataquis River at Dover-Foxcroft, Maine, October 18, 2000. (Photography by Laura Flight, U.S. Geological Survey)

Hydraulic-Geometry Relations for Rivers in Coastal and Central Maine

By Robert W. Dudley

In Cooperation with the
Maine Atlantic Salmon Commission and U
.S. Fish and Wildlife Service

Scientific Investigations Report 2004-5042

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
Charles G. Groat, Director

U.S. Geological Survey, Augusta, Maine: 2004

For sale by U.S. Geological Survey, Information Services
Box 25286, Denver Federal Center
Denver, CO 80225

For more information about the USGS and its products:
Telephone: 1-888-ASK-USGS
World Wide Web: http://www.usgs.gov/

CONTENTS

Figures

Tables

Appendix 1: Descriptions of U.S. Geological Survey Streamflow-Gaging Stations

Conversion Factors

Multiply	By	To obtain
gallon per minute (gal/min)	3.785	liter per minute
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.589	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

To convert temperature in degrees Fahrenheit (°F) to degrees Celsius (°C) use the following equation:

°C = 5/9 * (°F - 32)

Hydraulic-Geometry Relations for Rivers in Coastal and Central Maine

By Robert W. Dudley

Abstract

Hydraulic-geometry relations (curves) were derived for 15 sites on 12 rivers in coastal and central Maine on the basis of site-specific (at-a-station) hydraulic-geometry relations and hydraulic models. At-a-station hydraulic-geometry curves, expressed as well-established power functions, describe the relations between channel geometry, velocity, and flow at a given point on a river. The derived at-a-station hydraulic-geometry curves indicate that, on average, a given increase in flow at a given river cross section in the study area will be nearly equally conveyed by increases in velocity and channel cross-sectional area.

Regional curves describing the bankfull streamflow and associated channel geometry as functions of drainage area were derived for use in stream-channel assessment and restoration projects specific to coastal and central Maine. Regional hydraulic-geometry curves were derived by combining hydraulic-geometry information for 15 river cross sections using bankfull flow as the common reference streamflow. The exponents of the derived regional hydraulic-geometry relations indicate that, in the downstream direction, most of the conveyance of increasing contribution of flow is accommodated by an increase in cross-sectional area—with about 50 percent of the increase in flow accommodated by an increase in channel width, and 32 percent by an increase in depth. The remaining 18 percent is accommodated by an increase in streamflow velocity.

On an annual-peak-series basis, results of this study indicate that the occurrence of bankfull streamflow for rivers in Maine is more frequent than the 1.5-year streamflow. On a flow-duration basis, bankfull streamflow for rivers in coastal and central Maine is equaled or exceeded approximately 8.1 percent of the time on mean—or about 30 days a year. Bankfull streamflow is roughly three times that of the mean annual streamflow for the sites investigated in this study. Regional climate, snowmelt hydrology, and glacial geology may play important roles in dictating the magnitude and frequency of occurrence of bankfull streamflows observed for rivers in coastal and central Maine.

Introduction

Understanding the physical processes that control the dimension, plan, profile, and function of natural, self-maintaining river channels is critical to understanding river conditions favorable for stable and productive fish habitat. Although biologists have a good understanding of the physical characteristics of favorable habitat for Atlantic salmon, less information is available on the form and function of natural, self-maintaining river channels in Maine. Improved understanding of the relation of river-channel geometry to streamflow (also referred to as discharge), watershed characteristics, and productivity of salmon habitat can assist regulatory agencies in evaluating the effects of anthropogenic disturbance on habitat productivity and can guide the restoration of such sites (Jowett, 1998).

The dimensions of a river channel are a result of the ability of the water to erode the land surface opposed by the ability of land surface to resist that erosion. A river's ability to erode sediment is a function of the magnitude and frequency of streamflow and suspended-sediment load in the system. Farming and forestry practices, residential and urban development (filling in wetlands, paving surfaces, constructing bridges and culverts), and water management (damming, withdrawing, and diverting) can affect the amount, location, and timing of water movement through a watershed. Physical alteration of a watershed can introduce hydraulic instability in the system and cause the river to adjust its ability to transport water and sediment at the point of the activity; these changes can, in turn, propagate upstream and (or) downstream. Such changes can include increased deposition (aggradation), increased erosion (degradation), bank slumping, overwidening, and the abandonment of existing channels for new ones (Dunne and Leopold, 1978; Rosgen, 1996). A river channel affected by changes that compromise the stream's ability to be self-maintaining is described as "disturbed."

With growing public interest in instream restoration projects in Maine, the number and extent of disturbed river reaches needs to be objectively quantified—requiring a baseline knowledge of the characteristics of relatively undisturbed river channels in the region. Hydraulic geometry has been used for half a century to help assess the physical and hydraulic variables in natural channel stability (Leopold and Maddock, 1953). Stable, self-maintaining, natural channels conform to a cross-sectional geometry, plan, and profile proportional to the size of the upstream watershed, streamflow, and sediment load (Dunne and Leopold, 1978). Within a region of homogenous geology and climate, the mean characteristics describing the shape of the channel are sufficiently consistent for the degree of deviation from what is commonly observed in the region to be interpreted as the magnitude of the effect of disturbance (Dunne and Leopold, 1978). Regional statistical models or curves that relate river-channel geometry to drainage area and streamflow make use of this concept and are a valuable tool used to characterize disturbed river reaches and to help water-resources managers ensure the efficacy and longevity of restoration projects. To develop these regional statistical curves for rivers in Maine, the U.S. Geological Survey (USGS) entered into a cooperative agreement with the Maine Atlantic Salmon Commission (ASC), and U.S. Fish and Wildlife Service (USFWS) in 2001.

Purpose and Scope

This report presents the data, methods, and results of a cooperative study (from 2001 to 2003) to collect hydraulic-geometry data at 15 sites on 12 streams in coastal and central Maine, and to derive regional hydraulic-geometry curves based on those data. Regional hydraulic-geometry curves relate river-channel hydraulic geometry (morphology) to explanatory characteristics of a drainage basin, such as drainage area, for rivers in a particular region of study (region of similar geology and climate). The regional hydraulic-geometry curves, based on the USGS streamflow-measurement and stage-discharge relation data, as well as data obtained from Instream Flow Incremental Methodology (IFIM) studies, were developed to assist the cooperating agencies and other natural-resources managers with river morphology and habitat assessment, and river restoration projects in coastal and central Maine. The scope of this investigation was confined to rivers in coastal and central Maine that have USGS streamflow measurement and stage-discharge relation data available or were investigated in an earlier IFIM study for the ASC, and (or) contain Atlantic salmon habitat. The regional curves developed here are compared to regional curves that have been developed for the States of North Carolina, Maryland, Vermont, and Pennsylvania (Sweet and Geratz, 2003; McCandless and Everett, 2002; Harman and others, 2001; Jaquith and Kline, 2001; White, 2001; Harman and others, 1999).

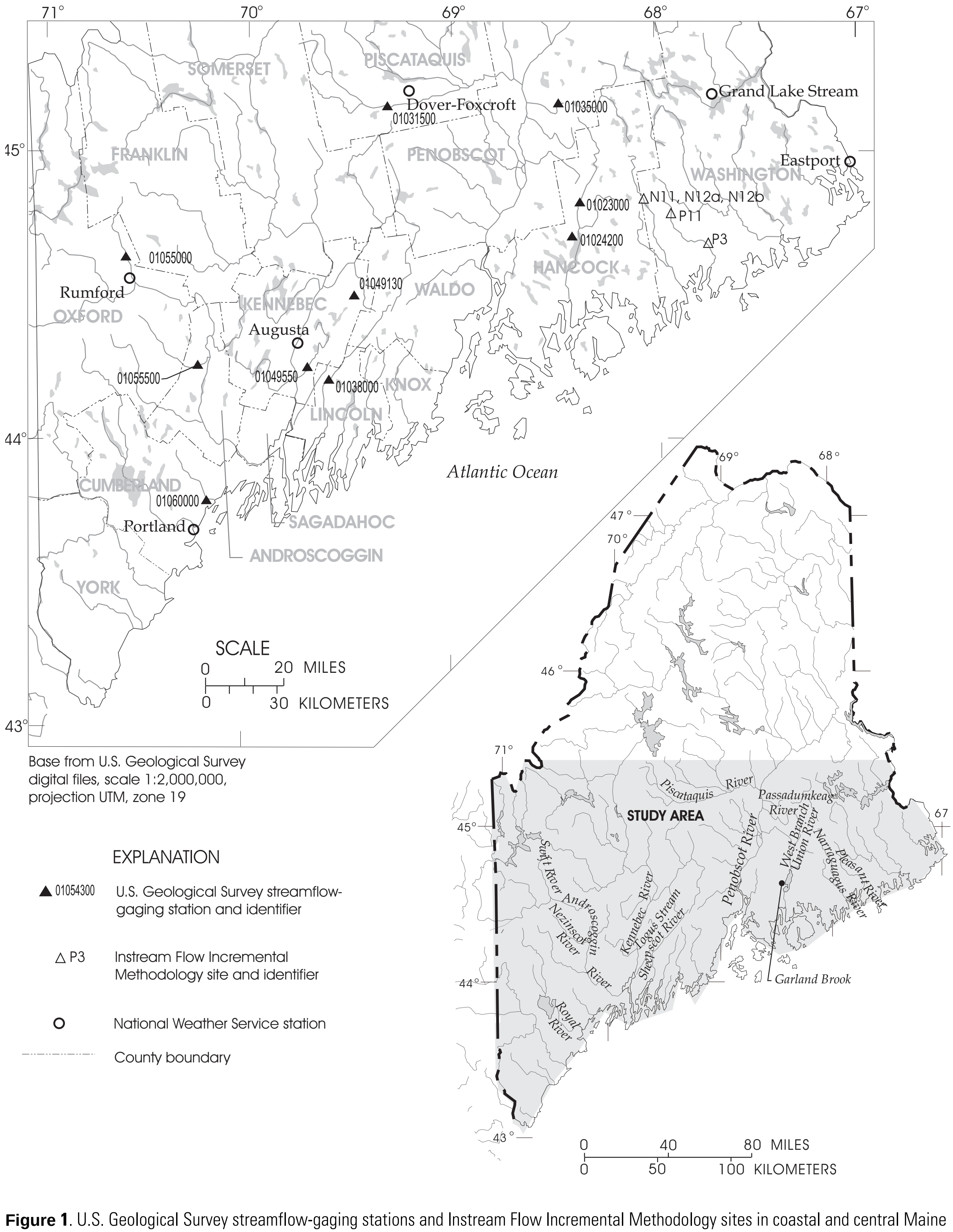
Description of the Study Area

The study area includes 15 sites on 12 rivers in coastal and central Maine. Ten sites currently are or historically have been gaged by the USGS (table 1; fig. 1). The five other site are IFIM sites on the Pleasant River (2 sites) and Narraguagus River (3 sites) (table 1; fig. 1). Sites were selected in coastal and central Maine to minimize variations in the hydraulic-geometry curves caused by differences in physiographic setting, including but not limited to rivers that contain known Atlantic salmon habitat.

Physiography and Hydrogeology

Continental glaciers intermittently covered Maine from about 1.5 million to 10,000 years ago. As the glaciers slowly moved across the land they altered the landscape by eroding, transporting, and depositing rock debris for miles. The surficial geology of present-day Maine largely consists of sand, gravel, and other unconsolidated sediments produced by this erosion, transport, and deposition by glaciers (Marvinney and Thompson, 2000; Johnson, 1925). The surficial material for all the watersheds in this study is predominantly glacial till (a heterogeneous, unsorted mix of material ranging in size from fine sand to boulders, with generally low permeability) and stratified drift, which occasionally includes glaciomarine deposits and eskers (Thompson and Borns, 1985). Sand and gravel deposits and fractured bedrock serve as ground-water aquifers throughout the State.

The five IFIM sites P3, P11, N11, N12a, and N12b and USGS stations 01038000, 01049130, 01049550, and 01060000 (table 1; fig. 1) are in coastal and near-coastal



Base from U.S. Geological Survey digital files, scale 1:2,000,000, projection UTM, zone 19

Figure 1. U.S. Geological Survey streamflow-gaging stations and Instream Flow Incremental Methodology sites in coastal and central Maine used in this study.

Table 1. U.S. Geological Survey streamflow-gaging stations and Instream Flow Incremental Methodology sites in coastal and central Maine used in this study.

U.S. Geological Survey streamflow-gaging station Number	 Name	Latitude (north, decimal degrees)	Longitude (west, decimal degrees)	Drainage area (square miles)	Period of record for streamflow data
01023000	West Branch Union River at Amherst, Maine	44.840	68.372	148	1910-1919, 1929-1979
01024200	Garland Brook near Mariaville, Maine	44.721	68.411	9.79	1964-1982
01031500	Piscataquis River near Dover-Foxcroft, Maine	45.175	69.315	298	1903-2001
01035000	Passadumkeag River at Lowell, Maine	45.185	68.474	297	1916-1979
01038000	Sheepscot River at North Whitefield, Maine	44.223	69.593	145	1938-2001
01049130	Johnson Brook at South Albion, Maine	44.498	69.486	2.92	1980-1991
01049550	Togus Stream at Togus, Maine	44.266	69.698	23.7	1982-1995
01055000	Swift River near Roxbury, Maine	44.642	70.588	96.9	1929-2001
01055500	Nezinscot River at Turner Center, Maine	44.270	70.230	169	1941-1996
01060000	Royal River at Yarmouth, Maine	43.799	70.179	141	1950-2001
Instream Flow Incremental Methodology site					
Number	**Name**				
P3	Pleasant River Transect Number 3	44.67	67.74	94.0	--
P11	Pleasant River Transect Number 11	44.78	67.92	22.5	--
N11	Narraguagus River Transect Number 11	44.74	68.01	93.6	--
N12a	Narraguagus River Transect Number 12a	44.84	68.07	65.0	--
N12b	Narraguagus River Transect Number 12b	44.85	68.07	65.0	--

river watersheds. These watersheds are in a physiographic region of broad lowlands that were inundated by the ocean during deglaciation. Randall (2001) describes this region as composed of sparse and scattered coarse-grained stratified drift deposited early during deglaciation with some fine-grained stratified drift generally at or close to land surface.

The remaining six USGS sites are in a formerly glaciated region that generally sloped away (south to south-east) from the ice. Stations 01024200 and 01055500 are in a region with abundant coarse-grained stratified drift in the stream valleys. Stations 01023000 and 01035000 are in a region with sparser coarse-grained stratified drift deposited mostly in eskers. Stations 01031500 and 01055000 are in a high-relief area with coarse stratified drift commonly perched above the modern stream grade on the valley sides. The valley-fill material in this region is capped by alluvium and there are scattered bedrock outcrops (Randall, 2001).

Land Use

The 15 sites are in counties that are 70- to 97-percent forested and characterized by rolling topography with no urban development (Irland, 1998). The greatest changes in land use in Maine have occurred with the replacement of agriculture and pasture lands by forest during the past century. The State’s overall forest cover, estimated at about 70 percent in 1900, increased to approximately 90 percent by 1995 (Irland, 1998). Six of the 12 study watersheds (Pleasant, Narraguagus, Garland, West Branch Union, Passadumkeag, and Piscataquis) are in the sparsely populated counties of Washington, Hancock, southern Penobscot and southern Piscataquis counties (fig. 1). During 1880-1995, the increase in forest cover in these counties has been relatively minor, ranging from about 11 to 22 percent (Irland, 1998). Four of the watersheds (Sheepscot, Johnson, Togus, and Royal) are in the historically more populated counties of Lincoln, Androscoggin, Cumberland, Kennebec, and Waldo (fig. 1). These counties were historically more heavily deforested and have seen increases in forest cover ranging from approximately 100 to 186 percent during 1880-1995 (Irland, 1998). The remaining two watersheds (Swift and Nezinscot) are in western Maine in Franklin, Oxford, and western Androscoggin counties. Since 1880, these three counties have seen mean increases in forest area of 33, 67, and 100 percent, respectively (Irland, 1998).

Climate

The climate of coastal and central Maine is typified as temperate and humid with mild summers and cold winters with little spatial variability (table 2). Records from National Weather Service (NWS) stations in Portland, Rumford, Augusta, Dover-Foxcroft, Grand Lake Stream, and Eastport (fig. 1) indicate a mean normal annual temperature, based on the 30-year period 1971-2000, of 44 ^{O}F (table 2). Mean monthly temperatures range from 18 ^{O}F in January to 67 ^{O}F in July. The mean annual precipitation is about 44 in., and is fairly evenly distributed throughout the year (National Oceanic and Atmospheric Administration, 2002). High streamflows in coastal and central Maine typically occur in the spring due to snowmelt, which largely determines the relative magnitude and frequency of high streamflows.

Methods of Data Collection and Analysis

Streamflow

The 10 USGS streamflow-gaging stations used in this study were selected on the basis of several criteria: (1) only unregulated, nonurban rivers gaged by the USGS with 10 or more years of continuous-streamflow record were considered; (2) only sites in coastal and central Maine were eligible for consideration; (3) rivers with known Atlantic salmon habitat and similar channel substrate based on regional surficial geology were included where possible (all the rivers in this study have channels composed of gravel, cobbles, boulders, and bedrock); and (4) only USGS streamflow-gaging stations with measurements available at natural, stable cross sections were used. Stations with streamflow measurements at or near bridges or other hydraulic structures that could represent an unnatural cross-sectional geometry were not included.

Daily mean streamflow data for the 10 USGS streamflow-gaging stations (table 1; fig. 1) were obtained from the USGS National Water Information System (U.S. Geological Survey, 1998). The stations had periods of record ranging from 12 to 99 years in length with a mean of 51 years. For each of the streamflow-gaging

Table 2. Climatological data, 1971-2000, for National Weather Service stations in coastal and central Maine.

National Weather Service station locations	Mean annual temperature (^{O}F)	Mean monthly January temperature (^{O}F)	Mean monthly July temperature (^{O}F)	Annual precipitation (in.)
Portland	45.7	21.7	68.7	45.8
Rumford	43.9	17.1	68.2	44.9
Augusta	45.8	19.5	70.1	42.3
Dover-Foxcroft	40.3	12.1	66.0	44.0
Grand Lake Stream	42.3	15.3	67.3	44.8
Eastport	44.1	22.1	64.0	44.8
Mean	43.7	18.0	67.4	44.4

stations used in this study, continuous records of streamflow were computed by applying the relation between the continuously recorded height of the gaged water surface relative to an established datum plane (stage) and the flow of the river (discharge) (Rantz and others, 1982). The river channel or structure (riffle, bedrock falls, bridge opening, culvert opening) that controls the level of the gaged water surface is called the hydraulic control for the station. The stage-discharge relation is a function of the geometry of the river channel or structure and can vary over time as the channel fills and (or) scours. The historical stage-discharge relations for each station were obtained from station-analysis files archived at the USGS Maine District office. These historical stage-discharge relations were qualitatively evaluated for systematic trends over time to determine if the river channels near the stations were systematically aggrading or degrading. All stations evaluated appeared to be stable and self-maintaining with regard to the variability observed in the stage-discharge relations.

A range of streamflow measurements was made at each IFIM site as part of the IFIM studies. Streamflows were measured using standard streamflow measurement techniques (Rantz and others, 1982) with a Marsh-McBirney Model 2000 Flowmate electronic current meter attached to a top-setting wading rod (Kleinschmidt Associates, 1999a, 1999b). The streamflow measurements were used to calibrate a hydraulic model at each of the IFIM cross sections. Once calibrated, the hydraulic models provide a method for estimating streamflow at the IFIM cross section given a surveyed water-surface elevation.

Bankfull Streamflow

A common reference flow with a specific recurrence interval is used to integrate the hydraulic-geometry data for a variety of rivers in a region. Regional hydraulic-geometry curves often are calibrated to a reference flow known as bankfull flow (Q_{bkf}). Bankfull flow is the flow that completely fills the channel up to the elevation of the floodplain, without overtopping the channel banks. Bankfull flow is a useful reference flow because it can be estimated at ungaged sites based on observable, physical channel features and does not require knowledge of flow frequency in the river. Furthermore, bankfull flow is generally thought to be the flow that determines the dominant morphological characteristics of river channels. Dunne and Leopold (1978) describe bankfull flow as the "discharge at which channel maintenance is the most effective, that is, the discharge at which moving sediment, forming or removing bars, forming or changing bends and meanders, and generally doing work that results in the mean morphologic characteristics of channels."

The elevation of the bankfull streamflow at each USGS streamflow-gaging station and IFIM site was determined by surveying the elevation of nearby bankfull morphological features. Morphological features defining the extent of the "active channel" (U.S. Geological Survey, 1975) include: (1) tops of point bars—composed of sediment deposited on the insides of meander bends; (2) changes in vegetation—the low limit of upland, perennial vegetation on the bank, or sharp breaks in vegetation density and (or) type; (3) changes in channel-bank slope—the change from a vertical bank to a horizontal surface (floodplain); and (4) changes in bank materials—clear changes in sediment-particle sizes that may be associated with changes in bank slope (McCandless and Everett, 2002; Brunner, 1999; Rosgen, 1996). Change in channel-bank slope was the most common bankfull feature used to identify bankfull stage in this study. Bankfull streamflow at each USGS streamflow-gaging station was determined by applying the most recent stage-discharge relation (rating curve) for that site to determine the streamflow that corresponded to the surveyed bankfull elevation. The surveyed bankfull elevation at each IFIM cross section was applied to the calibrated hydraulic model for that cross section to compute the corresponding bankfull streamflow.

Stream-Channel Geometry

When making measurements at streamflow-gaging stations, hydrographers measure streamflow velocity, channel width, and channel depth. Streamflow-measurement notes provide the quantitative data used to develop the at-a-station curves that describe the manner in which width, depth, and velocity change with streamflow at the 10 USGS streamflow-gaging stations. Hydraulic-geometry curves that reflect the most recent watershed land use (primarily reforestation since the early 20th century) were developed using measurement notes from the most recent available date backwards until a minimum of nine measurements, representing a wide range of streamflows, were identified.

The flow of a river may be measured in different locations depending on the flow conditions; for example, low flows may be measured at a wading cross section and high flows may be measured from a bridge at a different cross section nearby. For each USGS streamflow-gaging station, measurements that represent a single, natural-channel cross section were selected. This selection process required careful review of the streamflow-measurement notes to determine the location of each measurement. Several stations offered ideal natural-channel cross sections equipped with cableways that enabled hydrographers to measure a range of flows at a single, repeatable location. Conversely, some sites had measurements at a number of different locations, making it difficult to select a group of at least 9 to 10 measurements that represented a single cross section. For the IFIM sites, cross-sectional geometry data were surveyed in the field at one location for each site.

The fundamental relations between channel-geometry dimensions, velocity, and flow can be expressed as the following well-established power functions (Leopold and Maddock, 1953; Dunne and Leopold, 1978; Osterkamp and others, 1983; Leopold and others, 1992):

$$w=aQ^{b}, \tag{1}$$

$$d=cQ^{f}, \tag{2}$$

$$v=kQ^{m} \tag{3}$$

Where Q is streamflow in ft^3/s, w is cross section width in ft, d is mean cross section depth in ft (cross-sectional area, A, in ft^2, divided by w), v is the mean cross-sectional velocity in ft/s (Q divided by A), b, f, and m are derived exponents, and a, c, and k are derived coefficients (fig. 2).

Because flow is the product of velocity and area,

$$Q = Av \tag{4}$$

From the equations above:

$$Q = (aQ^{b})(cQ^{f})(kQ^{m}) \tag{5}$$

Then,

$$b + f + m = 1 \tag{6}$$

$$a * c * k = 1 \tag{7}$$

The power relations for each site are referred to as “at-a-station curves” and describe how the river channel accommodates changes in flow at a particular point in the river (for example, see Emmett’s (1975) at-a-station analyses for the Upper Salmon River Area, Idaho). The at-a-station curves were derived for each of the 10 USGS streamflow-gaging stations by linear regression of the base-10 logarithms of w, d, and v against the base-10 logarithm of Q.

Hydraulic-geometry data used to derive the regional curves were computed by substituting the bankfull streamflow (Q_{bkf}) determined for each of the 10 USGS streamflow-gaging stations into the derived at-a-station curves for that site. For the IFIM sites, bankfull hydraulic-geometry data were computed from surveyed cross-section data used to develop the hydraulic models for each site (Kleinschmidt Associates, 1999a, 1999b).

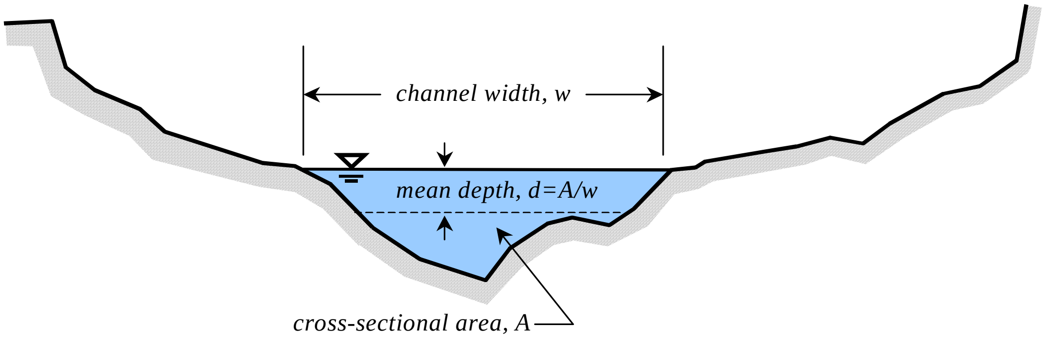


Figure 2. Schematic diagram showing measures of channel geometry.

The base-10 logarithms of the bankfull *w*, *d*, and *v* (denoted w_{bkf}, d_{bkf}, v_{bkf}) were individually regressed against the base-10 logarithm of Q_{bkf} for all 15 stations to derive regional curves as a function of bankfull streamflow. These resulting regression lines are also referred to as "downstream curves" because they describe the manner in which a river conveys increasing contribution of flow in a downstream direction by changes in width, depth, and velocity.

A fundamental condition for regional curves is that they are derived from data representative of stable, self-maintaining reaches whose form is not systematically changing over time. To quantitatively ensure that this condition is met, temporal trends were analyzed for the cross-sectional-area data for each site using the nonparametric Mann-Kendall test (Helsel and Hirsch, 1992). None of the sites had a significant ($p<0.1$) temporal trend in cross-sectional area.

Hydraulic-Geometry Relations for Rivers in Coastal and Central Maine

Bankfull Streamflow

Based on regional curve analyses in many regions outside Maine, bankfull streamflow occurs, in general, every 1 to 2 years, averaging about every 1.5 years (Dunne and Leopold, 1978; Emmett, 1975; Leopold and others, 1992). The cited recurrence intervals are computed on the basis of an annual-peak-series analysis (Interagency Advisory Committee on Water Data, 1982). McCandless and Everett (2002), Jaquith and Kline (2001), and Emmett (1975) found that bankfull streamflows for their sites had mean recurrence intervals of about 1.5 years. Harman and others (1999) and White (2001) found bankfull streamflows for sites in the Piedmont regions of North Carolina, Pennsylvania and Maryland had a mean recurrence interval of 1.4 years. Harman and others (2001) found bankfull streamflows for sites in the North Carolina Blue Ridge region had a mean recurrence interval of 1.3 years. Emmett (1975) stated that the occurrence of bankfull flow in the Upper Salmon River area of Idaho was approximately four times that of the mean annual flow. On average, on a flow-duration basis, Emmett (1975) noted that bankfull streamflow was equaled or exceeded about 4 percent of the time.

Results of this study indicate that, on an annual-peak-series basis, the occurrence of bankfull streamflow for rivers in Maine is more frequent than the occurrence of bankfull flow observed in other regions. All the bankfull streamflows in this study were of lesser magnitude than the corresponding 1.5-year peak-flow event (table 3). Sweet and Geratz (2003) also found that the occurrence of bankfull streamflows in the Coastal Plain of North Carolina to be much shorter than the 1.5-year interval estimated by other national and North Carolina studies. A derived linear-regression relation between bankfull and mean annual streamflows in Maine indicates that bankfull streamflow is roughly three times that of the mean annual streamflow (fig. 3). In comparison, Dunne and Leopold (1978) observed that rivers in Pennsylvania, where peak flows are typically caused by heavy rain events, had bankfull to mean-annual flow ratios 2 to 4 times higher than ratios for rivers in Wyoming, where peak flows typically result from mountain snowmelt.

Although the occurrence of bankfull flows in coastal and central Maine, on an annual-peak-series basis, is more frequent than the 1.5-year peak-flow event, bankfull streamflows are equaled or exceeded approximately 8.1 percent of the time on mean—or about 30 days a year on a flow-duration basis (table 3). The flow-duration occurrence of bankfull streamflow in coastal and central Maine is similar to the 4-percent flow-duration exceedance probability (15 days a year) computed by Emmett (1975) for bankfull flows in the Upper Salmon River watershed in Idaho.

At the high-frequency end of an annual-peak series (streamflows approaching the 1-year recurrence interval), flows of equal flow-duration exceedance probability on different streams will occur more frequently in streams for which the rainfall-runoff response is quicker. Streams will have a quick rainfall-runoff response if they have characteristics such as steep basin slopes, little to no surface-water storage, and (or) impervious or low-permeability basin areas. For example, the drainage areas for the stations on the Passadumkeag River at Lowell, Maine (USGS station 01035000) and Togus Stream at Togus, Maine (USGS station 01049550) have more than 20 percent surface-water storage in the form of lakes, pond, and wetlands. The 1.5-year flood streamflows (computed on an annual-peak-series basis) for these two streams have flow-duration exceedance probabilities of 2.8 percent and 0.6 percent, respectively. By contrast, the Swift River near Roxbury, Maine (USGS station 01055000), and the Wild River at Gilead, Maine (USGS station 01054200), have quicker rainfall-runoff responses, because each has less than 4 percent of their drainage area as surface-water storage. Consequently, the 1.5-year-flood streamflows at these streams have flow-duration exceedance probabilities of 0.07 percent

Table 3. Mean annual, 1.5-year peak, and bankfull streamflows, and flow duration of bankfull streamflow for rivers in coastal and central Maine.

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

U.S. Geological Survey streamflow-gaging station		Mean annual streamflow (ft^3/s)	1.5-year peak streamflow (ft^3/s)	Bankfull streamflow (ft^3/s)	Flow duration of bankfull streamflow (percent)
Number	**Name**				
01023000	West Branch Union River at Amherst, Maine	270	1,500	943	4.7
01024200	Garland Brook near Mariaville, Maine	22	324	41	14.3
01031500	Piscataquis River near Dover-Foxcroft, Maine	600	6,770	3,260	2.8
01035000	Passadumkeag River at Lowell, Maine	506	1,760	924	15.3
01038000	Sheepscot River at North Whitefield, Maine	248	1,630	582	11.3
01049130	Johnson Brook at South Albion, Maine	4.7	58	16	6.0
01049550	Togus Stream at Togus, Maine	41	339	94	10.7
01055000	Swift River near Roxbury, Maine	202	4,760	688	6.2
01055500	Nezinscot River at Turner Center, Maine	301	2,670	883	7.4
01060000	Royal River at Yarmouth, Maine	271	3,120	1,460	2.6
				Mean:	8.1

and 0.02 percent respectively. Compared to streams in the western and southern United States, where other regional curves have been derived, Maine streams could be considered to have a quicker rainfall-runoff response due to the effects of hydrogeology and climate.

The glacial geology of Maine may play a role in dictating the magnitude and frequency of occurrence of bankfull streamflows in Maine. Given the relatively recent glacial activity, the river systems in coastal and central Maine are relatively young compared to those in other regions of the United States. Coastal and central Maine stream-channel beds typically contain bedrock and large boulders. The boulders are typically of such size that they are not regularly transported downstream except during extreme high-flow events with flow magnitudes much greater than bankfull flows. In other regions of the United States, where the surficial material is homogenous, fine-grained sediment, river systems that are unregulated and self-maintaining are free to form meandering patterns and channel slopes according to their drainage-area sizes, and water and sediment supplies. In comparison, streams in coastal and central Maine examined in this study appear to carry little suspended fine-grained sediment load and their meanders and slopes are commonly controlled by bedrock outcrops and fissures (Stephen M. Dickson, Maine Geological Survey, oral commun., 2003; Johnson, 1925).

At-a-Station Hydraulic-Geometry Relations

The derived at-a-station hydraulic-geometry relations indicate that, on average, a given increase in flow at a given river cross section in the study area will be nearly equally conveyed by increases in velocity and cross-sectional area (table 4). Based on the mean derived at-a-station hydraulic-geometry-equation exponents, about 48 percent of the increase in flow is accommodated by an increase in velocity, 33 percent by an increase in depth, and 19 percent by an increase in width.

Comparison of the exponent values derived for rivers in coastal and central Maine (table 4) to those derived for other regions illustrates the variability in these relations due to climate and physiographic setting. Williams (1978) graphically computed hydraulic exponents for 165 streams across the United States, representing many physiographic regions, resulting in exponent ranges of $0.00 < b < 0.82$, $0.10 < f < 0.78$, and $0.03 < m < 0.81$. Mackey and others (1998) derived mean at-a-station exponents of $b = 0.16$, $f = 0.30$, and $m = 0.55$ for 24 river sites in Massachusetts as part of a hydraulic-

Table 4. Coefficients and exponents for the at-a-station hydraulic-geometry equations for selected U.S. Geological Survey streamflow-gaging stations in coastal and central Maine.

[w, channel width in feet; d, mean channel depth in feet; v, mean streamflow velocity in feet per second; Q, streamflow in cubic feet per second; a, c, k, coefficients of hydraulic-geometry curves; b, f, m, exponents of hydraulic-geometry curves; equations defined in table footer]

USGS streamflow-gaging station		Coefficients				Exponents			
Number	**Name**	**a**	**c**	**k**	**Product**	**b**	**f**	**m**	**Sum**
01023000	West Branch Union River at Amherst, Maine	28.7	0.342	0.102	1.00	0.164	0.321	0.515	1.00
01024200	Garland Brook near Mariaville, Maine	5.89	0.311	0.545	1.00	0.314	0.411	0.275	1.00
01031500	Piscataquis River near Dover-Foxcroft, Maine	32.8	0.319	0.096	1.00	0.200	0.320	0.480	1.00
01035000	Passadumkeag River at Lowell, Maine	31.8	0.199	0.158	1.00	0.159	0.388	0.453	1.00
01038000	Sheepscot River at North Whitefield, Maine	35.2	0.498	0.057	1.00	0.103	0.281	0.617	1.00
01049130	Johnson Brook at South Albion, Maine	3.22	0.310	1.002	1.00	0.509	0.399	0.093	1.00
01049550	Togus Stream at Togus, Maine	13.5	0.250	0.297	1.00	0.224	0.378	0.398	1.00
01055000	Swift River near Roxbury, Maine	95.1	0.731	0.014	0.99	0.046	0.272	0.681	1.00
01055500	Nezinscot River at Turner Center, Maine	42.0	0.504	0.047	1.00	0.106	0.290	0.604	1.00
01060000	Royal River at Yarmouth, Maine	90.4	0.653	0.017	1.00	0.068	0.272	0.660	1.00
					Mean	0.189	0.333	0.478	

General forms of hydraulic-geometry equations: $w=aQ^b$; $d=cQ^f$; $v=kQ^m$

geometry investigation. Emmett (1975) derived at-a-station curves for 39 sites in the upper Salmon River area in Idaho as part of a hydrologic evaluation of the area. The resulting mean at-a-station exponent values were $b = 0.14$, $f = 0.40$, and $m = 0.46$. Leopold and Maddock (1953) derived mean exponent values of $b = 0.26$, $f = 0.40$, and $m = 0.34$ for 20 semiarid river sites in the Great Plains and southwestern United States.

The USGS cross sections used to derive the at-a-station hydraulic relations at each streamflow-gaging station in Maine are described by station in appendix 1.

Regional Hydraulic-Geometry Relations

Regional hydraulic-geometry curves were derived by combining at-a-station relation information for the 10 USGS stations and hydraulic-geometry information from the 5 IFIM sites, referenced to bankfull streamflow. The Q_{bkf} specific to each USGS streamflow-gaging-station, determined from field surveys of bankfull geomorphic features, was input to the derived at-a-station power functions, and their associated widths, depths, and mean velocities (w_{bkf}, d_{bkf}, v_{bkf}) were computed. For the IFIM sites, bankfull hydraulic-geometry data were computed from the calibrated cross-sectional hydraulic model for each site. The base-10 logarithms of these bankfull flow, velocity, and geometry data were used in linear regression analyses to derive regional curves with Q_{bkf} as the explanatory variable (table 5).

The exponents of the derived regional hydraulic-geometry relations indicate that, in the downstream direction, most of the conveyance of increasing flow is accommodated by an increase in cross-sectional area—about 50 percent of the increase in flow is accommodated by an increase in channel width, and 32 percent by an increase in depth. The remaining 18 percent is accommodated by an increase in streamflow velocity. These exponents agree closely with other field-derived exponents presented by Cao and Knight (1996), who report results from 10 studies in Canada, China, United Kingdom, and the United States. The mean exponents are 0.51, 0.34, and 0.15 for width, mean depth, and mean flow velocity, respectively. In the same paper, Cao and Knight (1996) derive theoretical exponents of 0.50, 0.33, and 0.17 (width, mean depth, and mean flow velocity, respectively) based on the concepts of stream power and fluvial process probability.

To make these regional relations more directly field-applicable to stream assessment, the bankfull

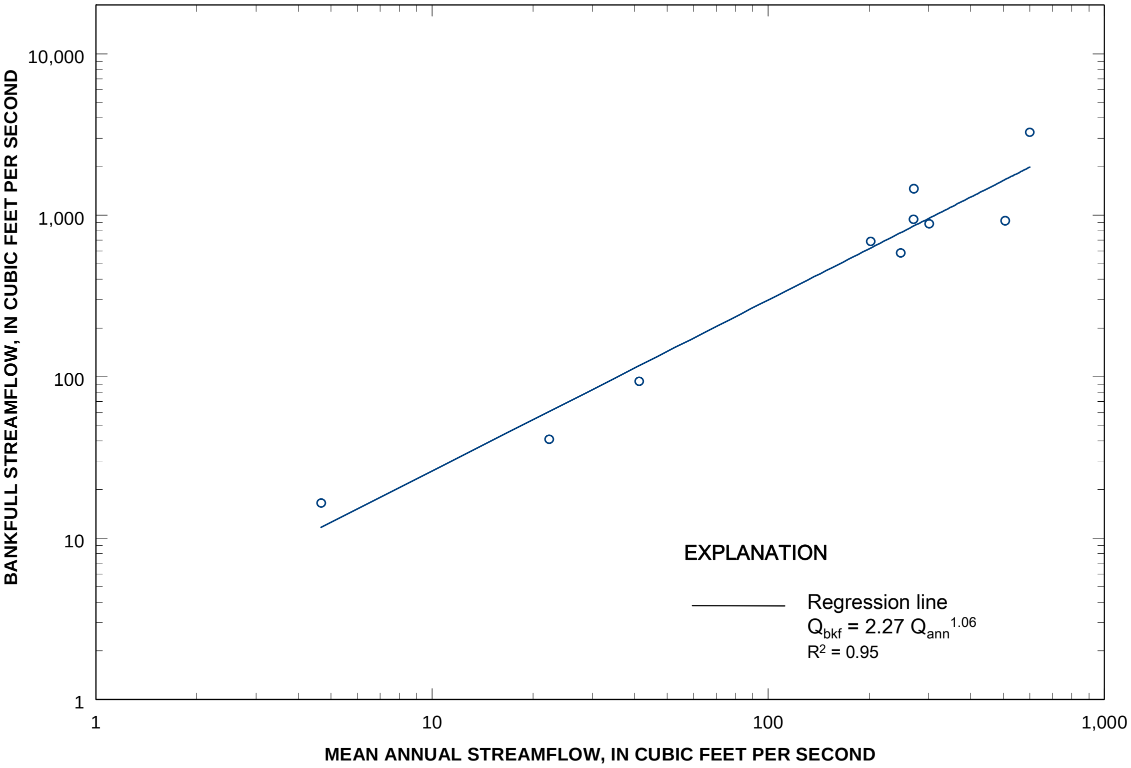


Figure 3. Relation of bankfull streamflow to mean annual streamflow for rivers in coastal and central Maine. [Q_{bkf}, bankfull streamflow; Q_{ann}, mean annual streamflow; R^2, fraction of variance explained by regression].

streamflow and its associated channel geometry are commonly derived as a function of drainage area (for examples, see: McCandless and Everett, 2002; Harman and others, 2001; White, 2001; Harman and others, 1999). In particular, the relation of bankfull channel width to drainage area is a commonly used assessment tool because the width is easily measured in the field, assuming the river stage of the bankfull streamflow is known or can be otherwise identified by morphological features. Similarly, the drainage area is commonly derived using topographic maps or a Geographic Information System (GIS). Thus, the measured channel width can be compared to the range of regional values expected for a drainage basin of that size as described by the regional curve derived for the appropriate reference flow, climate, and physiographic region of interest.

Regional curves describing the bankfull streamflow and associated channel geometry as functions of drainage area were derived for the sites used in this study (table 6, figs. 4 to 7). The derived regression exponents agree reasonably well with exponents derived by other studies in the eastern United States (table 7) (Sweet and Geratz, 2003; McCandless and Everett, 2002; Harman and others, 2001; Jaquith and Kline, 2001; White, 2001; Harman and others, 1999).

Summary and Conclusions

Baseline knowledge of the characteristics of natural river channels in central and coastal Maine will assist water-resources managers with instream-restoration projects. Stable, self-maintaining, natural channels conform to a cross-sectional geometry, plan, and profile proportional to the size of the upstream watershed, streamflow, and sediment load. Within a region of similar hydrogeology and climate, the mean characteristics describing the shape of the channel are sufficiently

Table 5. Regional regression equations for estimating bankfull channel width, channel depth, and streamflow velocity as functions of bankfull streamflow for rivers in coastal and central Maine.

[Q_{bkf}, bankfull streamflow in cubic feet per second; w_{bkf}, bankfull channel width, in feet; d_{bkf}, bankfull mean channel depth, in feet; v_{bkf}, bankfull mean streamflow velocity, in feet per second; R^2, fraction of variance explained by regression]

Regression equation	Average standard error of estimate	R^2
$w_{bkf} = 3.36Q_{bkf}^{0.50}$	+21.2 to -17.5	0.94
$d_{bkf} = 0.361Q_{bkf}^{0.32}$	+24.5 to -19.7	0.82
$v_{bkf} = 0.825Q_{bkf}^{0.18}$	+43.3 to -30.2	0.37

consistent that the degree of deviation from what is commonly observed in the region can be interpreted as the magnitude of the effect of disturbance. Regional statistical models or curves that relate river-channel geometry to drainage area and streamflow make use of this concept and are a valuable tool used to characterize disturbed river reaches and to help water-resources managers ensure the efficacy and longevity of restoration projects.

This report presents the data, methods, and results of a cooperative study (from 2001 to 2003) between the U.S. Geological Survey (USGS), Maine Atlantic Salmon Commission (ASC), and U.S. Fish and Wildlife Service to collect hydraulic-geometry data for rivers in coastal and central Maine and derive regional hydraulic-geometry curves calibrated to the bankfull reference flow. Bankfull flow is the flow that completely fills the channel up to the elevation of the floodplain, without overtopping the banks. Bankfull flow is a useful reference flow because it can be estimated at ungaged sites based on observable, physical channel features and does not require knowledge of flow frequency in the river. In addition, bankfull flow is generally thought to be the flow that determines the dominant morphological characteristics of river channels. The regional curves, based on the USGS streamflow-measurement data and data obtained from Instream Flow Incremental Methodology (IFIM) studies, were developed to assist the cooperating agencies and other natural-resources managers incorporate river morphology with habitat assessment in river-restoration projects in coastal and central Maine.

This investigation was confined to rivers in coastal and central Maine that had USGS streamflow-measurement and stage-discharge relation data available or had been investigated previously as part of an IFIM study by the ASC. The 15 sites used in this study are in heavily forested watersheds that are characterized by rolling topography and no urban development. All the selected sites are in coastal and central Maine to minimize variations caused by differences in physiographic setting. Only channel-geometry data available at natural, stable cross sections were used.

On an annual-peak-series basis, results of this study indicate that the occurrence of bankfull streamflow for rivers in Maine is more frequent than the occurrence of bankfull streamflow observed in other regions. On a flow-duration basis, bankfull streamflow for rivers

Table 6. Regional regression equations for estimating bankfull streamflow, channel width, channel depth, and channel cross-sectional area as functions of drainage area for rivers in coastal and central Maine.

[Q_{bkf}, bankfull streamflow in cubic feet per second; w_{bkf}, bankfull channel width, in feet; d_{bkf}, bankfull mean channel depth, in feet; A_{bkf}, bankfull cross-sectional area, in square feet ; DA, drainage area in square miles; R^2, fraction of variance explained by regression]

Regression equation	Average standard error of estimate	R^2
$Q_{bkf} = 5.19DA^{1.05}$	+66.0 to -39.8	0.88
$w_{bkf} = 7.67DA^{0.52}$	+37.9 to -27.5	0.82
$d_{bkf} = 0.594DA^{0.34}$	+29.4 to -22.7	0.76
$A_{bkf} = 4.55DA^{0.86}$	+70.5 to -41.3	0.82

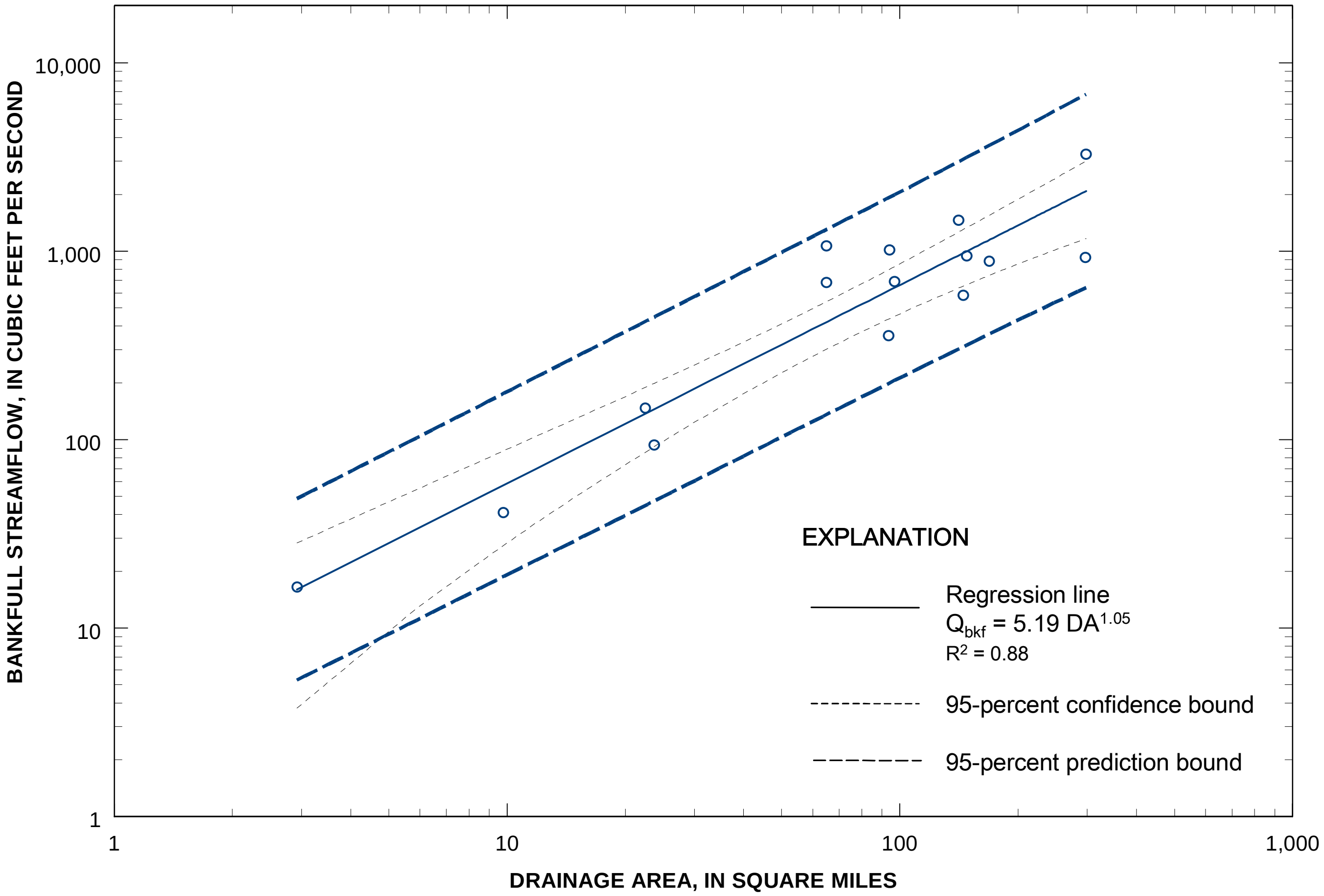


Figure 4. Regional relation of bankfull streamflow to drainage area for rivers in coastal and central Maine. [$Q_{bkf,}$ bankfull streamflow; DA, drainage area; R^2, fraction of variance explained by regression].

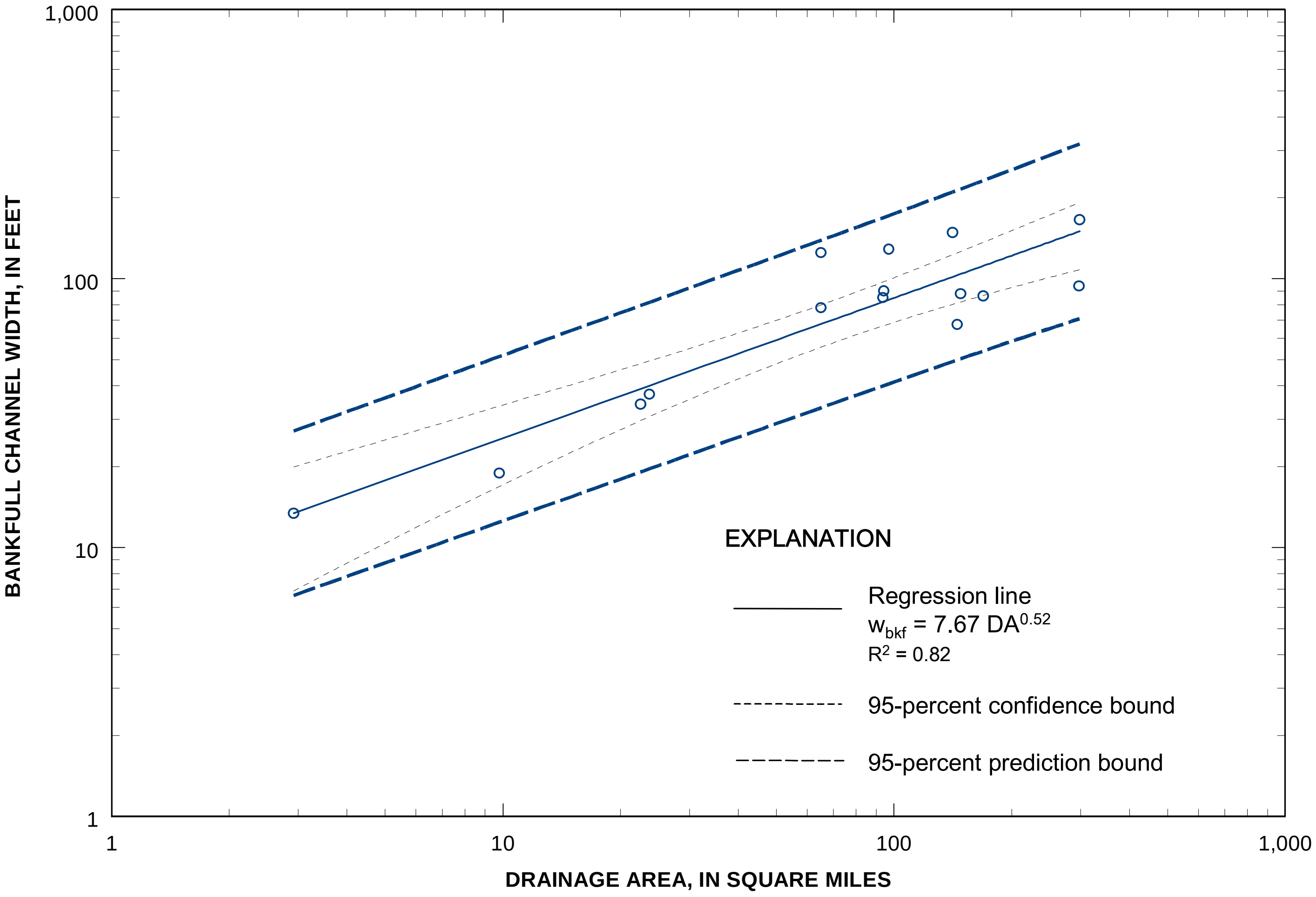


Figure 5. Regional relation of bankfull channel width to drainage area for rivers in coastal and central Maine. [w_{bkf}, channel width associated with the bankfull streamflow; DA, drainage area; R^2, fraction of variance explained by regression].

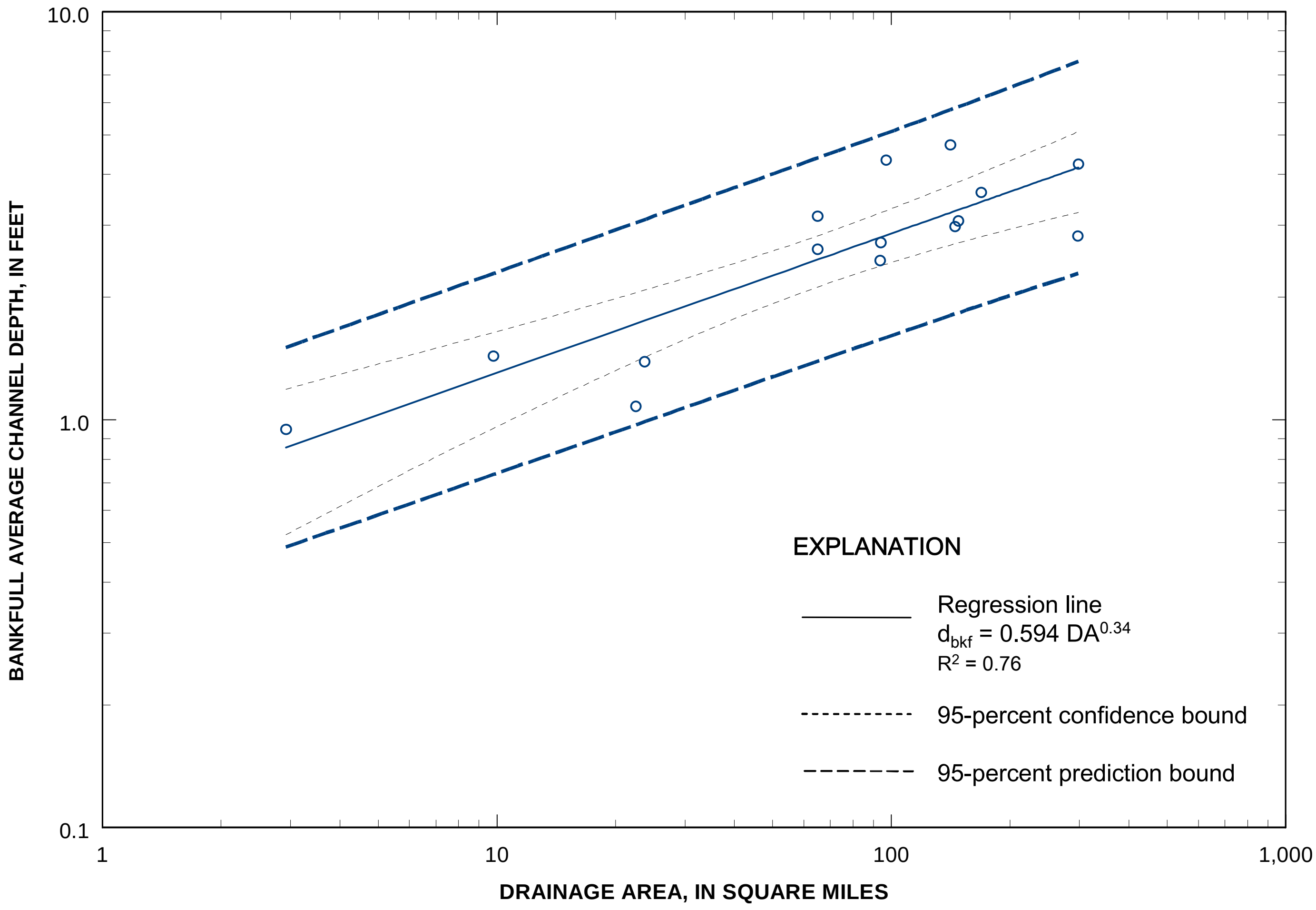


Figure 6. Regional relation of bankfull mean channel depth to drainage area for rivers in coastal and central Maine. [d_{bkf}, mean channel depth associated with the bankfull streamflow; DA, drainage area; R^2, fraction of variance explained by regression].

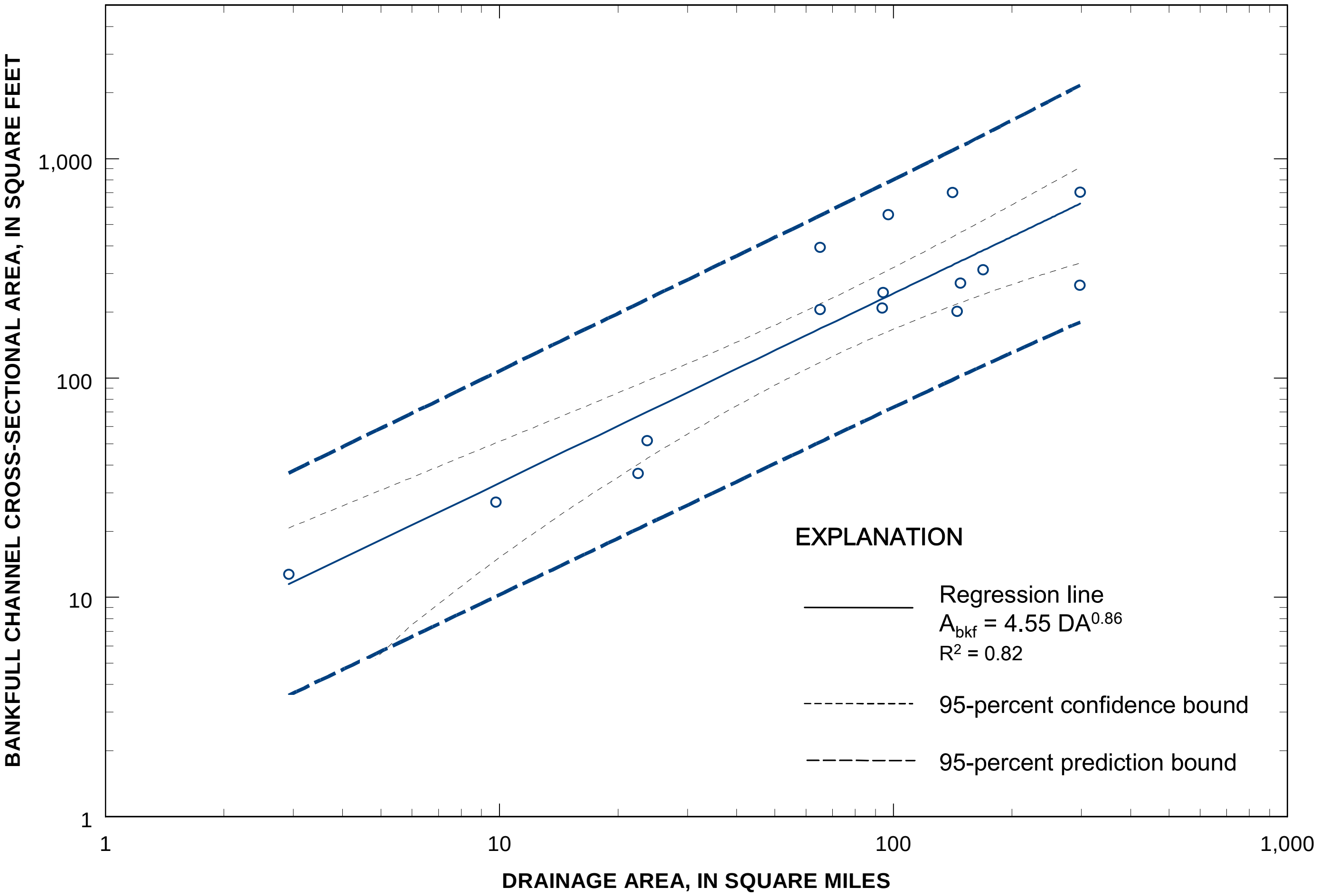


Figure 7. Regional relation of bankfull channel cross-sectional area to drainage area for rivers in coastal and central Maine. [A_{bkf}, channel cross-sectional area associated with the bankfull streamflow; DA, drainage area; R^2, fraction of variance explained by regression].

Table 7. Regional regression equations for estimating bankfull streamflow, bankfull channel width, mean bankfull channel depth, and bankfull channel cross-sectional area for various regions in the eastern United States.

[Q_{bkf}, bankfull streamflow in cubic feet per second; $w_{bkf,}$ bankfull channel width, in feet; d_{bkf}, bankfull mean channel depth, in feet; A_{bkf}, bankfull channel cross-sectional area, in square feet; DA, drainage area in square miles]

Investigators	Region studied	Bankful streamflow	Banfull channel width	Average bankfull channel depth	Bankfull channel cross-sectional area	Number of stations used to derive regression equations
This study (2004)	Central and coastal Maine	$Q_{bkf} = 5.19DA^{1.05}$	$w_{bkf} = 7.67DA^{0.52}$	$d_{bkf} = 0.594DA^{0.34}$	$A_{bkf} = 4.55DA^{0.86}$	15
Sweet and Geratz (2003)	North Carolina Coastal Plain	$Q_{bkf} = 8.79DA^{0.76}$	$w_{bkf} = 9.64DA^{0.38}$	$d_{bkf} = 0.98DA^{0.36}$	$A_{bkf} = 9.43DA^{0.74}$	24
McCandless and Everett (2002)	Maryland Piedmont	$Q_{bkf} = 84.6DA^{0.76}$	$w_{bkf} = 14.8DA^{0.39}$	$d_{bkf} = 1.18DA^{0.34}$	$A_{bkf} = 17.4DA^{0.73}$	23
Harman and others (2001)	North Carolina Blue Ridge	$Q_{bkf} = 115.7DA^{0.73}$	$w_{bkf} = 19.9DA^{0.36}$	$d_{bkf} = 1.10DA^{0.31}$	$A_{bkf} = 22.1DA^{0.67}$	12
Jaquith and Kline (2001)	Vermont (statewide)	$Q_{bkf} = 17.7DA^{1.07}$	$w_{bkf} = 10.2DA^{0.50}$	$d_{bkf} = 1.22DA^{0.25}$	$A_{bkf} = 12.21DA^{0.75}$	14
White (2001)	Pennsylvania and Maryland Piedmont	$Q_{bkf} = 69.6DA^{0.79}$	$w_{bkf} = 14.8DA^{0.46}$	$d_{bkf} = 0.780DA^{0.39}$	$A_{bkf} = 11.7DA^{0.85}$	6
Harman and others (1999)	North Carolina Piedmont	$Q_{bkf} = 66.6DA^{0.89}$	$w_{bkf} = 11.9DA^{0.43}$	$d_{bkf} = 1.50DA^{0.32}$	$A_{bkf} = 21.4DA^{0.68}$	13

in coastal and central Maine is equaled or exceeded approximately 8.1 percent of the time on average—or about 30 days a year. Bankfull streamflow is roughly three times that of the mean annual streamflow for the sites investigated in this study. Regional climate, snowmelt hydrology, and glacial geology may play important roles in dictating the magnitude and frequency of occurrence of bankfull streamflows observed for rivers in coastal and central Maine.

The fundamental relations between channel-geometry dimensions, velocity, and flow can be expressed as well-established power functions, also referred to as "at-a-station curves." The derived at-a-station hydraulic-geometry relations indicate that, on average, a given increase in flow at a given river cross section in the study area, will be nearly equally accommodated by increases in velocity and cross-sectional area. Based on the mean derived at-a-station hydraulic-geometry equation exponents, about 48 percent of the increase in flow is accommodated by an increase in velocity, 33 percent by an increase in depth, and 19 percent by an increase in width.

Regional hydraulic-geometry curves were derived by combining at-a-station relation information from the 10 USGS sites and hydraulic-geometry information from the 5 IFIM sites, referenced to bankfull streamflow. The exponents of the derived regional hydraulic-geometry relations indicate that, in the downstream direction, most of the conveyance of increasing contribution of flow is accommodated by an increase in cross-sectional area—about 50 percent of the increase in flow is accommodated by an increase in channel width, and 32 percent by an increase in depth. The remaining 18 percent is accommodated by an increase in streamflow velocity.

Regional curves describing the bankfull streamflow and associated channel geometry as functions of drainage area also were derived for the sites in this study. The derived regression exponents agree reasonably well with exponents derived in other studies in the eastern United States.

References Cited

Brunner, D.S., 1999, Methods for estimating bankfull discharge in gaged and ungaged urban streams: Waterloo, University of Waterloo, B.S. thesis, 29 p.

Cao and Knight, 1996, Regime theory of alluvial channels based upon the concepts of stream power and probability: Proceedings of the Institution of Civil Engineers, Water, Maritime and Energy Division, v.118, p 160-167.

Dunne, T. and Leopold, L.B., 1978, Water in Environmental Planning: San Francisco, Calif., Freeman and Co., 818 p.

Emmett, W.W., 1975, The channels and waters of the Upper Salmon River area, Idaho: U.S. Geological Survey Professional Paper 870-A, 115 p.

Harman, W.H., Wise, D.E., Walker, M.A., Morris, R., Cantrell, M.A., Clemmons, M., Jennings, G.D., Clinton, D., Patterson, J., 2001, Bankfull regional curves for North Carolina mountain streams: Raleigh, North Carolina, North Carolina Stream Restoration Institute, accessed December 31, 2003, at http://www.bae.ncsu.edu/programs/extension/wqg/sri/mtnpaper.html

Harman, W.H., Jennings, G.D., Patterson, J.M., Clinton, D.R., Slate, L.O., Jessup, A.G., Everhart, J.R., Smith, R.E., 1999, Bankfull hydraulic-geometry relationships for North Carolina streams, in Olsen, D.S. and Potyondy, J.P. (ed.), AWRA Wildland Hydrology Symposium, Proceedings: Bozeman, Montana, Summer Symposium.

Helsel D.R. and Hirsch R.M., 1992, Statistical methods in water resources: Amsterdam, Elsevier, 529 p.

Interagency Advisory Committee on Water Data, 1982, Guidelines for determining flood flow frequency—Bulletin 17B of the Hydrology Subcommittee: U.S. Geological Survey, Office of Water-Data Coordination, 183 p.

Irland, L.C., 1998, Maine's forest area, 1600-1995—Review of available estimates: College of Natural Sciences, Forestry, and Agriculture, University of Maine, Maine Agricultural and Forest Experiment Station Miscellaneous Publication 736, February 1998, 12 p.

Jaquith, S., and Kline, M., 2001, Vermont regional hydraulic-geometry curves, 2001 provisional: Waterbury, Vermont, Vermont Department of Environmental Conservation, Water Quality Division, accessed December 31, 2003, at http://www.vtwaterquality.org/Rivers/01hydraulicgeometrycurves.PDF

Johnson, D.W., 1925, The New England-Acadian shoreline, New York, Hafner Publishing Co., 608 p.

Jowett, I.G., 1998, Hydraulic-geometry of New Zealand rivers and its use as a preliminary method of habitat assessment: Regulated Rivers—Research and Management, v. 14, p. 451-466.

Kleinschmidt Associates, 1999a, Maine Atlantic salmon conservation plan—report on instream flow studies—volume I—Pleasant River: Pittsfield, Maine, Kleinschmidt Associates Consulting Engineers & Scientists, February 1999, 97 p.

Kleinschmidt Associates, 1999b, Maine Atlantic salmon conservation plan—report on instream flow studies—volume II—Narraguagus River and Mopang Stream: Pittsfield, Maine, Kleinschmidt Associates Consulting Engineers & Scientists, February 1999, 162 p..

Leopold, L.B. and Maddock, T. Jr., 1953, The hydraulic-geometry of river channels and some physiographic implications: U.S. Geological Survey Professional Paper 252, 57 p.

Leopold, L.B., Wolman, M.G., and Miller, J.P., 1992, Fluvial processes in geomorphology: Dover Publications, New York, 522 p.

Mackey, P., Barlow, P.M., Ries, K.G., III, 1998, Relations between discharge and wetted perimeter and other hydraulic-geometry characteristics at selected streamflow-gaging stations in Massachusetts: U.S. Geological Survey Water-Resources Investigations Report 98-4094, 44 p.

Marvinney, R. G. and Thompson, W. B., 2000, A geologic history of Maine, in King, V. T. (editor), Mineralogy of Maine, volume 2—Mining History, Gems, and Geology, Augusta, Maine, Maine Geological Survey, p.1-8.

McCandless, T.L. and Everett, R., 2002, Maryland river survey—Bankfull discharge and channel characteristics of streams in the Piedmont hydrologic region: U.S. Fish and Wildlife Service Chesapeake Bay Field Office Report, CBFO-S02-01, 175 p.

National Oceanic and Atmospheric Administration, 2002, Climatography of the United States, no. 81, Monthly station normals of temperature, precipitation, and heating and cooling degree days, 1971-2000—Region 17, Maine: Asheville, N.C., National Oceanic and Atmospheric Administration,16 p.

Osterkamp, W.R., Lane, L.J., and Foster, G.R., 1983, An analytic treatment of channel-morphology relations: U.S. Geological Survey Professional Paper 1288, 21 p.

Randall, A.D., 2001, Hydrogeologic framework of stratified drift aquifers in the glaciated northeastern United States: U.S. Geological Survey Professional Paper 1415-B, 179 p., 1 plate showing hydrophysiographic regions in the glaciated northeastern United States, scale 1:2,500,000.

Rantz, S.E. and others, 1982, Measurement and computation of streamflow (2 volumes): U.S. Geological Survey Water-Supply Paper 2175, 631 p.

Rosgen, D.L., 1996, Applied River Morphology, Pagosa Springs, Colorado, Wildland Hydrology Books, 390 p.

Sweet, W.V. and Geratz, J.W., 2003, Bankfull hydraulic-geometry relationships and recurrence intervals for North Carolina's Coastal Plain: Journal of the American Water Resources Association, v. 39, no. 4, p. 861-871.

Thompson, W.B. and Borns, H.W., 1985, Surficial geologic map of Maine: Maine Geological Survey, Department of Conservation, scale 1:5,000,000.

U.S. Geological Survey, 1975, Estimating flow characteristics from channel size: U.S. Geological Survey Surface-Water Technical Memorandum no. 75.16, 6 p.

U.S. Geological Survey, 1998, National Water Information System (NWIS). U.S. Geological Survey Fact Sheet FS-027-98. Reston, Virginia, 2 p.

White, K.E., 2001, Regional curve development and selection of a reference reach in the non-urban, lowland sections of the Piedmont Physiographic Province, Pennsylvania and Maryland: U.S. Geological Survey Water-Resources Investigations Report 01-4146, 20 p.

Williams, G.P., 1978, Hydraulic-geometry of river cross sections—Theory of minimum variance: U.S. Geological Survey Professional Paper 1029, 47 p.

Appendix 1: Descriptions of U.S. Geological Survey Streamflow-Gaging Stations

References to left and right side of the river correspond to one's left and right when facing downstream.

01023000 West Branch Union River at Amherst, Maine (Period of record: 1910-19, 1929-79)

The West Branch Union River streamflow-gaging station was located on the right bank, about 1 mi upstream from State Route 9 bridge in Amherst. Bedrock falls serve as the hydraulic control for the station. The cross section where the data used to derive the hydraulic-geometry relations were collected is approximately 0.25 mi downstream from the station. The river channel at the cross section is characterized as rocky, composed of bedrock, cobbles, and gravel, with some silt. All the measurement data are from wading measurements (fig. A1).

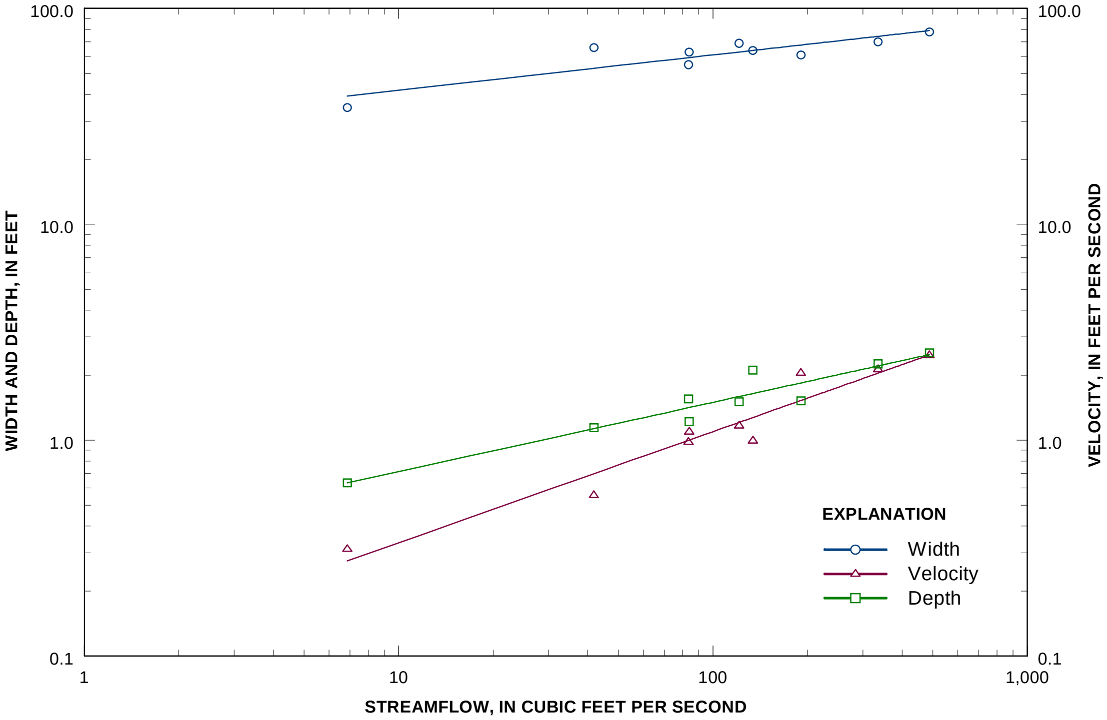


Figure A1. At-a-station relations of channel width, mean depth, and mean velocity to streamflow for the West Branch Union River at Amherst, Maine (USGS streamflow-gaging station number 01023000).

01024200 Garland Brook near Mariaville, Maine (Period of record: 1964-82)

The Garland Brook streamflow-gaging station was located on the left bank, about 22 ft upstream from State Route 18 in Mariaville. The State Route 18 culvert serves as the hydraulic control for the station. The cross section where the data used to derive the hydraulic-geometry relations were collected is approximately at the station. The river channel at the cross section is characterized as rocky, composed of sand, gravel, cobbles, and some bedrock. All the measurement data are from wading measurements (fig. A2).

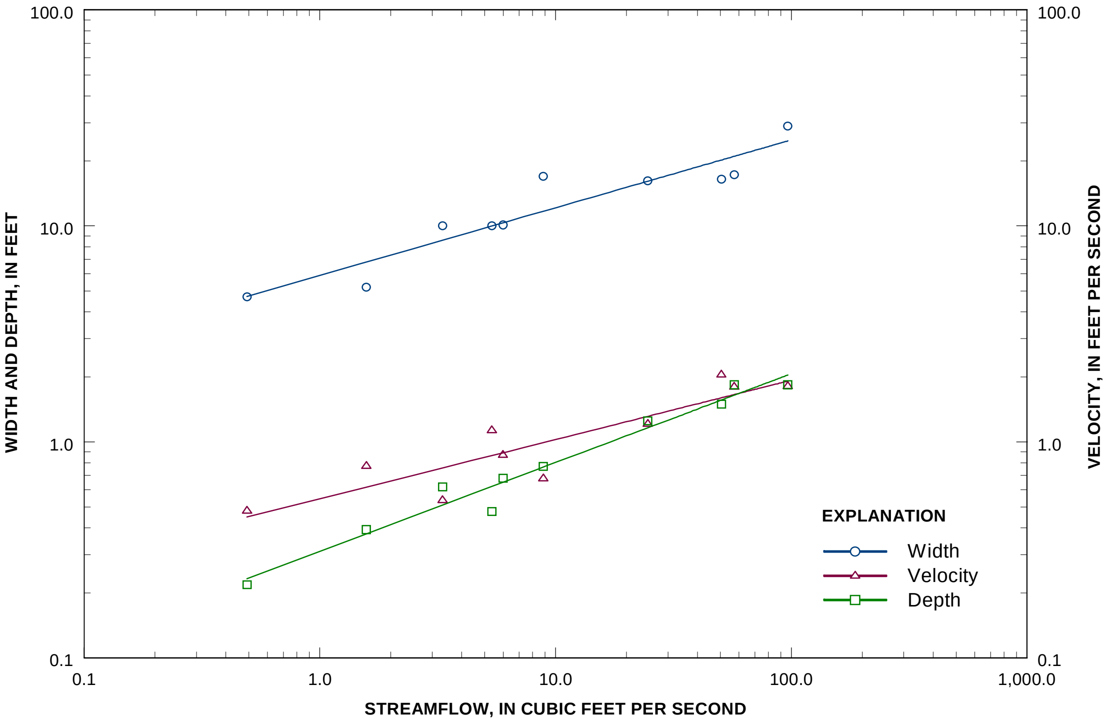


Figure A2. At-a-station relations of channel width, mean depth, and mean velocity to streamflow for Garland Brook near Mariaville, Maine (USGS streamflow-gaging station number 01024200).

01031500 Piscataquis River near Dover-Foxcroft, Maine (Period of record: 1902-present)

The Piscataquis River streamflow-gaging station is currently (2004) active and is on the left bank about 30 ft downstream from Lows Bridge in Dover-Foxcroft. Bedrock and boulders 200 ft downstream from the station serve as the hydraulic control for the station at low and medium flows. At high flows, the channel becomes the hydraulic control. The cross section where the data used to derive the hydraulic-geometry relations were collected is approximately 400 ft downstream from the station. The river channel at the cross section is characterized as rocky, composed of gravel, cobbles, and some boulders. All the measurement data are from wading measurements except for one boat measurement at high flow (fig. A3).

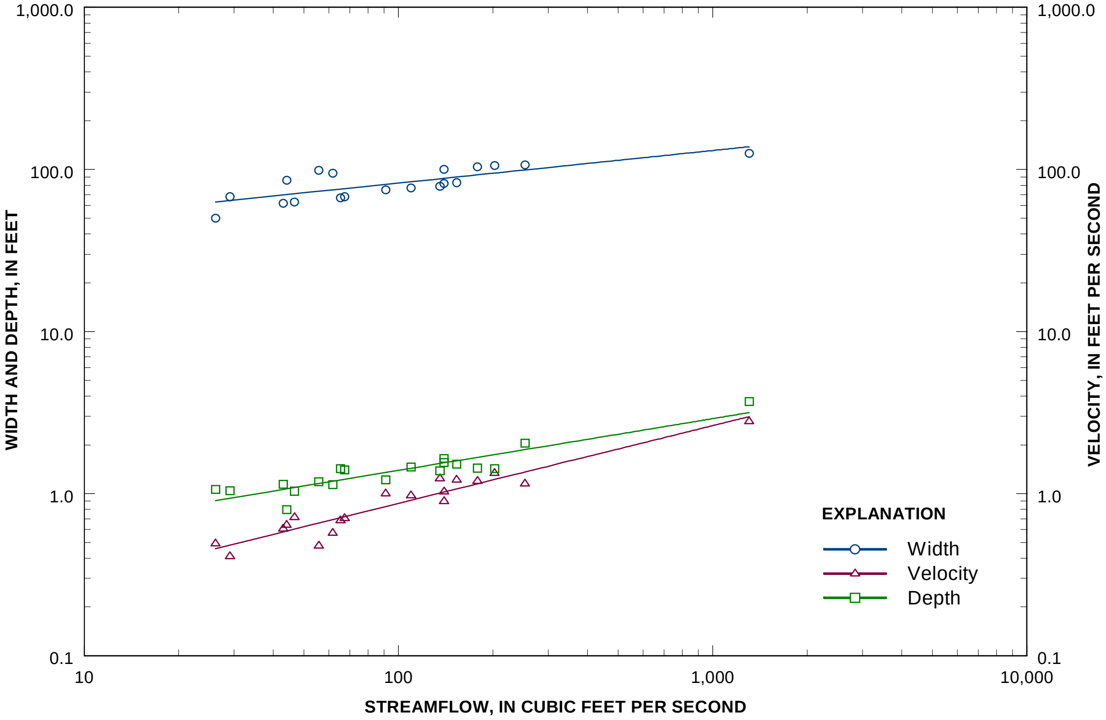


Figure A3. At-a-station relations of channel width, mean depth, and mean velocity to streamflow for the Piscataquis River near Dover-Foxcroft, Maine (USGS streamflow-gaging station number 01031500).

01035000 Passadumkeag River at Lowell, Maine (Period of record: 1916-79)

The Passadumkeag River streamflow-gaging station was on the right bank about 0.5 mi downstream from Fogg Brook Road Bridge and the dam in Lowell. Coarse gravel rips serve as the hydraulic control for the station. During the years the river was gaged, the streamflow was not regulated by the dam. The cross section where the data used to derive the hydraulic-geometry relations were collected is approximately 100 ft downstream from the station at a cableway. The river channel at the cross section is characterized as rocky, composed of coarse gravel, cobbles, and some bedrock. All measurement data are from wading and cable measurements made at or beneath the cableway providing a data set with very little variability (fig. A4).

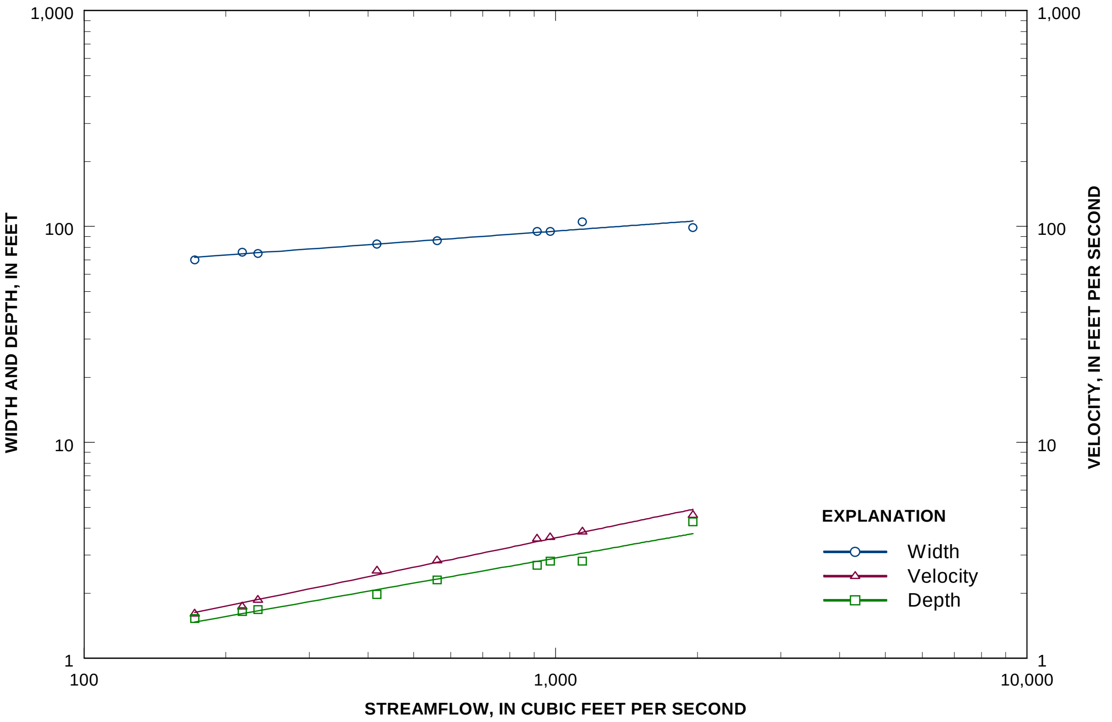


Figure A4. At-a-station relations of channel width, mean depth, and mean velocity to streamflow for the Passadumkeag River at Lowell, Maine (USGS streamflow-gaging station number 01035000).

01038000 Sheepscot River at North Whitefield, Maine (Period of record: 1939-present)

The Sheepscot River streamflow-gaging station is currently (2004) active and is on the left bank about 50 ft upstream from the State Route 126 bridge in North Whitefield. A bedrock outcrop 50 ft downstream from the station serves as the hydraulic control for the station. The bridge opening acts as the high-water hydraulic control only at stages exceeding 5.0 ft—well above the bankfull flow. The cross section where the data used to derive the hydraulic-geometry relations were collected is at a cableway between the station and the bridge. The river channel at the cross section is characterized as rocky, composed of cobbles, boulders, and bedrock. All measurement data are from wading and cable measurements made at or beneath the cableway providing a data set with very little variability (fig. A5).

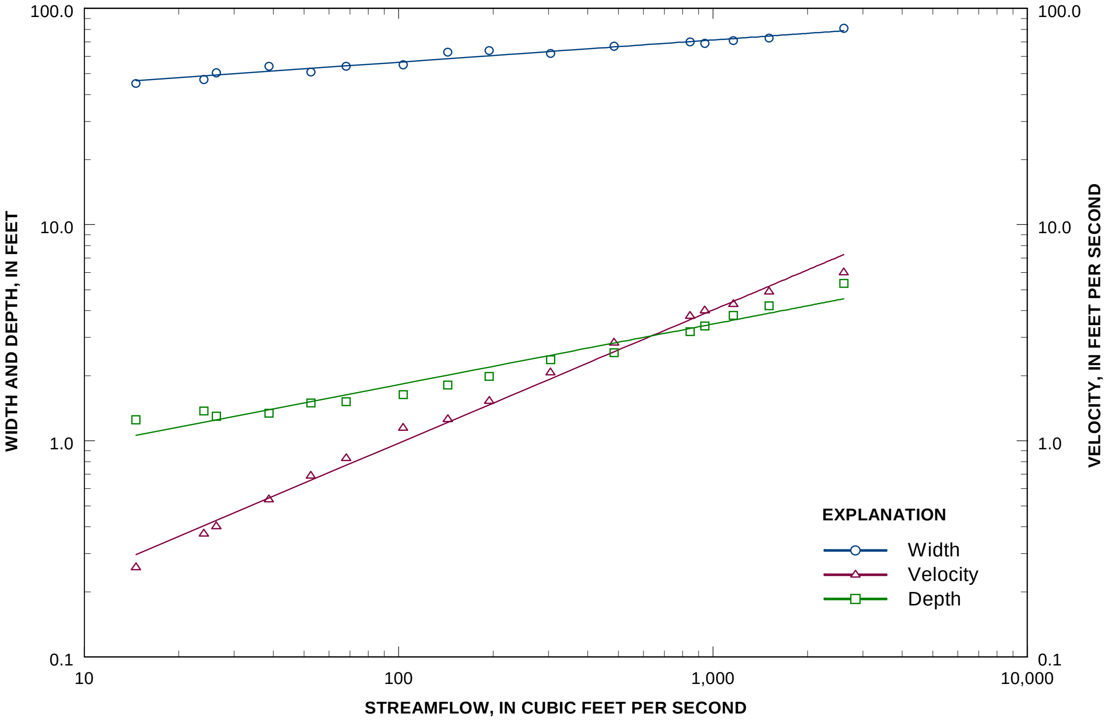


Figure A5. At-a-station relations of channel width, mean depth, and mean velocity to streamflow for the Sheepscot River at North Whitefield, Maine (USGS streamflow-gaging station number 01038000).

01049130 Johnson Brook at South Albion, Maine (Period of record: 1980-91)

The Johnson Brook streamflow-gaging station was on the right bank upstream from the Dutton Road culvert, about 0.2 mi south of State Highway 9 and 202 in South Albion. A v-notch weir in the culvert served as the hydraulic control for the station. The cross section where the data used to derive the hydraulic-geometry relations were collected is approximately 200 ft upstream from the station, though locations of measurement at this site were highly variable. The river channel at the cross section is characterized as gravelly, composed of sand, gravel, and cobbles. All the measurement data are from wading measurements (fig. A6).

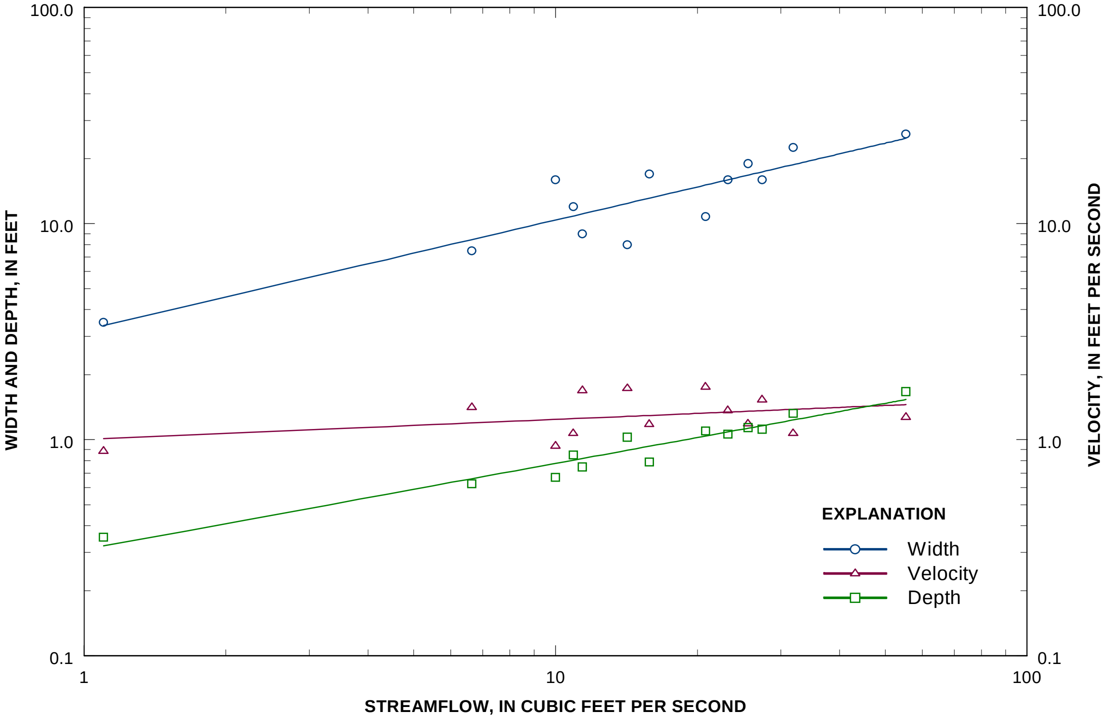


Figure A6. At-a-station relations of channel width, mean depth, and mean velocity to streamflow for Johnson Brook at South Albion, Maine (USGS streamflow-gaging station number 01049130).

01049550 Togus River at Togus, Maine (Period of record: 1982-95)

The Togus River streamflow-gaging station was located on the right bank about 600 ft downstream from the State Route 226 Bridge. A concrete broad-crested weir 50 ft downstream from the station served as the hydraulic control for the station. The cross section where the data used to derive the hydraulic-geometry relations were collected is at a cableway approximately 100 ft downstream from the station. The river channel at the cross section is characterized as rocky, composed of cobbles and bedrock. All measurement data are from wading and cable measurements made at or beneath the cableway providing a data set with little variability (fig. A7).

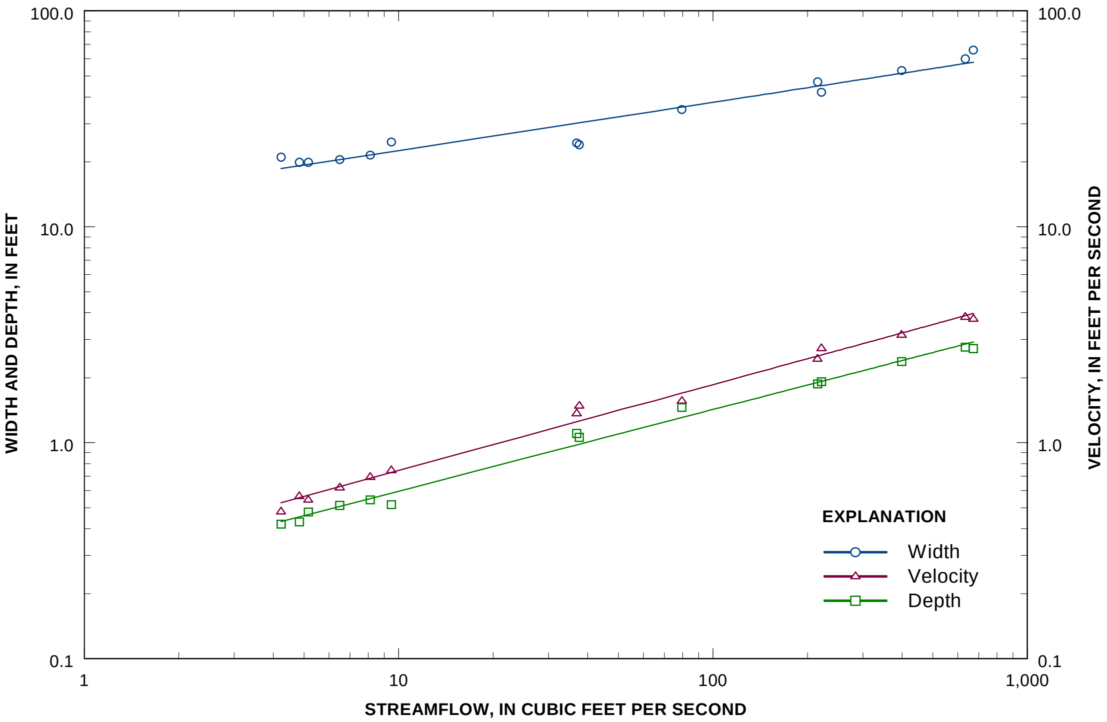


Figure A7. At-a-station relations of channel width, mean depth, and mean velocity to streamflow for the Togus River at Togus, Maine (USGS streamflow-gaging station number 01049550).

01055000 Swift River near Roxbury, Maine (Period of record: 1929-present)

The Swift River streamflow-gaging station is currently (2004) active and is on the left bank at Swift River Falls, about 7.2 mi upstream from the confluence of the Swift River with the Androscoggin River. The bedrock falls 50 ft downstream from the station serve as the hydraulic control for the station. The cross section where the data used to derive the hydraulic-geometry relations were collected is at a cableway approximately 400 ft upstream from the station. The river channel at the cross section is characterized as rocky, composed of gravel, cobbles, and boulders. All measurement data are from cableway measurements providing a data set with very little variability (fig. A8).

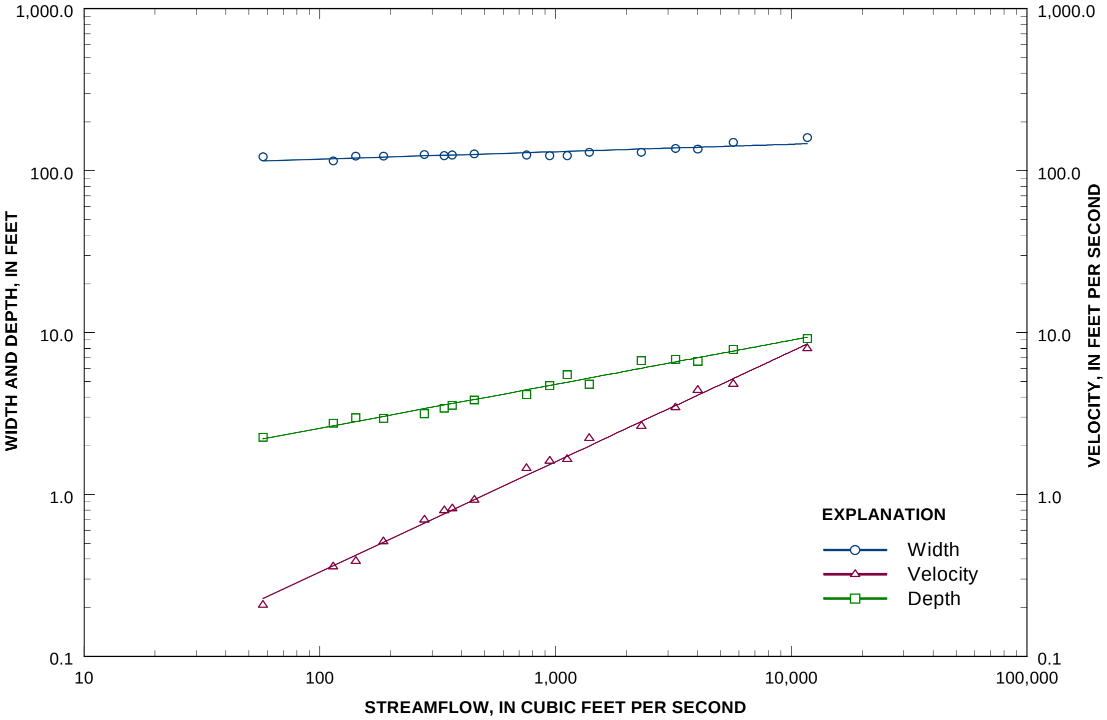


Figure A8. At-a-station relations of channel width, mean depth, and mean velocity to streamflow for the Swift River near Roxbury, Maine (USGS streamflow-gaging station number 01055000).

01055500 Nezinscot River at Turner Center, Maine (Period of record: 1941-96, 2001-present)

The Nezinscot River streamflow-gaging station is currently (2004) active and is on the left bank 500 ft upstream from State Route 117 Bridge in Turner. Bedrock, cobble, and boulder rips 300 ft downstream from the station serve as the hydraulic control for the station. The cross section where the data used to derive the hydraulic-geometry relations were collected is at a cableway at the station. The river channel at the cross section is characterized as rocky, composed of cobbles and boulders. All the measurement data are from measurements made at or beneath the cableway providing a data set with very little variability (fig. A9).

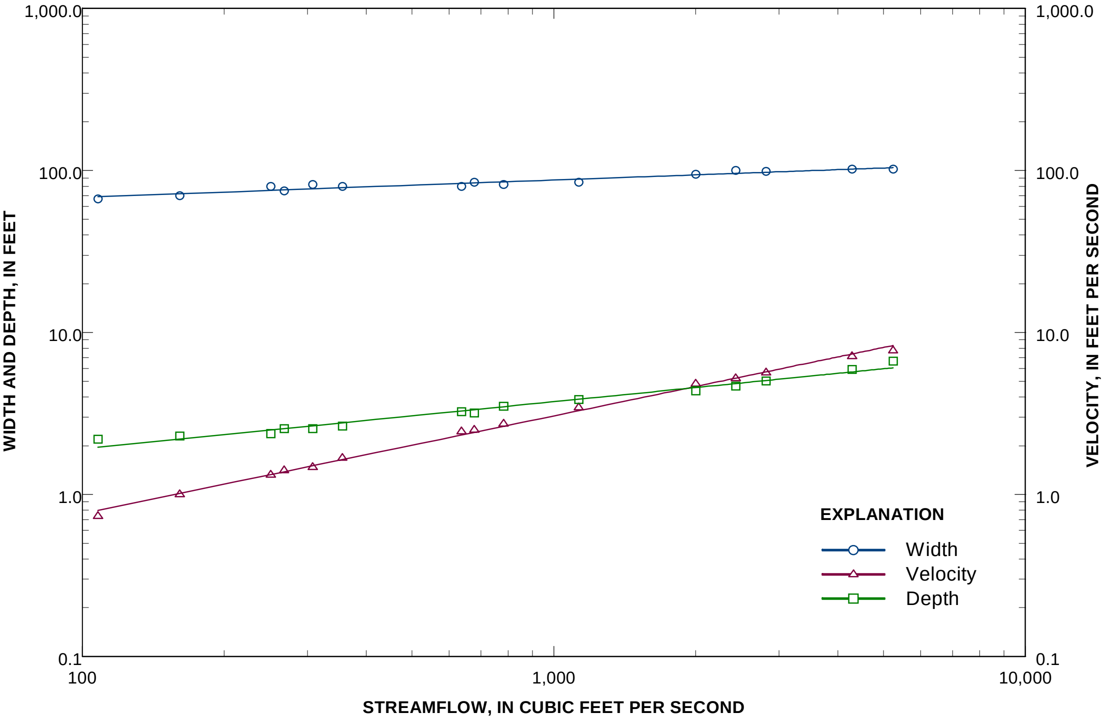


Figure A9. At-a-station relations of channel width, mean depth, and mean velocity to streamflow for the Nezinscot River at Turner Center, Maine (USGS streamflow-gaging station number 01055500).

01060000 Royal River at Yarmouth, Maine (Period of record: 1950-present)

The Royal River streamflow-gaging station is currently (2004) active and is on the right bank about 150 ft upstream from the East Main Street bridge in Yarmouth. Bedrock falls 50 ft downstream from the station serve as the hydraulic control for the station. The cross section where the data used to derive the hydraulic-geometry relations were collected is at a cableway approximately 300 ft upstream from the station. The river channel at the cross section is characterized as rocky, composed of cobbles, bedrock, and some silt. All the measurement data are from cableway measurements providing a data set with very little variability (fig. A10).

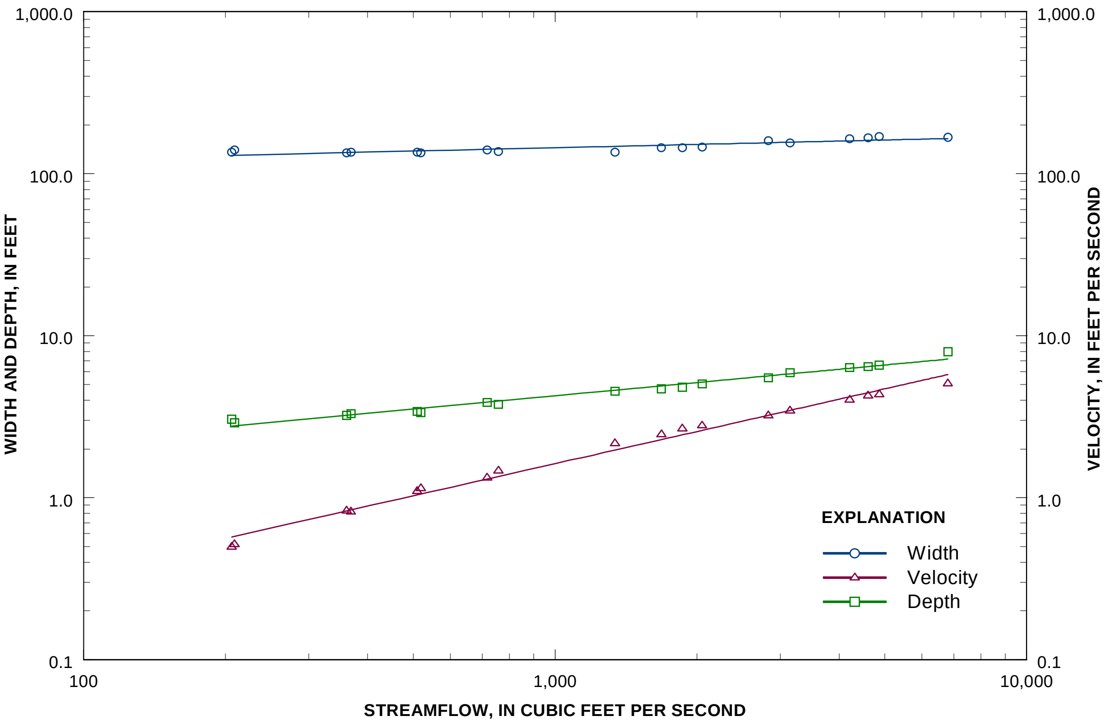


Figure A10. At-a-station relations of channel width, mean depth, and mean velocity to streamflow for the Royal River at Yarmouth, Maine (USGS streamflow-gaging station number 01060000).

Dudley, Robert W. —**Hydraulic-Geometry Relations for Rivers in Coastal and Central Maine**—USGS Scientific Investigations Report 2004-5042

125 years of science for America

1879–2004