USGS
science for a changing world

Prepared in cooperation with the
Massachusetts Department of Environmental Protection
Bureau of Resource Protection
Wetlands and Waterways Program and
Massachusetts Environmental Trust

Equations for Estimating Bankfull Channel Geometry and Discharge for Streams in Massachusetts

Scientific Investigations Report 2013–5155

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

Front cover. Photograph of bankfull conditions on the Green River near Great Barrington, Massachusetts (USGS streamgage 01198000), looking upstream of Hurlburt Street on March 5, 2008.

Back cover. Photograph of bankfull survey at cross section #6 looking downstream on Cadwell Creek near Belchertown, Massachusetts (USGS streamgage 01174900), on December 9, 2004.

Equations for Estimating Bankfull Channel Geometry and Discharge for Streams in Massachusetts

By Gardner C. Bent and Andrew M. Waite

Prepared in cooperation with the
Massachusetts Department of Environmental Protection
Bureau of Resource Protection
Wetlands and Waterways Program and
Massachusetts Environmental Trust

Scientific Investigations Report 2013–5155

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

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2013

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment, visit http://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod

To order this and other USGS information products, visit http://store.usgs.gov

Suggested citation:
Bent, G.C., and Waite, A.M., 2013, Equations for estimating bankfull channel geometry and discharge for streams in Massachusetts: U.S. Geological Survey Scientific Investigations Report 2013–5155, 62 p., *http://dx.doi.org/10.3133/sir20135155*.

ISSN 2328-031X (print)
ISSN 2328-0328 (online)
ISBN 978-1-4113-3693-3

Acknowledgments

The authors thank Barry Baldigo and Jeff Chaplin of the U.S. Geological Survey (USGS) for valuable input and training on field methods in bankfull studies. The authors also thank Pete Cinotto, USGS, for use of a spreadsheet developed for bankfull data entry and calculations; Thomas Garday and Dennis Verdi of the U.S. Department of Agriculture, Natural Resources Conservation Service, for sharing data collected for bankfull assessments at two USGS streamgages in Massachusetts; and Mickey Marcus, New England Environmental, Inc., Amherst, Massachusetts, for hosting a bankfull workshop in Amherst, Mass., during May 2004. Special thanks and appreciation go to Heidi Davis, Massachusetts Department of Environmental Protection, for field assistance.

THIS PAGE INTENTIONALLY LEFT BLANK

Contents

Figures

Tables

Conversion Factors, Datum, and Abbreviations

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations

GIS	Geographic Information Systems
MAGIC	University of Connecticut Map and Geography Information Center
MassGIS	Massachusetts Office of Geographic Information
MDEP	Massachusetts Department of Environmental Protection
NED	National Elevation Dataset
NHD	National Hydrography Dataset
NH GANIT	New Hampshire Geographical Information System
NYSGIS	New York State Geographical Information System
RIGIS	Rhode Island Geographic Information System
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
VCGI	Vermont Center for Geographic Information

THIS PAGE INTENTIONALLY LEFT BLANK

Equations for Estimating Bankfull Channel Geometry and Discharge for Streams in Massachusetts

By Gardner C. Bent and Andrew M. Waite

Abstract

Regression equations were developed for estimating bankfull geometry—width, mean depth, cross-sectional area—and discharge for streams in Massachusetts. The equations provide water-resource and conservation managers with methods for estimating bankfull characteristics at specific stream sites in Massachusetts. This information can be used for the adminstration of the Commonwealth of Massachusetts Rivers Protection Act of 1996, which establishes a protected riverfront area extending from the mean annual high-water line corresponding to the elevation of bankfull discharge along each side of a perennial stream. Additionally, information on bankfull channel geometry and discharge are important to Federal, State, and local government agencies and private organizations involved in stream assessment and restoration projects.

Regression equations are based on data from stream surveys at 33 sites (32 streamgages and 1 crest-stage gage operated by the U.S. Geological Survey) in and near Massachusetts. Drainage areas of the 33 sites ranged from 0.60 to 329 square miles (mi^2). At 27 of the 33 sites, field data were collected and analyses were done to determine bankfull channel geometry and discharge as part of the present study. For 6 of the 33 sites, data on bankfull channel geometry and discharge were compiled from other studies done by the U.S. Geological Survey, Natural Resources Conservation Service of the U.S. Department of Agriculture, and the Vermont Department of Environmental Conservation. Similar techniques were used for field data collection and analysis for bankfull channel geometry and discharge at all 33 sites. Recurrence intervals of the bankfull discharge, which represent the frequency with which a stream fills its channel, averaged 1.53 years (median value 1.34 years) at the 33 sites. Simple regression equations were developed for bankfull width, mean depth, cross-sectional area, and discharge using drainage area, which is the most significant explanatory variable in estimating these bankfull characteristics. The use of drainage area as an explanatory variable is also the most commonly published method for estimating these bankfull characteristics. Regional curves (graphic plots) of bankfull channel geometry and discharge by drainage area are presented. The regional curves are based on the simple regression equations and can be used to estimate bankfull characteristics from drainage area. Multiple regression analysis, which includes basin characteristics in addition to drainage area, also was used to develop equations. Variability in bankfull width, mean depth, cross-sectional area, and discharge was more fully explained by the multiple regression equations that include mean-basin slope and drainage area than was explained by equations based on drainage area alone. The Massachusetts regional curves and equations developed in this study are similar, in terms of values of slopes and intercepts, to those developed for other parts of the northeastern United States.

Limitations associated with site selection and development of the equations resulted in some constraints for the application of equations and regional curves presented in this report. The curves and equations are applicable to stream sites that have (1) less than about 25 percent of their drainage basin area occupied by urban land use (commercial, industrial, transportation, and high-density residential), (2) little to no streamflow regulation, especially from flood-control structures, (3) drainage basin areas greater than 0.60 mi^2 and less than 329 mi^2, and (4) a mean basin slope greater than 2.2 percent and less than 23.9 percent. The equations may not be applicable where streams flow through extensive wetlands. The equations also may not apply in areas of Cape Cod and the Islands and the area of southeastern Massachusetts close to Cape Cod with extensive areas of coarse-grained glacial deposits where none of the study sites are located. Regardless of the setting, the regression equations are not intended for use as the sole method of estimating bankfull characteristics; however, they may supplement field identification of the bankfull channel when used in conjunction with field verified bankfull indicators, flood-frequency analysis, or other supporting evidence.

Introduction

Information about the channel geometry and discharge of streams under bankfull conditions is important for many hydrologic applications. Bankfull discharge is the streamflow that occurs when the stream fills its channel and any additional discharge will result in the stream overflowing its banks.

Bankfull geometry (width, cross-sectional area, mean depth) defines the physical extent of the stream when the stream is bankfull. The geometry of a stream and the location of the water's edge at bankfull conditions are fundamental measures of the size and location of the stream.

Information about bankfull channel geometry is important for the application of the Commonwealth of Massachusetts Rivers Protection Act of 1996–310 Code of Massachusetts Regulations (CMR) 10.00–Section 10.58 (The Commonwealth of Massachusetts, 2009). This Act specifies that riverfront areas of all perennial streams be protected, where the riverfront area is defined as a 200-foot-wide strip (25-foot-wide strip in selected densely developed areas) of land on each side of a stream that starts at the mean annual high-water line of perennial streams. The Act states that the mean annual high-water line is best represented by bankfull field indicators, such as change in slope, changes in vegetation, stain lines, top of point bars, changes in bank material, or bank undercuts along streambanks that correspond to the elevation of the water surface of the stream when the stream fills its banks and establishes the bankfull stream width. Town and city conservation commissions and the Massachusetts Department of Environmental Protection (MDEP) are charged with enforcing the Riverfront Protection Act by regulating work in the riverfront areas and, thus, must be able to accurately determine the bankfull stream width of perennial streams.

In Massachusetts, bankfull data are being used in the design of bridges and culverts for stream crossings, such that they can accommodate fish and wildlife passage and avoid adverse effects on ecological systems (Massachusetts Department of Transportation, 2010; Massachusetts Executive Office of Energy and Environmental Affairs, 2012). State and Federal regulations required that the new and replacement structures span the stream channel width by a minimum of 1.2 times the bankfull width. The River and Stream Continuity Partnership (2011) developed revised river and stream crossing standards for Massachusetts using the same standard of 1.2 times the bankfull width. Additionally, the U.S. Army Corps of Engineers–New England District is using these same river and stream crossing standards for its State General Permit (http://www.nae.usace.army.mil/Regulatory/SGP/ma.htm) in Massachusetts.

Information about bankfull channel geometry and discharge is important to Federal, State, and local governments and private organizations involved in stream assessment and restoration projects. Stream-restoration projects during the last two decades have focused on using a natural-channel design approach that depends on estimates of natural bankfull channel geometry and discharge rather than traditional engineering practices that may involve straightening, widening, deepening, or hardening banks and channels.

Bankfull channel geometry and discharge are commonly estimated using equations and graphical plots that relate bankfull width, mean depth, cross-sectional area, and discharge to drainage area; the graphical plots are referred to as "regional curves." In Massachusetts and throughout the eastern United States where sub-regional or statewide regional curves are not available, regional curves published by Dunne and Leopold (1978) are used by Federal, State, and local governments and private organizations to estimate bankfull geometry and discharge. Though widely used, the curves developed by Dunne and Leopold (1978) for the eastern United States were developed from sites of unknown locations (Emmett, 2004), and the accuracy of these curves when applied to streams in Massachusetts is unknown. Moreover, regional curves such as these are based on simple regression equations and use one explanatory variable, drainage area, to estimate the response variables of bankfull width, mean depth, cross-sectional area, and bankfull discharge. However, much variability is present in relations between drainage area and bankfull geometry and discharge. These simple regression equations for bankfull channel geometry and discharge cannot account for the variance that may result from other factors such as basin slope, basin elevation, surficial geology, soil type, the presence of water bodies and wetlands, and land use in the basin. These factors could be incorporated in multiple regression equations that could provide better estimates of bankfull geometry and discharge than the commonly used regional curves. Improved methods of estimating bankfull geometry and discharge are needed to support implementation of the Riverfront Protection Act of 1996 and other hydrologic applications in Massachusetts than are currently available with the generalized regional curves for the eastern United States or other field-based approaches. To address this need, the U.S. Geological Survey (USGS), in cooperation with the MDEP, Bureau of Resource Protection, Wetlands and Waterways Program and Massachusetts Environmental Trust, conducted a study to develop equations for estimating bankfull geometry and discharge from data collected at stream sites in and near Massachusetts, using simple and multiple regression techniques.

Purpose and Scope

This report describes the methods used, data collected, and equations developed for estimating bankfull channel geometry and discharge for streams in Massachusetts. As a part of this study, bankfull channel geometry data were collected and analyzed for 27 sites—20 streams in Massachusetts, 3 streams in northern Connecticut, 2 streams in southern New Hampshire, and 2 streams in northern Rhode Island—during July through December 2004. Bankfull channel geometry and discharge data for six other streams in or near Massachusetts collected as part of other studies were also used in the development of equations. The six additional sites include two in Massachusetts, three in New York, and one in Vermont. The simple regression equations were developed by relating bankfull width, mean depth, cross-sectional area, and discharge to drainage area at these 33 sites in and near Massachusetts. Multiple regression with additional basin characteristics also was used to develop equations. The simple regression equations developed for Massachusetts are compared to equations developed for other areas in the eastern United States and southeastern Canada. Limitations of the regional curves, methods used in data collection, and estimation of the bankfull discharge are discussed.

Description of Study Area

The bankfull geometry and discharge at a stream location can be greatly affected by the geography, climate, and surficial geology upstream from that location. In Massachusetts, these factors, particularly the extent and type of surficial deposits, could affect stream channel and flow characteristics.

Massachusetts encompasses 8,093 square miles (mi^2) in the northeastern United States (fig. 1). Elevations range from sea level in coastal areas to about 3,500 feet (ft) above sea level (NAVD 88) in the northwest. Elevations generally increase from eastern to western Massachusetts. The climate in Massachusetts is humid with average annual precipitation ranging from about 40 to 45 inches (in.) in eastern Massachusetts to about 40 to 50 in. in western Massachusetts, where higher elevations may cause orographic effects. Average annual temperature is about 50 degrees Fahrenheit (˚F) in eastern Massachusetts and about 45 ˚F in western Massachusetts.

Surficial deposits that overlie bedrock in most of Massachusetts were deposited mainly during the last glacial period but can include areas of recent floodplain alluvium deposits. In this report, these surficial deposits are classified as either till (which includes till, till with bedrock outcrops, sandy till over sand, and end-moraine deposits) or stratified deposits (which include sand and gravel, coarse sand, fine-grained sand, and floodplain alluvium deposits). Till (also known as ground moraine) is an unsorted, unstratified mixture of clay, silt, sand, gravel, cobbles, and boulders, typically deposited by glaciers on top of bedrock throughout much of the State. Till is primarily found in upland areas but can also be found at depth in river valleys. Stratified deposits include sorted and layered glaciofluvial and glaciolacustrine deposits. Glaciofluvial deposits are material of all grain sizes (clay, silt, sand, gravel, and cobbles) deposited by glacial meltwater streams in outwash plains and river valleys. Glaciolacustrine deposits generally consist of clay, silt, and fine sand deposited in temporary lakes that formed after the retreat of the glacial ice sheet. Stratified deposits are more widespread in eastern Massachusetts than in western Massachusetts. In eastern Massachusetts, stratified deposits can be extensive outwash plains, particularly in the southeast. In other areas of the State, stratified deposits are more likely to be found in river valleys.

On Cape Cod and the Islands and the area of southeastern Massachusetts close to Cape Cod, the surficial geology is almost entirely stratified deposits (Simcox, 1992, p. 47, 51, and 52) (area labeled as U.S. Environmental Protection Agency (USEPA) Level III ecoregion–Atlantic Coastal Pine Barrens in fig. 2). In these areas, precipitation mainly percolates into the soil and through the unsaturated zone to the groundwater table (reducing surface runoff) and later discharges to the stream as base flow. Thus, runoff peaks can be greatly diminished in magnitude, which may also affect the streamflows that form bankfull channel discharges.

The geomorphic and hydrologic variability associated with different physiographic provinces can be an important factor in determining bankfull characteristics. Denny (1982) identifies seven physiographic provinces within the study area. From eastern to western Massachusetts, the physiographic provinces are the Coastal Plain, Coastal Lowlands, Central Highlands, Connecticut Valley, Hudson-Green-Notre Dame Highlands, Vermont Valley, and the Taconic Highlands (fig. 2). Additionally, the USEPA has divided the United States into ecological regions (U.S. Environmental Protection Agency, 2006). These regions are based on ecosystems that generally are similar and have been identified through the analysis of the patterns and the composition of biotic and abiotic features. These features include geology, physiography, vegetation, climate, soils, land use, wildlife, and hydrology. The study area includes four Level III ecoregions (U.S. Environmental Protection Agency, 2006). From eastern to western Massachusetts, the USEPA Level III ecoregions are Atlantic Coastal Pine Barrens, Northeastern Coastal Zone, Northeastern Highlands, and Eastern Great Lakes and Hudson Lowlands (fig. 2).

Methods of Data Collection and Analysis

The methods used for site selection, data collection for bankfull channel geometry, and data analysis to determine bankfull discharge and recurrence interval are similar to those used in other studies of bankfull characteristics of streams in the eastern United States. As in the other studies, the data collection and analyses were based on surveys done at USGS streamgages and associated stream reaches using methods outlined by Leopold (1994) and Rosgen (1994, 1996). Field data were collected between July and December 2004. The methods described in this section were used at the 27 sites for which data were collected and analyzed as part of the current study, unless otherwise indicated. Methods of data collection and analysis for the six additional sites are similar and are described in other reports. Methods for the two sites in Massachusetts are described by the U.S. Department of Agriculture, Natural Resources Conservation Service (Thomas Garday, U.S. Department of Agriculture, written commun., 2005). The three sites in eastern New York studied by the USGS are described in Mulvihill and Baldigo (2007). The one site in Vermont is described in Jaquith and Kline (2006) for the Vermont Department of Environmental Conservation, Water Quality Division, River Management Program.

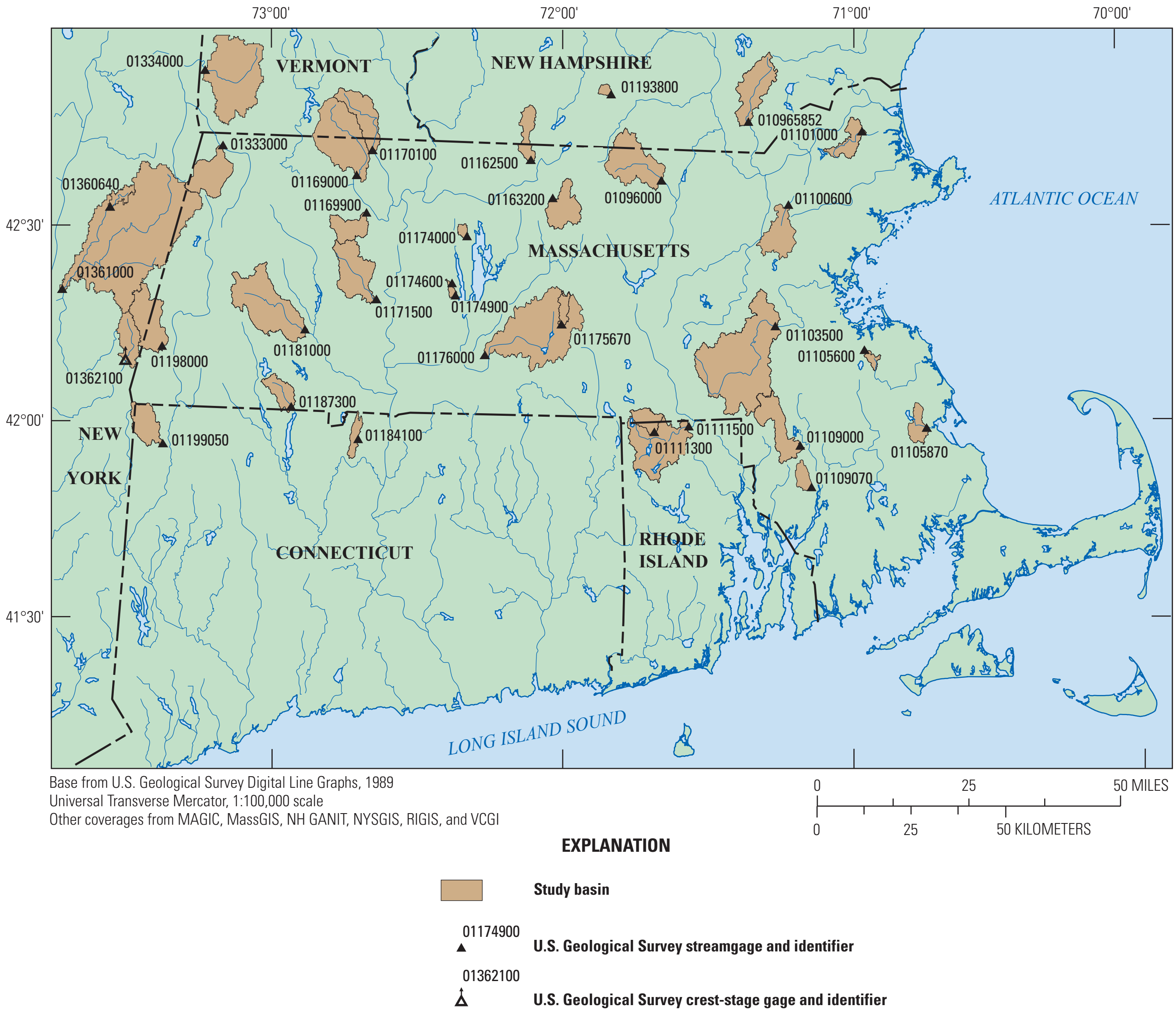
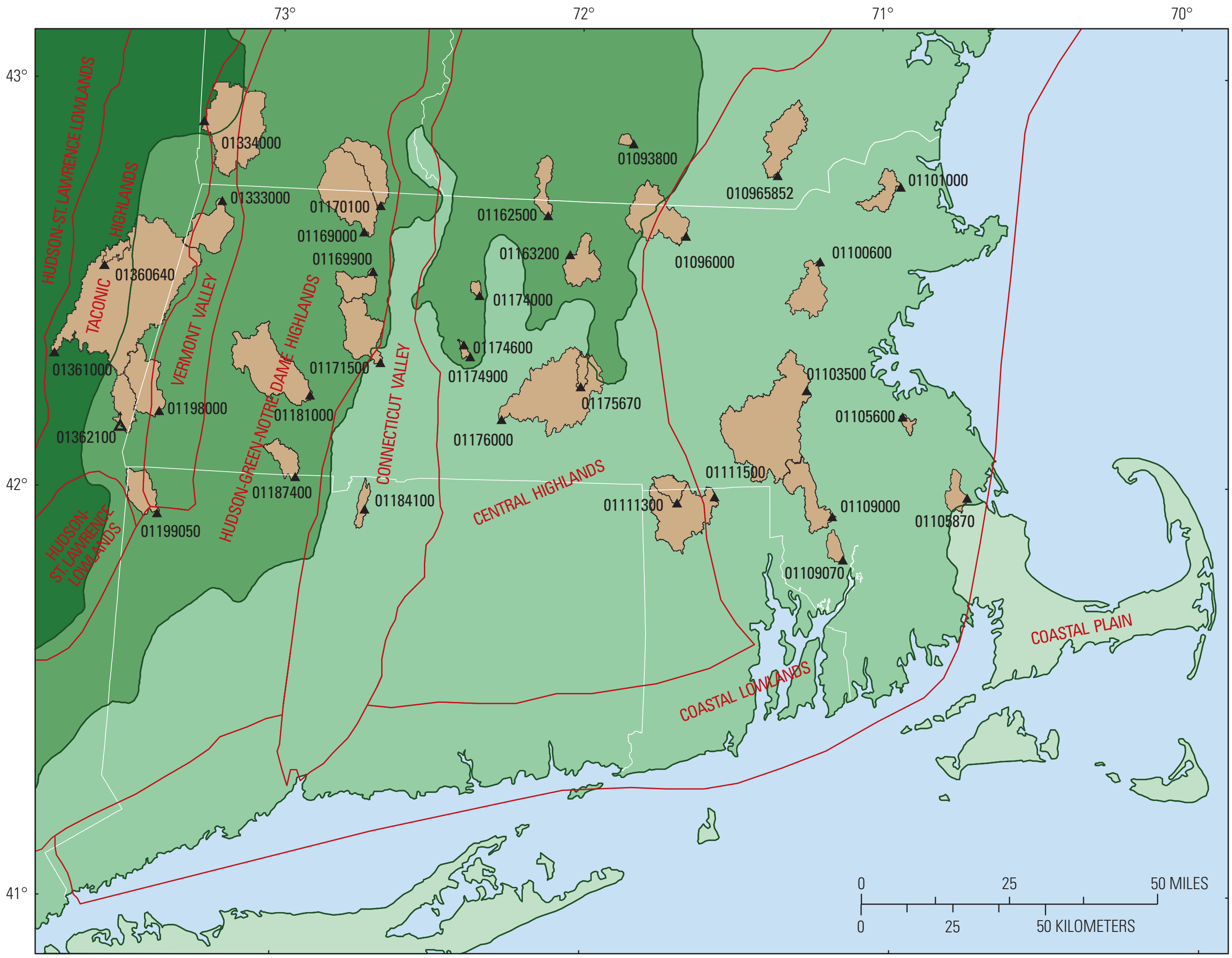


Figure 1. Location of U.S. Geological Survey streamgage and crest-stage gage study sites used in the development of bankfull channel geometry and discharge equations for streams in and near Massachusetts.



Base from U.S. Geological Survey Digital Line Graphs, 1989
Universal Transverse Mercator, 1:100,000 scale
Other coverages from MAGIC, MassGIS, NH GANIT, NYSGIS, RIGIS, and VCGI

Modified from Denny, 1992

EXPLANATION

Level III ecoregions (U.S. Environmental Portection Agency, 2006)
- Eastern Great Lakes and Hudson Lowlands
- Northeastern Highlands
- Northeastern Coastal Zone
- Atlantic Coastal Pine Barrens

Study basin

Physiographic province boundary (Denny, 1982)

01109070 **U.S. Geological Survey streamgage and identifier**

01362100 **U.S. Geological Survey crest-stage gage and identifier**

Figure 2. Locations of the physiographic provinces and U.S. Environmental Protection Agency Level III ecoregions in and near Massachusetts.

Site Selection

The stream sites that were used in this study met a number of general selection criteria that are similar to the criteria used in other bankfull studies in the eastern United States. These criteria are

1. the site is at a continuous or recently discontinued USGS streamgage or crest-stage gage in or near Massachusetts;
2. the streamgage or crest-stage gage at the site has a minimum of 10 years of streamflow record;
3. streamflow at the site is relatively naturally flowing with little to no high-flow regulation by dams, diversions, or other features;
4. the drainage area contains less than 25 percent urban land use, where urban land use includes commercial, industrial, transportation, and high-density residential (MassGIS, 2009);
5. the site is wadeable for surveying; and
6. identifiable bankfull indicators are present.

Additionally, sites with differing drainage areas were included to develop equations that would be applicable throughout the State.

All current and discontinuous streamgages in and near Massachusetts with data in the USGS National Water Information System (NWIS) were reviewed in terms of these selection criteria. Twenty-seven streamgages were identified in NWIS that met the criteria (table 1 and fig. 1).

As a guide to field investigations and for comparison with field observations, the stream stages of peak discharges with recurrence intervals of 1 to 10 years were estimated from discharge data at the streamgage associated with each site (table 2). Previous studies have shown that bankfull conditions are associated with peak discharges that recur, on average, every 1.5 years (Dunne and Leopold, 1978; Harrelson and others, 1994; Rogen, 1996). The stages associated with the 1- to 2-year recurrence interval peak discharges were used in the field to help identify the general areas along streambanks to be examined for bankfull indicators. Recurrence intervals of annual peak discharges were calculated using a Log-Pearson Type III analysis following procedures outlined by the Interagency Advisory Committee on Water Data (1982) for the associated streamgage at each site for the period of record. The estimated peak discharges for the 1- to 2-year recurrence intervals then were used with the 2004 water year[1] stage-discharge rating curve for active streamgages to determine the corresponding stream stage of these peak discharges; the most recent stage-discharge rating curve available for the time period when the streamgage was in operation was used for discontinued streamgages. In the field, the elevations on the streambank of water levels (stage) that would be associated with these peak discharges were determined using the difference between the elevation (stage) of water surface at the time of the field survey and the peak discharge stage values. Generally field bankfull indicators were found to fall within the range of elevations (stage) associated with the 1- to 2-year recurrence interval peak discharges at each site. In all cases, however, the best field bankfull indictor was used, even if it was above or below the range of elevations (stage) estimated from peak discharges.

Bankfull Stage Indicators

Bankfull stage is the elevation of the streamwater surface when the stream fills its channel; it can be recognized in the field by a number of physical indicators and characteristics along the stream's banks. Identification of bankfull-stage indicators (henceforth "bankfull indicators") generally followed procedures discussed in Harrelson and others (1994), Leopold (1994), U.S. Department of Agriculture, Forest Service (1995, 2003, and 2004), Rosgen (1996), and Powell and others (2004). For this study the emphasis was on the following bankfull indicators in this order: (1) the active floodplain (a flat depositional surface adjacent to the stream channel) where the stream overtops its banks, (2) depositional features (such as point bars), (3) changes in the bank slope, (4) changes in the particle size of bank material, (5) undercuts or scour lines in the bank, and (6) changes in vegetation on the bank (for example, an area with no trees, transitioning to an area with trees). The most common feature used for the identification of the bankfull stage was the active floodplain where the stream overtopped its banks.

Bankfull Channel Geometry

The procedures for determining bankfull channel-geometry characteristics generally followed the methodologies presented in a number of widely used publications. Bankfull-stage indicators were identified at 14 to 25 locations (averaged 20 locations) along the stream channel, separated by a distance equivalent to approximately one bankfull width, at each of the 27 sites. The latitude and longitude of the most upstream location and the most downstream location at each of the 27 sites are presented in appendix 1. The total length of stream surveyed at each site averaged about 1,384 feet (ft) (range 552–2,661 ft). At the 14 to 25 locations at each site, the bankfull indicators were flagged on the left and right stream banks (looking downstream). The best indicators (right and left banks) were identified, and any other likely indicators at higher or lower elevations were also identified. The type of bankfull indicator generally was noted, and generally, a relative rating of good, fair, or poor was noted.

[1]A water year is the 12-month period beginning October 1 and ending September 30. It is designated by the calendar year in which it ends.

The elevations of bankfull indicators, the water surface, and the stream thalweg were determined relative to the established datum at the streamgage at each site using standard surveying techniques (Harrelson and others, 1994; Leopold, 1994; U.S. Department of Agriculture, 1995, 2003, and 2004; Rosgen, 1996; and Powell and others, 2004). The accuracy of the elevation points surveyed was recorded to the nearest 0.01 ft, and all loops within the survey closed within 0.02 ft of the starting elevations. The horizontal distances between the locations were measured, generally along the thalweg of the stream.

Detailed cross sections to define bankfull channel geometry (width, mean depth, and cross-sectional area) were surveyed at two of the locations where bankfull indicators were flagged at each site. These detailed cross-sectional surveys were made at riffle sections at the two locations that were most representative of the bankfull channel geometry of the entire stream reach. The detailed cross-sectional survey consisted of 20 to 25 points in a section across the stream at which the elevation of the stream channel bottom and streambanks were determined; points along the cross sections were more closely spaced where changes in the elevation of the stream channel bottom and streambanks were greatest. Additional data on streambed materials were collected at the two riffle locations, using methods described by Wolman (1954) (appendix 2). The data included measurements of the intermediate particle-size diameter at 50 locations across each of the two cross sections.

The elevations of the bankfull indicators, water surface, and thalweg and the distance along the stream reach were entered into a Microsoft EXCEL spreadsheet template developed for bankfull stream reach surveys (Peter Cinotto, U.S. Geological Survey, written commun., 2004). The spreadsheet plotted a profile of the bankfull indicators, water surface, and thalweg of the stream reach and the surveyed cross section at the two selected riffle locations. The spreadsheet calculated the bankfull and water-surface slopes. The spreadsheet also calculated bankfull width, mean depth, cross-sectional area, and the particle-size distribution of the streambed material at the two detailed cross sections.

Bankfull Discharge

Bankfull discharge for each of the 27 sites was calculated using the elevations of bankfull indicators at locations that were in the gage pool of the streamgage. This method was the primary method of calculating bankfull discharge for the present study, and the values of bankfull discharge calculated in this way were used to develop the equations. The gage pool is the area of the stream reach in which the stream stage is recorded and for which the existing stage-discharge relation (rating curve) is determined. Only locations within the gage pool could be used because the elevations needed to be related to the elevation of the water surface in the gage pool in order to use the stage-discharge relation developed for the streamgage to calculate bankfull discharge. In most cases, only one of the locations where bankfull indicators were flagged along the stream reach at each site was located in the gage pool. In those cases, the elevations of the bankfull indicators from the right and left banks were averaged to determine the bankfull elevation at the streamgage. In cases where more than one location was in the gage pool, the elevations of the bankfull indicators from right and left banks for all those locations were averaged. The bankfull stage then was used with the stage-discharge rating curve that was applicable when the data were collected (water year 2004) for that streamgage to estimate the bankfull discharge. For discontinuous streamgages, the most recent stage-discharge rating curve that was available for the time period when the streamgage was operating was used.

The recurrence interval of the bankfull discharge at each of the 33 sites was determined from an analysis of the annual instantaneous peak discharges for the period of record through water year 2009 at each site. The Log-Pearson Type III method (Interagency Advisory Committee on Water Data, 1982) was used to determine flood frequency (recurrence interval of specific flood discharges) from the streamflow record. The number of water years of record analyzed for the 33 sites ranged from 19 to 97 with an average of about 54 years and a median of 49 years (table 2). A minimum of 10 years of record is typically used for a peak-flow analysis. The recurrence intervals of bankfull discharges were taken as equal to the recurrence interval of the equivalent annual instantaneous peak discharge (table 2). For those sites with bankfull discharges between recurrence intervals of the computed peak discharges in table 2, the bankfull discharge recurrence intervals were estimated by interpolation.

Bankfull discharge was also estimated for each of the 27 sites using two alternative methods that use data collected at the two riffle locations at each site where detailed cross sections were surveyed. These methods were considered check methods of the primary method of estimating bankfull discharge, which was done using the elevation of bankfull indicators in the gage pool of each site and the corresponding stage-discharge rating curve. Detailed data used in the two alternative check methods are provided in appendix 2.

The first alternative check method, which is the more common method, uses the Manning's equation.

$$Q = \frac{1.49}{n} A R^{\frac{2}{3}} S^{\frac{1}{2}}, \tag{1}$$

where

- Q = discharge, in cubic feet per second;
- n = Manning's roughness coefficient;
- A = cross-sectional area of channel, in square feet;
- R = hydraulic radius, in feet; and
- S = energy gradient or friction slope, in feet per foot.

Table 1. Description of U.S. Geological Survey streamgage and crest-stage gage study sites used in development of bankfull channel geometry and discharge equations for streams in and near Massachusetts.

[USGS station no.: Streamgages shown in figure 1. USGS, U.S. Geological Survey; no., number; mi^2, square miles; CT, Connecticut; MA, Massachusetts; NH, New Hampshire; NY, New York; RI, Rhode Island; VT, Vermont; °, degrees; ′, minutes; ″, seconds; p, present; --, none; CSG, crest-stage gage]

USGS station no.	Station name	Station latitude	Station longitude	Major river basin	Drain-age area (mi^2)	Period of record	Remarks
Data collected for this study							
01093800	Stony Brook Tributary near Temple, NH	42° 51′ 36″	71° 50′ 00″	Merrimack	3.6	1963–2004	--
01096000	Squannacook River near West Groton, MA	42° 38′ 03″	71° 39′ 30″	Nashua	63.7	1949–p	Occasional regulation at low flow by mill upstream; regulation greater prior to 1961.
010965852	Beaver Brook at North Pelham, NH	42° 46′ 58″	71° 21′ 15″	Merrimack	47.8	1986–p	Some regulation at low and medium flows.
01100600	Shawsheen River near Wilmington, MA	42° 34′ 05″	71° 12′ 55″	Shawsheen	36.5	1963–p	Diversions at times since 1973 for municipal supply.
01101000	Parker River at Byfield, MA	42° 45′ 10″	70° 56′ 46″	Parker	21.3	1945–p	Occasional regulation by mill and ponds.
01103500	Charles River at Dover, MA	42° 15′ 22″	71° 15′ 38″	Charles	183	1937–p	Flow affected by diversions to and from basin for municipal supply.
01105600	Old Swamp River near South Weymouth, MA	42° 11′ 25″	70° 56′ 43″	Boston Harbor	4.5	1966–p	--
01105870	Jones River at Kingston, MA	41° 59′ 27″	70° 44′ 03″	South Coastal	15.7	1966–p	Flow regulated by pond upstream.
01109000	Wading River near Norton, MA	41° 56′ 51″	71° 10′ 38″	Taunton	43.3	1925–p	Flow regulated to some extent by lakes and reservoirs and diversions to and from basin for municipal supplies.
01109070	Segreganset River near Dighton, MA	41° 50′ 25″	71° 08′ 36″	Taunton	10.6	1966–p	Occasional regulation by ponds and diversion for municipal supply.
01111300	Nipmuc River near Harrisville, RI	41° 58′ 52″	71° 41′ 11″	Blackstone	16.0	1964–1991, 1993–p	--
01111500	Branch River at Forestdale, RI	41° 59′ 47″	71° 33′ 47″	Blackstone	91.2	1909–1913, 1940–p	Occasional regulation by pond, and prior to 1957 greater regulation by mills and reservoirs.
01162500	Priest Brook near Winchendon, MA	42° 40′ 57″	72° 06′ 56″	Millers	19.4	1916–p	Prior to 1962, occasional diurnal fluctuation at low flow by mill.
01163200	Otter River at Otter River, MA	42° 35′ 18″	72° 02′ 29″	Millers	34.1	1964–p	--
01169000	North River at Shattuckville, MA	42° 38′ 18″	72° 43′ 32″	Deerfield	89.0	1939–p	Diurnal fluctuation at times caused by mill.
01169900	South River near Conway, MA	42° 32′ 31″	72° 41′ 39″	Deerfield	24.1	1966–p	Diurnal fluctuation by small powerplant since April 1982.
01170100	Green River near Colrain, MA	42° 42′ 12″	72° 40′ 16″	Deerfield	41.4	1967–p	--
01171500	Mill River at Northampton, MA	42° 19′ 05″	72° 39′ 21″	Connecticut	52.6	1938–p	Flow regulated by mill.

Table 1. Description of U.S. Geological Survey streamgage and crest-stage gage study sites used in development of bankfull channel geometry and discharge equations for streams in and near Massachusetts.—Continued

[USGS station no.: Streamgages shown in figure 1. USGS, U.S. Geological Survey; no., number; mi^2, square miles; CT, Connecticut; MA, Massachusetts; NH, New Hampshire; NY, New York; RI, Rhode Island; VT, Vermont; °, degrees; ′, minutes; ″, seconds; p, present; --, none; CSG, crest-stage gage]

USGS station no.	Station name	Station latitude	Station longitude	Major river basin	Drainage area (mi^2)	Period of record	Remarks
			Data collected for this study—Continued				
01174900	Cadwell Creek near Belchertown, MA	42° 20′ 08″	72° 22′ 12″	Chicopee	2.55	1961–1997	--
01175670	Sevenmile River near Spencer, MA	42° 15′ 54″	72° 00′ 19″	Chicopee	8.81	1960–p	Occasional regulation by ponds since 1971.
01176000	Quaboag River at West Brimfield, MA	42° 10′ 56″	72° 15′ 51″	Chicopee	150	1912–p	Slight diurnal fluctuation at low flow caused by mill prior to 1956; regulation much greater prior to 1938.
01181000	West Branch Westfield River at Huntington, MA	42° 14′ 14″	72° 53′ 46″	Westfield	94.0	1935–p	Prior to 1950, some diurnal fluctuation at low flow caused by mill.
01184100	Stony Brook near West Suffield, CT	41° 57′ 38″	72° 42′ 39″	Connecticut	10.4	1960–1981 (CSG), 1981–p	--
01187300	Hubbard Brook near West Hartland, CT	42° 02′ 14″	72° 56′ 22″	Connecticut	19.9	1938–55, 1956–p	--
01198000	Green River near Great Barrington, MA	42° 11′ 31″	73° 23′ 28″	Housatonic	51.0	1951–1971, 1994–1996, and 2007–p	--
01199050	Salmon Creek at Lime Rock, CT	41° 56′ 32″	73° 23′ 29″	Housatonic	29.4	1961–p	--
01333000	Green River at Williamstown, MA	42° 42′ 32″	73° 11′ 50″	Hudson	42.6	1949–p	Slight diurnal fluctuation at times caused by mill.
			Data collected for other studies				
[1]01174000	Hop Brook near New Salem, MA	42° 28′ 42″	72° 20′ 05″	Chicopee	3.39	1947–82	--
[1]01174600	Cadwell Creek near Pelham, MA	42° 21′ 16″	72° 23′ 18″	Chicopee	0.60	1961–94	--
[2]01334000	Walloomsac River near North Bennington, VT	42° 54′ 46″	73° 15′ 25″	Hudson	111	1931–p	Occasional diurnal fluctuation at low flow caused by mills upstream; diurnal fluctuation greater prior to 1960.
[3]01360640	Valatie Kill near Nassau, NY	42° 33′ 07″	73° 35′ 31″	Hudson	9.48	1990–p	--
[3]01361000	Kinderhook Creek at Rossman, NY	42° 19′ 50″	73° 44′ 40″	Hudson	329	1906–15, 1928, 1984, and 1988–p (CSG); and 1929–68	--
[3]01362100	Roeliff Jansen Kill near Hillsdale, NY	42° 09′ 14″	73° 31′ 14″	Hudson	27.5	1957–59 and 1960–p (CSG)	--

[1]Data from Thomas Garday, U.S. Department of Agriculture, Natural Resources Conservation Service, written commun., 2005.

[2]Data from Jaquith and Kline, 2006.

[3]Date from Mulvihill and Baldigo, 2007.

Table 2. Estimated peak discharge for the 1.01, 1.05, 1.11, 1.25, 1.5, 2, 2.33, 5, and 10-year recurrence intervals for the study sites used in development of bankfull channel geometry and discharge equations for streams in and near Massachusetts.

[USGS station no.: Streamgages shown in figure 1 and described in table 1. USGS, U.S. Geological Survey; no., number; mi², square mile; ft³/s, cubic foot per second; CT, Connecticut; MA, Massachusetts; NH, New Hampshire; NY, New York; RI, Rhode Island; VT, Vermont; --, no data]

USGS station no.	Station name	Drainage area (mi²)	Water years analyzed	Number of water years analyzed	Recurrence intervals (years)									
					1.005	1.01	1.05	1.11	1.25	1.50	2	2.33	5	10
					Peak discharge (ft³/s)									
01093800	Stony Brook Tributary near Temple, NH	3.6	1964–2004	41	54	60	81	96	120	148	188	208	308	407
01096000	Squannacook River near West Groton, MA	63.7	1950–2009	60	343	394	574	703	900	1,136	1,452	1,608	2,357	3,044
010965852	Beaver Brook at North Pelham, NH	47.8	1987–2009	23	222	246	332	396	496	620	796	887	1,357	1,838
01100600	Shawsheen River near Wilmington, MA	36.5	1964–2009	46	175	193	258	304	374	459	574	632	917	1,191
01101000	Parker River at Byfield, MA	21.3	1946–2009	64	70	76	98	115	140	171	215	237	352	469
01103500	Charles River at Dover, MA	183	1938–2009	72	511	550	682	772	903	1,056	1,254	1,350	1,803	2,212
01105600	Old Swamp River near South Weymouth, MA	4.5	1967–2009	43	41	48	71	87	113	145	188	210	317	419
01105870	Jones River at Kingston, MA	15.7	1967–2009	43	78	86	110	126	149	175	207	223	293	353
01109000	Wading River near Norton, MA	43.3	1926–2009	84	175	191	245	281	335	397	478	517	700	864
01109070	Segreganset River near Dighton, MA	10.6	1967–2009	43	--	--	186	214	255	301	360	388	518	632
01111300	Nipmuc River near Harrisville, RI	16	1965–1991, 1994–2009	43	111	127	186	229	298	382	500	560	865	1,164
01111500	Branch River at Forestdale, RI	91.2	1940–2000	70	511	566	762	901	1,113	1,369	1,718	1,892	2,752	3,575
01162500	Priest Brook near Winchendon, MA	19.4	1917, 1919–2009	92	120	130	164	189	228	277	346	381	566	757
01163200	Otter River at Otter River, MA	34.1	1965–2009	45	--	--	258	291	337	389	456	487	630	753
01169000	North River at Shattuckville, MA	89	1940–2009	70	1,376	1,538	2,111	2,517	3,139	3,885	4,895	5,399	7,866	10,200
01169900	South River near Conway, MA	24.1	1967–2009	43	650	704	900	1,042	1,266	1,545	1,937	2,139	3,185	4,258
01170100	Green River near Colrain, MA	41.4	1968–2009	42	--	--	1,395	1,568	1,816	2,095	2,450	2,619	3,388	4,055
01171500	Mill River at Northampton, MA	52.6	1939–2009	71	--	--	1,000	1,201	1,496	1,831	2,259	2,462	3,377	4,151
01174900	Cadwell Creek near Belchertown, MA	2.55	1962–1997	36	35	39	54	65	80	97	119	129	178	219
01175670	Sevenmile River near Spencer, MA	8.81	1961–2009	49	--	--	82	97	119	146	182	200	287	370
01176000	Quaboag River at West Brimfield, MA	150	1913–2009	97	624	640	711	768	865	994	1,185	1,287	1,848	2,469
01181000	West Branch Westfield River at Huntington, MA	94	1936–2009	74	1,280	1,436	2,016	2,449	3,145	4,026	5,296	5,959	9,459	13,120
01184100	Stony Brook near West Suffield, CT	10.4	1960–2009	50	90	102	148	183	238	308	407	459	726	1,001
01187300	Hubbard Brook near West Hartland, CT	19.9	1938–55, 1957–2009	71	171	200	314	402	545	730	999	1,140	1,883	2,652
01198000	Green River near Great Barrington, MA	51.0	1952–71, 1994–1996, and 2008–09	25	--	--	645	742	899	1,102	1,398	1,556	2,413	3,355
01199050	Salmon Creek at Lime Rock, CT	29.4	1962–2009	48	150	170	242	296	380	483	628	702	1,076	1,446
01333000	Green River at Williamstown, MA	42.6	1950–2009	60	--	--	737	846	1,006	1,191	1,430	1,545	2,083	2,563
[1]01174000	Hop Brook near New Salem, MA	3.39	1948–82	35	--	--	73	86	104	125	151	163	217	261
[1]01174600	Cadwell Creek near Pelham, MA	0.60	1962–94	33	--	--	18	21	24	28	33	35	46	55
[2]01334000	Walloomsac River near North Bennington, VT	111	1932–2009	78	1,121	1,244	1,657	1,934	2,337	2,793	3,374	3,650	4,904	5,980
[3]01360640	Valatie Kill near Nassau, NY	9.48	1991–2009	19	135	153	214	255	316	384	471	512	698	854
[3]01361000	Kinderhook Creek at Rossman, NY	329	1909, 1928–68, and 1988–2009	64	2,110	2,274	2,870	3,305	3,989	4,839	6,038	6,656	9,863	13,160
[3]01362100	Roeliff Jansen Kill near Hillsdale, NY	27.5	1958–2009	52	--	--	359	430	536	661	826	906	1,287	1,631

[1]Study site from Thomas Garday, U.S. Department of Agriculture, Natural Resources Conservation Service, written commun., 2005.

[2]Study site from Jaquith and Kline, 2006.

[3]Study site from Mulvihill and Baldigo, 2007.

For this study, the variable S was approximated using the estimated water-surface slope at the riffle cross section. Jarrett (1984) reports that the use of the water-surface slope in place of the energy or friction slope, S, is a common practice. The water-surface slope was estimated using the slope of a best-fit line through the water-surface elevations at the surveyed location one bankfull width upstream from the riffle section, at the riffle section, and at the surveyed location one bankfull width downstream from the riffle section.

The Manning's roughness coefficient "n" was calculated using four equations developed by Limerinos (1970) using the d_{16}, d_{50}, d_{84}, and d_w of the streambed material. For this study, the particle-size distributions of the streambed material at the d_{16}, d_{50}, and d_{84} [intermediate particle diameter that equals or exceeds that of 16, 50, and 84 percent of the particle diameters, respectively, determined by methods described by Wolman (1954)] were determined from the 50-point pebble count of the intermediate particle-size diameter at each of the two riffle cross sections. The d_w (weighted particle-size distribution) was determined from the following equation that weights the d_{16}, d_{50}, and d_{84}.

$$d_w = \left(\left(0.1d_{16}\right) + \left(0.3d_{50}\right) + \left(0.6d_{84}\right)\right) \tag{2}$$

Manning's roughness coefficient "n" using the d_{16} was

$$\frac{0.0926\ \overline{}}{0.10 \quad 1.60 log \frac{}{16}}, \tag{3}$$

using the d_{50}, the equation was

$$n = \frac{0.0926R^{\frac{1}{6}}}{0.35 + 2.0 log \frac{R}{d_{50}}}, \tag{4}$$

using the d_{84}, the equation was

$$n = \frac{0.0926R^{\frac{1}{6}}}{1.16 + 2.0 log \frac{R}{d_{84}}}, \text{ and} \tag{5}$$

using the d_w, the equation was

$$n = \frac{0.0926R^{\frac{1}{6}}}{0.90 + 2.0 log \frac{R}{d_w}}, \tag{6}$$

where

n = Manning's roughness coefficient;
R = hydraulic radius, in feet;
d_{16} = 16th percentile particle diameter of bed material, in feet;
d_{50} = 50th percentile (median) particle diameter of bed material, in feet;
d_{84} = 84th percentile particle diameter of bed material, in feet; and
d_w = weighted particle diameter of bed material, in feet (see equation 2).

With a second alternative check method, bankfull discharge also was calculated using an equation developed by Jarrett (1984) for high-gradient streams.

$$Q = 3.8AR^{0.83}S^{0.12}, \tag{7}$$

where

Q = discharge, in cubic feet per second;
A = cross-sectional area of channel, in square feet;
R = hydraulic radius, in feet; and
S = energy gradient or friction slope, in feet per foot.

Jarrett (1986, p. 15) notes that S (the energy gradient or friction slope) is the slope of the energy line of a body of flowing water. Also, Jarrett (1986) states that, on the basis of data from 21 streams used to develop equation 7 (Jarrett, 1984), the friction slope and water-surface slope can be used interchangeably. The major limitation of the equation is that the water-surface slope of the stream channel must be between 0.002 to 0.04 ft/ft. Other limitations are discussed by Jarrett (1984) in greater detail.

Development of Equations for Estimating Bankfull Geometry and Discharge

The common method of estimating bankfull channel geometry and discharge is to relate bankfull width, mean depth, cross-sectional area, and discharge to drainage area through regression equations and graphic plots. The plots of the regression equations for bankfull channel geometry and discharge are commonly referred to as "regional curves." Regional curves are based on simple regression equations, which use one explanatory variable, drainage area, to estimate the response variables of bankfull width, mean depth, cross-sectional area, and bankfull discharge. Multiple regression equations have more than one explanatory variable, such as factors and basin characteristics other than drainage area, that may affect bankfull geometry and discharge.

Factors Affecting Bankfull Channel Geometry and Discharge

Drainage area of a basin is the main factor affecting bankfull channel geometry and discharge. However, physical, hydrologic, land-use, and climatic characteristics of a drainage basin can affect bankfull channel geometry and discharge. For example, bankfull studies in Pennsylvania (Chaplin, 2005) and Virginia (Keaton and others, 2005) found that the presence of carbonate bedrock was inversely related to values of bankfull discharge, width, mean depth, and cross-sectional area. Sherwood and Hutiger (2005) found that main-channel slope and elevation were related (positive and negative, respectively) to bankfull channel geometry and discharge. Anthropogenic factors, such as flood control dams or major diversions, also can affect bankfull channel geometry and discharge, but because the present study used naturally flowing streams with little to no peak-flow regulations, anthropogenic factors were not considered here.

Characteristics that could affect bankfull channel geometry and discharge were summarized by reviewing peak-flow studies in states in northeastern United States: Connecticut (Ahearn, 2004), Maine (Hodgkins, 1999), Massachusetts (Wandle, 1983; Murphy, 2001), New Hampshire (Olson, 2009), New York (Lumia and others, 2006), Rhode Island (Zarriello and others, 2012), and Vermont (Olson, 2002). All of these studies found drainage area to be a significant variable, along with characteristics of the basin such as areal percentage of lakes and ponds (Olson, 2002), areal percentage of wetlands (Hodgkins, 1999 and Olson, 2009), areal percentage of basin storage (lakes, ponds, and swamps) (Wandle, 1983; Lumia and others, 2006; and Zarriello and others, 2012), areal percentage of forest land (Lumia and others, 2006), main-channel slope (Wandle, 1983; Lumia and others, 2006; and Olson, 2009), ratio of main-channel slope to basin slope (Lumia and others, 2006), percent of a basin above a set elevation (Olson, 2002 and Lumia and others, 2006), mean basin elevation (Wandle, 1983; Ahearn, 2004), difference between the mean and minimum basin elevations (Murphy, 2001), basin lag factor (Lumia and others, 2006), drainage density (Zarriello and others, 2012), mean-annual runoff (Lumia and others, 2006), maximum snow depth (Lumia and others, 2006), mean annual precipitation (Lumia and others, 2006), mean April precipitation (Olson, 2009), and the recurrence interval associated with 24-hour rainfall amounts (Ahearn, 2004). Characteristics that were shown by these studies to have positive effects on peak flow are drainage area, main-channel slope, percent of a basin higher than a set elevation, mean basin elevation, mean annual precipitation, and the recurrence interval of 24-hour rainfall amounts. Characteristics shown to have negative effects on peak flows are basin storage, percentage of lakes and ponds, areal percentage of wetlands, percentage of forest land, average main-channel elevation, and basin shape.

Bankfull Channel Geometry and Discharge at Study Sites

Bankfull geometry (width, mean depth, and cross-sectional area) and discharge are presented in table 3 for the 27 sites at which data were collected as part of the present study and for the 6 sites for which data were compiled from other studies. Data from all 33 sites were used to develop the equations and regional curves.

Bankfull width, mean depth, and cross-sectional area were determined from the two surveyed cross sections at riffle locations at the 27 sites at which data were collected as part of this study; values from the two cross sections were averaged for use in developing the equations. Bankfull geometry for the 6 additional sites was determined as the average of values from 1 to 7 cross sections per site (table 3). Average values for all 33 sites used in developing equations ranged from 13.5 to 148 ft for bankfull width, 0.73 to 5.8 ft for bankfull mean depth, and 9.77 to 858.5 ft^2 for bankfull cross-sectional area.

Estimates of bankfull discharge were made at the 27 sites using three methods—one primary method and two alternative check methods. Bankfull discharge calculated from the elevation of bankfull indicators and the stage-discharge rating curve at the streamgage was the primary method, and the values that were calculated from this method were used in developing equations (table 3). This method was used as the primary method because the stage-discharge rating curve is based on physical measurements of discharge and stage at the site. It also is the simplest method, requires the fewest assumptions, and requires estimation of the fewest number of variables. The two alternative methods for estimating bankfull discharge provided checks on the results of the bankfull indicator-stage method for comparison of the 27 sites where data were collected for this study. The two alternative check methods were based on data collected at the two surveyed riffle cross-section locations.

Bankfull discharge at the 27 study sites, based on the primary bankfull indicator-stage method for comparison with values determined using the other two check methods, ranged from 46 to 3,470 cubic feet per second (ft^3/s) (table 3). The recurrence intervals of bankfull discharges for the 27 study sites ranged from 1.03 to 3.48 years (table 3) with an average of 1.58 years and a median of 1.34 years. For all 33 sites that provided the data used to develop the equations, bankfull discharge ranged from 24 to 5,640 ft^3/s, and the recurrence intervals ranged from 1.03 to 3.48 years with an average of 1.53 years and a median of 1.34 years.

The average bankfull discharges calculated using the Limerinos d_w equation (equation 6) (1970) and the Manning's equation (equation 1) for each of the 27 sites ranged from 132 to 3,302 ft^3/s (table 4); that range compares well with the range of estimated bankfull discharges using the bankfull indicator elevations and the stage-discharge rating curve (primary) method for the 27 sites (table 3). Evaluation of the percent difference between the two methods found that the average and median difference was about 25 and 21 percent

Table 3. Bankfull channel geometry and discharge for study sites in and near Massachusetts.

[USGS station no.: Streamgages shown in figure 1 and described in table 1. USGS, U.S. Geological Survey; no., number; mi², square mile; ft, foot; ft², square foot; ft³/s, cubic foot per second; yr, year; CT, Connecticut; MA, Massachusetts; NH, New Hampshire; NY, New York; RI, Rhode Island; VT, Vermont; --, unknown]

USGS station no.	Station name	Drainage area (mi^2)	Bankfull discharge (ft^3/s)	Discharge recurrence interval (yr)	Cross-section no.	Bankfull width (ft)	Bankfull mean depth (ft)	Bankfull cross-sectional area (ft^2)
			Data collected for this study					
01093800	Stony Brook Tributary near Temple, NH	3.60	211	2.41	9	24.00	1.65	39.54
					17	25.00	1.50	37.42
					Average	24.50	1.58	38.48
01096000	Squannacook River near West Groton, MA	63.7	742	1.14	3	81.50	3.52	286.89
					16	65.90	3.01	198.36
					Average	73.70	3.27	242.63
010965852	Beaver Brook at North Pelham, NH	47.8	433	1.16	3	57.00	3.91	223.05
					14	43.80	2.82	123.47
					Average	50.40	3.37	173.26
01100600	Shawsheen River near Wilmington, MA	36.5	295	1.10	6	57.80	3.59	207.46
					10	74.30	2.47	183.59
					Average	66.05	3.03	195.53
01101000	Parker River at Byfield, MA	21.3	273	3.16	1	43.50	3.08	133.79
					2	49.40	2.47	121.93
					Average	46.45	2.78	127.86
01103500	Charles River at Dover, MA	183	954	1.33	11	98.50	3.96	390.01
					17	98.80	3.97	392.00
					Average	98.65	3.97	391.01
01105600	Old Swamp River near South Weymouth, MA	4.50	226	2.73	8	40.30	1.28	51.47
					14	30.80	1.34	41.29
					Average	35.55	1.31	46.38
01105870	Jones River at Kingston, MA	15.7	253	3.48	6	42.50	2.00	85.00
					13	34.80	2.16	75.05
					Average	38.65	2.08	80.03
01109000	Wading River near Norton, MA	43.3	295	1.15	5	40.00	2.13	85.06
					10	41.30	2.56	105.60
					Average	40.65	2.35	95.33
01109070	Segreganset River at Dighton, MA	10.6	193	1.07	8	31.30	2.28	71.42
					14	33.80	1.62	54.66
					Average	32.55	1.95	63.04
01111300	Nipmuc River near Harrisville, RI	16.0	318	1.31	9	46.00	2.24	103.07
					13	57.50	2.03	116.63
					Average	51.75	2.14	109.85
01111500	Branch River at Forestdale, RI	91.2	1,210	1.34	7	87.00	3.67	319.58
					9	79.80	3.18	253.39
					Average	83.40	3.43	286.49

Table 3. Bankfull channel geometry and discharge for study sites in and near Massachusetts.—Continued

[USGS station no.: Streamgages shown in figure 1 and described in table 1. USGS, U.S. Geological Survey; no., number; mi², square mile; ft, foot; ft², square foot; ft³/s, cubic foot per second; yr, year; CT, Connecticut; MA, Massachusetts; NH, New Hampshire; NY, New York; RI, Rhode Island; VT, Vermont; --, unknown]

USGS station no.	Station name	Drainage area (mi^2)	Bankfull discharge (ft^3/s)	Discharge recurrence interval (yr)	Cross-section no.	Bankfull width (ft)	Bankfull mean depth (ft)	Bankfull cross-sectional area (ft^2)
			Data collected for this study—Continued					
01162500	Priest Brook near Winchendon, MA	19.4	182	1.10	6	59.60	1.59	94.98
					9	51.50	2.48	127.82
					Average	55.55	2.04	111.40
01163200	Otter River at Otter River, MA	34.1	374	1.43	6	66.50	1.61	107.34
					13	52.90	1.93	102.18
					Average	59.70	1.77	104.76
01169000	North River at Shattuckville, MA	89.0	3,070	1.23	2	108.80	4.91	534.10
					17	103.80	4.80	497.87
					Average	106.30	4.86	515.99
01169900	South River near Conway, MA	24.1	1,710	1.71	9	61.10	4.09	249.68
					18	70.00	3.98	278.68
					Average	65.55	4.04	264.18
01170100	Green River near Colrain, MA	41.4	2,110	1.52	3	109.00	2.86	311.70
					15	100.50	3.52	353.37
					Average	104.75	3.19	332.54
01171500	Mill River at Northampton, MA	52.6	1,600	1.33	2	86.00	3.53	303.51
					6	83.00	3.60	298.96
					Average	84.50	3.57	301.24
01174900	Cadwell Creek near Belchertown, MA	2.55	46	1.03	6	20.30	1.28	26.05
					11	16.90	1.33	22.48
					Average	18.60	1.31	24.27
01175670	Sevenmile River near Spencer, MA	8.81	163	1.74	20	37.90	1.49	56.43
					13	25.50	1.80	45.99
					Average	31.70	1.65	51.21
01176000	Quaboag River at West Brimfield, MA	150	1,010	1.54	4	143.90	2.67	384.51
					20	121.00	2.71	327.46
					Average	132.45	2.69	355.99
01181000	West Branch Westfield River at Huntington, MA	94.0	3,470	1.34	2	112.50	3.14	353.66
					11	135.80	3.17	430.09
					Average	124.15	3.16	391.88
01184100	Stony Brook near West Suffield, CT	10.4	274	1.38	18	48.00	1.74	83.40
					22	39.50	1.58	62.26
					Average	43.75	1.66	72.83
01187300	Hubbard River near West Hartland, CT	19.9	507	1.21	6	72.00	2.38	171.40
					16	74.50	2.20	164.03
					Average	73.25	2.29	167.72

Table 3. Bankfull channel geometry and discharge for study sites in and near Massachusetts.—Continued

[USGS station no.: Streamgages shown in figure 1 and described in table 1. USGS, U.S. Geological Survey; no., number; mi², square mile; ft, foot; ft², square foot; ft³/s, cubic foot per second; yr, year; CT, Connecticut; MA, Massachusetts; NH, New Hampshire; NY, New York; RI, Rhode Island; VT, Vermont; --, unknown]

USGS station no.	Station name	Drainage area (mi²)	Bankfull discharge (ft³/s)	Discharge recurrence interval (yr)	Cross-section no.	Bankfull width (ft)	Bankfull mean depth (ft)	Bankfull cross-sectional area (ft²)
	Data collected for this study—Continued							
01198000	Green River near Great Barrington, MA	51.0	1,150	1.56	7	75.30	2.76	207.61
					20	62.80	3.25	204.40
					Average	69.05	3.01	206.01
01199050	Salmon Creek at Lime Rock, CT	29.4	490	1.52	14	49.00	2.14	104.75
					21	43.50	2.78	121.03
					Average	46.25	2.46	112.89
01333000	Green River at Williamstown, MA	42.6	1,220	1.56	8	84.00	2.84	241.38
					15	74.00	3.34	246.86
					Average	79.00	3.09	244.12
	Data collected for other studies							
[1]01174000	Hop Brook near New Salem, MA	3.39	80	1.09	1	16.41	1.10	17.54
					2	17.93	1.40	25.54
					6	19.70	1.40	27.21
					8	27.73	0.90	25.98
					Average	20.44	1.20	24.07
[1]01174600	Cadwell Creek near Pelham, MA	0.60	24	1.24	3	17.0	0.77	13.23
					4	10.8	0.86	9.29
					5	18.0	0.72	12.96
					8	10.5	0.56	5.86
					9	13.6	0.79	10.78
					10	6.7	0.85	5.66
					11	18.2	0.58	10.59
					Average	13.5	0.73	9.77
[2]01334000	Walloomsac River near North Bennington, VT	111	1,879	1.10	--	110	3.7	410
[3]01360640	Valatie Kill near Nassau, NY	9.48	227	[4]1.07	--	38.3	2.3	89.0
					--	34.5	2.2	76.8
					--	42.7	2.1	87.6
					--	38.7	1.8	69.6
					Average	38.55	2.1	80.75
[3]01362100	Kinderhook Creek at Rossman, NY	329	5,640	[4]1.83	--	139.6	5.8	806.5
					--	156.4	5.8	910.5
					Average	148.0	5.8	858.5
[3]01361000	Roeliff Jansen Kill near Hillsdale, NY	27.5	690	[4]1.59	--	54.4	3.5	189.1
					--	55.8	3.8	213.8
					--	60.4	3.1	185.2
					Average	56.87	3.47	196.03

[1]Data from Thomas Garday, U.S. Department of Agriculture, Natural Resources Conservation Service, written commun., 2005.

[2]Data from Jaquith and Kline, 2006.

[3]Data from Mulvihill and Baldigo, 2007.

[4]Recurrence interval published as 1.16, 2.1, and 1.8 years for stations 01360640, 01362100, and 01361000, respectively, by Mulvihill and Baldigo, 2007.

higher, respectively, for the Limerinos method than for the primary method. The estimated bankfull discharge using the Jarrett equation (equation 7) (1984) ranged from 69 to 3,678 ft^3/s (table 4); that range compares well with the range of estimated bankfull discharges from the primary method in table 3. A comparison of percent differences between these two methods found that the average and median differences were about 22 and 17 percent higher, respectively, for the Jarrett method than for the primary method. The Limerinos and Jarrett methods compared well with each other, as comparison of the percent difference found on average that Jarrett is about 3 percent higher than Limerinos, but the median is 4 percent lower for Jarrett (1984) than Limerinos (1970) (table 4).

The average bankfull width, mean depth, cross-sectional area, and discharge generally appear to be greater at the sites in and near western Massachusetts than at the sites in and near eastern Massachusetts. Specifically, these bankfull characteristics appear to be greater in the Hudson-Green-Notre Dame Highlands between the Connecticut Valley (east) and the Vermont Valley (west) physiographic provinces (fig. 2) defined by Denny (1982). These sites include North River at Shattuckville, Mass. (01169000), South River near Conway, Mass. (01169900), Green River near Colrain, Mass. (01170100), West Branch Westfield River at Huntington, Mass. (01181000), Hubbard River near West Hartland, Conn. (01187300), and Green River at Williamstown, Mass. (01333000). Although bankfull characteristics at these six sites appear to be slightly different from the others in and near western Massachusetts, comparison of selected basin and land-use characteristics (table 5), peak discharges for recurrence intervals ranging from about 1 to 10 years (table 2) on a per unit area basis, annual precipitation characteristics, and annual runoff characteristics did not find any notable differences from other sites in and near the region.

Equations

Simple and multiple regression equations for bankfull width, mean depth, cross-sectional area, and discharge are presented in table 6. All equations were developed using base-10 log-transformed bankfull channel geometry, discharge, and basin characteristic data (table 5) for all 33 study sites. The transforming of data is a common procedure that makes the data more symmetric, linear, and constant in variance (homoscedasticity) (Helsel and Hirsch, 2002). Detailed results for the simple and multiple regression analyses for bankfull channel geometry and discharge are shown in appendix 3. Although the equations were developed using log-transformed data, the equations are shown in table 6 in forms that allow the use of non-transformed data.

The simple regression analyses used the automated procedures in the statistical software package Minitab (2003). The standard techniques of simple regression analyses were followed as discussed in Helsel and Hirsch (2002). The bankfull channel geometry and discharge simple regression equations using drainage area as the explanatory variable were evaluated by reviewing the adjusted R^2 (coefficient of determination), predicted R^2, plots of residuals, and other statistical indicators of model fit/validity. The predicted R^2 for bankfull width (0.8635), mean depth (0.7995), cross-sectional area (0.9028), and discharge (0.7428) were all acceptable (table 6). Plots of the residuals were evaluated to verify that the residuals had no outliers, curvature, or heteroscedasticity (absence of homoscedasticity). Figures 3A–D show that the residuals of the simple regression equation for the bankfull channel geometry and discharge, by drainage area, have no outliers, curvature, or heteroscedasticity. The residuals are equally distributed on both the postitive and negative side of the zero line. The regression equation residuals were also reviewed spatially to make sure that no clear geographic trends were observed. Figure 4 shows the geographic distribution of the residuals for the bankfull width equation. There are six sites in western Massachusetts where residuals had higher positive values (regression equation is under predicting the actual value) than other sites in and near western Massachusetts. Four sites in southeastern Massachusetts had higher negative values (regression equation is over predicting the actual value) than other sites in and near eastern Massachusetts. All other areas of the State show a fairly even distribution of positive and negative residuals at the study sites with no clear pattern; overall, figure 4 shows a fairly even distribution of the residuals over the study area. More detailed output from the simple regression equations are presented in appendix 3. Graphic plots of the simple regression equations (equations 8–11 in table 6), which relate bankfull width, mean depth, cross-sectional area, and discharge to drainage area, are shown in figures 5A–D, respectively. These plots also serve as regional curves for Massachusetts and allow users to easily estimate bankfull geometry and discharge from a known drainage area for any site within the range of drainage areas shown. The graphs are plotted using logarithmic scales for “x” and “y” axes, which is common practice for regional curves.

In the multiple regression analysis, the basin characteristics listed in table 5 were investigated for their potential relation to bankfull width, mean depth, cross sectional area, and discharge. The automated statistical selection procedures “best subsets” and “stepwise” were used in Minitab (2003) to evaluate the basin characteristics as potential explanatory variables. Both selection procedures determined the statistical contribution of the explanatory variables (basin characteristics) that were entered into the equation, and variables were retained or deleted on the basis of their statistical importance. A statistical significance level of 0.05 for p-values of explanatory variables was generally used for entry or retention in the equations. Additionally, potential multiple regression equations were evaluated using the adjusted R^2, predicted R^2 plots of residuals, and so forth in determining the best possible equations. The standard techniques of multiple regression analyses were followed, as discussed in Helsel and Hirsch (2002).

Table 4. Estimated bankfull discharge using equations by Limerinos (1970) and Jarrett (1984) for study sites in and near Massachusetts.

[USGS station no.: Streamgages shown in figure 1 and described in table 1. USGS, U.S. Geological Survey; no., number; mi^2, square miles; d_w, weighted particle-size distribution—equation 2 in report (Limerinos, 1970); ft^3/s, cubic foot per second; yr, year; CT, Connecticut; MA, Massachusetts; NH, New Hampshire; RI, Rhode Island]

USGS station no.	Station name	Drainage area (mi^2)	Cross-section no.	Limerios (1970)		Jarrett (1984)		From table 3	
				Estimated bankfull discharge (ft^3/s) (based on d_w)	Recurrence interval of average discharge (based on d_w)	Estimated bankfull discharge (ft^3/s)	Recurrence interval of average discharge	Estimated bankfull discharge (ft^3/s)	Discharge recurrence interval (yr)
01093800	Stony Brook Tributary near Temple, NH	3.60	9	213		133			
			17	169		111			
			Average	191	2.05	122	1.27	211	2.41
01096000	Squannacook River near West Groton, MA	63.7	3	1,120		1,588			
			16	1,760		1,198			
			Average	1,440	1.98	1,393	1.90	742	1.14
010965852	Beaver Brook at North Pelham, NH	47.8	3	652		[1]1,013			
			14	627		581			
			Average	639	1.55	797	2.00	433	1.16
01100600	Shawsheen River near Wilmington, MA	36.5	6	489		[1]830			
			10	419		[1]551			
			Average	454	1.48	690	2.85	295	1.1
01101000	Parker River at Byfield, MA	21.3	1	221		[1]449			
			2	112		[1]362			
			Average	167	1.47	406	7.22	273	3.16
01103500	Charles River at Dover, MA	183	11	1,143		[1]1,918			
			17	1,065		[1]2,017			
			Average	1,104	1.62	1,968	6.94	954	1.33
01105600	Old Swamp River near South Weymouth, MA	4.50	8	198		134			
			14	133		104			
			Average	166	1.74	119	1.29	226	2.73
01105870	Jones River at Kingston, MA	15.7	6	276		[1]255			
			13	285		249			
			Average	281	4.55	252	3.40	253	3.48
01109000	Wading River near Norton, MA	43.3	5	352		304			
			10	360		[1]413			
			Average	356	1.33	358	1.34	295	1.15
01109070	Segreganset River at Dighton, MA	10.6	8	254		292			
			14	[2]234		178			
			Average	244	1.21	235	1.18	193	1.07

Table 4. Estimated bankfull discharge using equations by Limerinos (1970) and Jarrett (1984) for study sites in and near Massachusetts.—Continued

[USGS station no.: Streamgages shown in figure 1 and described in table 1. USGS, U.S. Geological Survey; no., number; mi², square miles; d_w, weighted particle-size distribution—equation 2 in report (Limerinos, 1970); ft³/s, cubic foot per second; yr, year; CT, Connecticut; MA, Massachusetts; NH, New Hampshire; RI, Rhode Island]

USGS station no.	Station name	Drainage area (mi²)	Cross-section no.	Limerios (1970) Estimated bankfull discharge (ft³/s) (based on d_w)	Limerios (1970) Recurrence interval of average discharge (based on d_w)	Jarrett (1984) Estimated bankfull discharge (ft³/s)	Jarrett (1984) Recurrence interval of average discharge	From table 3 Estimated bankfull discharge (ft³/s)	From table 3 Discharge recurrence interval (yr)
01111300	Nipmuc River near Harrisville, RI	16.0	9	536		406			
			13	324		[1]342			
			Average	430	1.70	374	1.47	318	1.31
01111500	Branch River at Forestdale, RI	91.2	7	1,640		1,824			
			9	[3]1,414		1,308			
			Average	1,527	1.65	1,566	1.78	1,210	1.34
01162500	Priest Brook near Winchendon, MA	19.4	6	402		262			
			9	368		[1]460			
			Average	385	2.38	361	2.13	182	1.1
01163200	Otter River at Otter River, MA	34.1	6	375		322			
			13	569		384			
			Average	472	2.17	353	1.32	374	1.43
01169000	North River at Shattuckville, MA	89.0	2	3,047		3,589			
			17	3,558		3,767			
			Average	3,302	1.30	3,678	1.43	3,070	1.23
01169900	South River near Conway, MA	24.1	9	1,863		1,605			
			18	1,619		1,533			
			Average	1,741	1.75	1,569	1.53	1,710	1.71
01170100	Green River near Colrain, MA	41.4	3	2,010		1,632			
			15	2,123		1,978			
			Average	2,066	1.47	1,805	1.24	2,110	1.52
01171500	Mill River at Northampton, MA	52.6	2	2,176		1,708			
			6	1,740		1,558			
			Average	1,958	1.65	1,633	1.35	1,600	1.33
01174900	Cadwell Creek near Belchertown, MA	2.55	6	150		74			
			11	138		65			
			Average	144	3.15	69	1.15	46	1.03
01175670	Sevenmile River near Spencer, MA	8.81	20	150		154			
			13	113		[1]135			
			Average	132	1.37	144	1.48	163	1.74

Table 4. Estimated bankfull discharge using equations by Limerinos (1970) and Jarrett (1984) for study sites in and near Massachusetts.—Continued

[USGS station no.: Streamgages shown in figure 1 and described in table 1. USGS, U.S. Geological Survey; no., number; mi^2, square miles; d_w, weighted particle-size distribution—equation 2 in report (Limerinos, 1970); ft^3/s, cubic foot per second; yr, year; CT, Connecticut; MA, Massachusetts; NH, New Hampshire; RI, Rhode Island]

USGS station no.	Station name	Drainage area (mi^2)	Cross-section no.	Limerios (1970)		Jarrett (1984)		From table 3	
				Estimated bankfull discharge (ft^3/s) (based on d_w)	Recurrence interval of average discharge (based on d_w)	Estimated bankfull discharge (ft^3/s)	Recurrence interval of average discharge	Estimated bankfull discharge (ft^3/s)	Discharge recurrence interval (yr)
01176000	Quaboag River at West Brimfield, MA	150	4	1,410		1,629			
			20	1,629		1,521			
			Average	1,519	3.43	1,575	3.68	1,010	1.54
01181000	W. Branch Westfield River at Huntington, MA	94.0	2	2,622		2,037			
			11	2,345		2,110			
			Average	2,484	1.12	2,073	1.06	3,470	1.34
01184100	Stony Brook near West Suffield, CT	10.4	18	[4]335		294			
			22	[4]186		203			
			Average	260	1.22	248	1.29	274	1.38
01187300	Hubbard River near West Hartland, CT	19.9	6	1,257		815			
			16	709		638			
			Average	983	1.97	726	1.49	507	1.21
01198000	Green River near Great Barrington, MA	51.0	7	682		[1]750			
			20	964		[1]920			
			Average	823	1.18	835	1.19	1,150	1.56
01199050	Salmon Creek at Lime Rock, CT	29.4	14	457		415			
			21	[5]265		509			
			Average	361	1.22	462	1.45	490	1.52
01333000	Green River at Williamstown, MA	42.6	8	1,919		1,236			
			15	1,275		1,094			
			Average	1,597	2.59	1,165	1.46	1,220	1.56

[1]For the cross-sections, the Jarrett (1984) calculation of discharge had water-surface slopes less than 0.002 ft/ft.

[2]For cross-section 14 at streamgage 01109070 Segreganset River at Dighton, MA, 12 of 50 Wolman (1954) pebble count samples were classified as bedrock and not used in calculation of the Manning's roughness coefficient (Limerinos, 1970) using the dw (equations 2 and 6 in this report).

[3]For cross-section 9 at streamgage 01111500 Branch River at Forestdale, RI, 27 of 50 Wolman (1954) pebble count samples were classified as bedrock and not used in calculation of the Manning's roughness coefficient (Limerinos, 1970) using the dw (equations 2 and 6 in this report).

[4]For cross-sections 18 and 22 at streamgage 01184100 Stony Brook near West Suffield, CT, 30 of 50 and 44 of 50, respectively, Wolman (1954) pebble count samples were classified as bedrock and not used in calculation of the Manning's roughness coefficient (Limerinos, 1970) using the dw (equations 2 and 6 in this report).

[5]For cross-section 21 at streamgage 01199050 Salmon Creek at Lime Rock, CT, 3 of 50 Wolman (1954) pebble count samples were classified as bedrock and not used in calculation of the Manning's roughness coefficient (Limerinos, 1970) using the dw (equations 2 and 6 in this report).

Table 5. Basin and land-use characteristics of the study sites used in development of bankfull channel geometry and discharge equations for streams in and near Massachusetts.

[USGS station no.: Streamgages shown in figure 1 and described in table 1. USGS, U.S. Geological Survey; no., number; mi², square miles; ft, foot; %, percent; CT, Connecticut; MA, Massachusetts; NH, New Hampshire; NY, New York; RI, Rhode Island; VT, Vermont; --, no data]

USGS station no.	Station name	Drainage area (mi²)	Mean basin elevation[1] (ft)	Maximum basin elevation[2] (ft)	Minimum basin elevation[2] (ft)	Basin relief[3] (ft)	Mean basin slope[4] (%)	Area of water bodies[1] (%)	Area of wetlands[1] (%)	Area of forest land[1] (%)	Area of urban land[1] (%)	Area of agricultural land[1] (%)	Area of sand and gravel deposits[1] (%)
01093800	Stony Brook Tributary near Temple, NH	3.60	[2]1,379	2,266	913	1,353	16.967	[5]0.0	[5]0.4	[5]92.9	[5]0.0	[5]4.3	[2]0.8
01096000	Squannacook River near West Groton, MA	63.7	622	1,492	249	1,243	8.129	0.9	2.2	82.0	1.3	6.0	27.0
010965852	Beaver Brook at North Pelham, NH	47.8	[2]348	635	149	486	5.510	[5]0.8	[5]7.2	[5]48.5	[5]1.0	[5]6.8	[2]7.2
01100600	Shawsheen River near Wilmington, MA	36.5	[5]161	[5]358	[5]82	274	4.414	0.5	4.0	29.0	24.0	2.5	39.0
01101000	Parker River at Byfield, MA	21.3	[5]116	[5]354	[5]30	325	6.084	2.4	10.0	58.0	1.4	8.2	43.0
01103500	Charles River at Dover, MA	183	[5]225	[5]581	[5]89	492	5.325	2.3	7.1	47.0	6.4	6.2	46.0
01105600	Old Swamp River near South Weymouth, MA	4.50	[2]142	199	74	125	3.384	0.2	6.0	40.6	8.2	0.0	33.0
01105870	Jones River at Kingston, MA	15.7	[5]82	[5]210	[5]13	215	4.189	7.3	14.0	55.0	1.0	7.7	96.0
01109000	Wading River near Norton, MA	43.3	179	435	62	373	3.845	2.7	9.2	57.0	6.7	4.4	58.0
01109070	Segreganset River at Dighton, MA	10.6	[5]112	[5]243	[5]26	212	3.144	0.4	6.9	75.0	1.6	6.1	16.0
01111300	Nipmuc River near Harrisville, RI	16.0	531	771	346	425	5.635	0.5	3.6	83.0	1.4	3.9	0.5
01111500	Branch River at Forestdale, RI	91.2	495	818	193	625	7.058	5.8	4.6	67.0	4.1	4.5	5.8
01162500	Priest Brook near Winchendon, MA	19.4	1,095	1,871	849	1,022	6.948	1.7	3.0	88.0	0.7	4.3	10.0
01163200	Otter River at Otter River, MA	34.1	[5]1,075	[5]1,335	[5]896	445	6.630	3.6	5.3	67.0	9.3	2.8	26.0
01169000	North River at Shattuckville, MA	89.0	1,425	2,322	433	1,889	15.139	0.4	0.6	86.0	0.3	10.0	5.9
01169900	South River near Conway, MA	24.1	1,126	1,819	475	1,344	15.611	0.4	0.3	78.0	0.3	15.0	13.0
01170100	Green River near Colrain, MA	41.4	1,352	2,410	465	1,945	17.141	0.5	0.5	91.0	0.1	5.6	0.5
01171500	Mill River at Northampton, MA	52.6	841	1,692	170	1,522	12.138	1.0	0.9	81.0	3.1	6.8	16.0
01174900	Cadwell Creek near Belchertown, MA	2.55	[2]923	[5]1,132	[5]541	621	7.231	[5]0.0	[5]6.2	[5]89.9	[5]0.0	[5]6.6	[2]0.7
01175670	Sevenmile River near Spencer, MA	8.81	871	1,072	651	421	8.587	2.3	3.7	73.0	0.2	14.0	13.0
01176000	Quaboag River at West Brimfield, MA	150	808	1,227	385	842	8.558	3.3	5.5	67.0	1.8	15.0	21.0
01181000	West Branch Westfield River at Huntington, MA	94.0	1,422	2,236	393	1,843	14.012	1.3	1.3	91.0	0.4	2.3	4.0
01184100	Stony Brook near Suffield, CT	10.5	[2]261	680	158	509	7.542	[5]0.6	[5]11.8	[5]51.2	[5]1.5	[5]25.3	[2]36.0
01187300	Hubbard Brook near West Hartland, CT	19.9	[2]1,287	1,643	603	1,017	8.754	[5]2.1	[5]4.7	[5]89.5	[5]0.0	[5]0.9	[2]0.3
01198000	Green River near Great Barrington, MA	51.0	[2]1,183	2,058	691	1,367	8.336	0.8	3.4	79.4	0.2	13.7	[2]9.8

Table 5. Basin and land-use characteristics of the study sites used in development of bankfull channel geometry and discharge equations for streams in and near Massachusetts.—Continued

[USGS station no.: Streamgages shown in figure 1 and described in table 1. USGS, U.S. Geological Survey; no., number; mi^2, square miles; ft, foot; %, percent; CT, Connecticut; MA, Massachusetts; NH, New Hampshire; NY, New York; RI, Rhode Island; VT, Vermont; --, no data]

USGS station no.	Station name	Drainage area (mi^2)	Mean basin elevation[1] (ft)	Maximum basin elevation[2] (ft)	Minimum basin elevation[2] (ft)	Basin relief[3] (ft)	Mean basin slope[4] (%)	Area of water bodies[1] (%)	Area of wetlands[1] (%)	Area of forest land[1] (%)	Area of urban land[1] (%)	Area of agricultural land[1] (%)	Area of sand and gravel deposits[1] (%)
01199050	Salmon Creek at Lime Rock, CT	29.4	[2]1,170	2,445	618	1,818	[6]13.186	[5]3.9	[5]3.7	[6]67.1	[5]0.4	[5]11.4	[2]15
01333000	Green River at Williamstown, MA	42.6	1,554	3,476	615	2,861	24.519	0.1	0.0	79.0	0.5	15.0	11.0
[9]01174000	Hop Brook near New Salem, MA	3.39	[2]1,030	[5]1,302	[5]735	570	10.786	[5]0.0	[5]1.3	[5]84.6	[5]0.0	[5]6.0	[2]2.1
[9]01174600	Cadwell Creek near Pelham, MA	0.60	[5]1,014	[5]1,132	[5]873	259	10.081	[5]0.0	[5]16.0	[5]73.7	[5]0.0	[5]1.6	--
[10]01334000	Walloomsac River near North Bennington, VT	111	[5]1,604	[5]3,737	[5]509	3,228	[6]15.512	[5]0.3	[5]4.6	[6]75.3	[5]0.4	[5]10.6	--
[11]01360640	Valatie Kill near Nassau, NY	9.48	[5]751	[5]1,342	[5]436	906	[6]11.218	[5]0.5	[5]2.2	[6]81.9	[5]0.1	[5]12.5	--
[11]01361000	Kinderhook Creek at Rossman, NY	329	[5]897	[5]2,653	[5]40	2,613	[6]14.417	--	--	[6]75.3	--	--	--
[11]01362100	Roeliff Jansen Kill near Hillsdale, NY	27.5	[7]1,040	[8]1,960	[8]590	1,370	[6]12.384	--	--	[6]72.6	--	--	--

[1]From Zarriello and Socolow (2003), unless otherwise footnoted.

[2]From Armstrong and others (2008), unless otherwise footnoted.

[3]Basin relief is the maximum basin elevation minus the minimum basin elevation.

[4]From 1:24,000 scale digital elevation models (DEMs) (U.S. Geological Survey, 2007a), unless otherwise footnoted.

[5]From Falcone (2011).

[6]From Lumia and others (2006).

[7]From Wandle (1983).

[8]From U.S. Geological Survey topographic maps.

[9]Study site from Thomas Garday, U.S. Department of Agriculture, Natural Resources Conservation Service, written commun., 2005.

[10]Study site from Jaquith and Kline (2006).

[11]Study site from Mulvihill and Baldigo (2007).

Table 6. Statistical summary of simple and multiple regression equations for estimating bankfull stream width, mean depth, cross-sectional area, and discharge for streams in and near Massachusetts.

[n, number; R^2, coefficient of determination; S_e, standard error of the estimate; S_p, standard error of the prediction; ft, foot; mi^2, square miles; ft^2, square foot; ft^3/s, cubic foot per second; log, base-10 logarithm; %, percent]

Equation number	Equation	n	R^2	Adjusted R^2	Predicted R^2	S_e (log)	S_e (%)	S_p (log)	S_p (%)
	Simple regression equation								
8	Bankfull width (ft) = 15.0418 [Drainage area (mi^2)]$^{0.4038}$	33	0.877	0.873	0.8635	0.0903	21.02	0.0950	22.14
9	Bankfull mean depth (ft) = 0.9502 [Drainage area (mi^2)]$^{0.2960}$	33	0.820	0.814	0.7995	0.0826	19.19	0.0873	20.30
10	Bankfull cross-sectional area (ft^2) = 14.1156 [Drainage area (mi^2)]$^{0.7026}$	33	0.911	0.908	0.9028	0.1308	30.81	0.1369	32.31
11	Bankfull discharge (ft^3/s) = 37.1364 [Drainage area (mi^2)]$^{0.7996}$	33	0.770	0.762	0.7428	0.2608	65.89	0.2757	70.43
	Multiple regression equation								
12	Bankfull width (ft) = 10.6640 [Drainage area (mi^2)]$^{0.3935}$ [Mean basin slope (%)]$^{0.1751}$	33	0.900	0.894	0.8780	0.0825	19.17	0.0913	21.26
13	Bankfull mean depth (ft) = 0.7295 [Drainage area (mi^2)]$^{0.2880}$ [Mean basin slope (%)]$^{0.1346}$	33	0.845	0.834	0.8159	0.0781	18.13	0.0850	19.76
14	Bankfull cross-sectional area (ft^2) = 7.6711 [Drainage area (mi^2)]$^{0.6842}$ [Mean basin slope (%)]$^{0.3105}$	33	0.937	0.932	0.9320	0.1123	26.30	0.1234	29.00
15	Bankfull discharge (ft^3/s) = 8.2490 [Drainage area (mi^2)]$^{0.7545}$ [Mean basin slope (%)]$^{0.7659}$	33	0.871	0.862	0.8366	0.1986	48.23	0.2234	55.02

The result of the multiple regression analyses was that drainage area was the most significant variable in explaining the variability of bankfull width, mean depth, cross-sectional area, and discharge. Evaluation of the other potential explanatory variables (basin and land-use characteristics) (table 5) found that mean basin slope [1:24,000 scale digital elevation models (DEMs); (U.S. Geological Survey, 2007a)] was a significant variable in the equations for bankfull width, mean depth, cross-sectional area, and discharge at a statistical significance level of 0.05 for p-values (appendix 3). The predicted R^2 for bankfull width (0.8780), mean depth (0.8159), cross-sectional area (0.9320), and discharge (0.8366) regression equations were all acceptable (table 6). Plots of the residuals were evaluated to verify that the residuals had no outliers, curvature, or heteroscedasticity (absence of homoscedasticity). Figures 6A–H show that the residuals of the multiple regression equation for the bankfull channel geometry and discharge in relation to drainage area and mean basin slope have no outliers, curvature, or heteroscedasticity. The residuals are equally distributed on both on the postitive and negative side of the zero line. Additionally, the residuals by drainage area for the multiple regression equations (figs. 6A, B, C, and D) are smaller (closer to zero) than those for each of the simple regression equations in figures 3A–D. Figure 7 shows the geographic distribution of the residuals for the bankfull width multiple regression equation. The distribution of positive and negative residuals across the State shows no clear geographic pattern. Clusters of sites with positive residuals in western Massachusetts and with negative residuals in southeastern Massachusetts, which occurred for the residuals of the simple regression equation for bankfull width (fig. 4), do not appear in the geographic plot of residuals for the multiple regression equation (fig. 6). More detailed output from the analyses of the multiple regression equations is presented in appendix 3. Multiple regression equations for bankfull width, mean depth, cross-sectional area, and discharge are shown as equations 12–15, respectively, in table 6.

Inclusion of mean basin slope as an explanatory variable in the multiple regression equations helps account for a significant amount of the variance that cannot be accounted for by drainage area alone. Statistical results for the simple and multiple regression equations in table 6 show that the R^2 statistics increased and that the standard error of the estimate and prediction decreased from the simple to multiple regression equations. These results show that the multiple regression equations for bankfull channel geometry and discharge equations are an improvement over the simple regression equations, which use only drainage area as the explanatory variable. Generally, mean basin slope is higher in basins in western Massachusetts than in eastern Massachusetts, the significance of which in the regression equations may be related to a number of factors that differ regionally across Massachusetts, such as topography, geology, and climate.

The significance of mean basin slope in the multiple regression equation, and the differences in geographic patterns between residuals of the single regression equation (without basin slope) and those of the multiple regression equation, indicate there may be regional patterns in bankfull geometry and discharge across Massachusetts. An alternative to representing these possible regional patterns in bankfull geometry and discharge across Massachusetts would be to develop separate equations for regions within the State. This approach has been followed in several recent studies with regional equations for bankfull geometry and discharge developed at statewide scales. For example, in Maryland, Pennsylvania, Virginia, and West Virginia, physiographic provinces were used as regions for the development of separate sets of equations for these states. Hydrologic regions, based on analyses of peak-flow characteristics, were used to delineate regions for bankfull equations in New York. In the present study, several possible types of regions were considered for use in developing separate sets of equations for different parts of Massachusetts—physiographic provinces (Denney, 1982; 6 provinces) (fig. 2), flood regions based on peak-flow analyses (Wandle, 1983; 3 regions—eastern, central, and western), and USEPA Level III ecoregions (U.S. Environmental Protection Agency, 2006; 4 regions) (fig. 2). All of these regional schemes generally divide the State longitudinally from west to east. Thus, they generally reflect patterns of topography, climate/precipitation, and to some extent, surficial geology. However, separate sets of equations were not developed for regions within Massachusetts in the present study because such equations would be based on small numbers of sites. In equations based on small numbers of sites, any one individual site, which may be anomalous in some way, has a larger influence on the equation parameters than in equations based on larger numbers of sites. Confidence and prediction intervals also are larger for equations that are based on smaller sample sizes. The approach of a single set of equations for Massachusetts is consistent with the approach taken in recent studies for the adjacent New England States of New Hampshire and Vermont. The multiple regression equations that include mean basin slope, a factor that represents regional differences, to some extent provide a function similar to separate sets of regional regression equations.

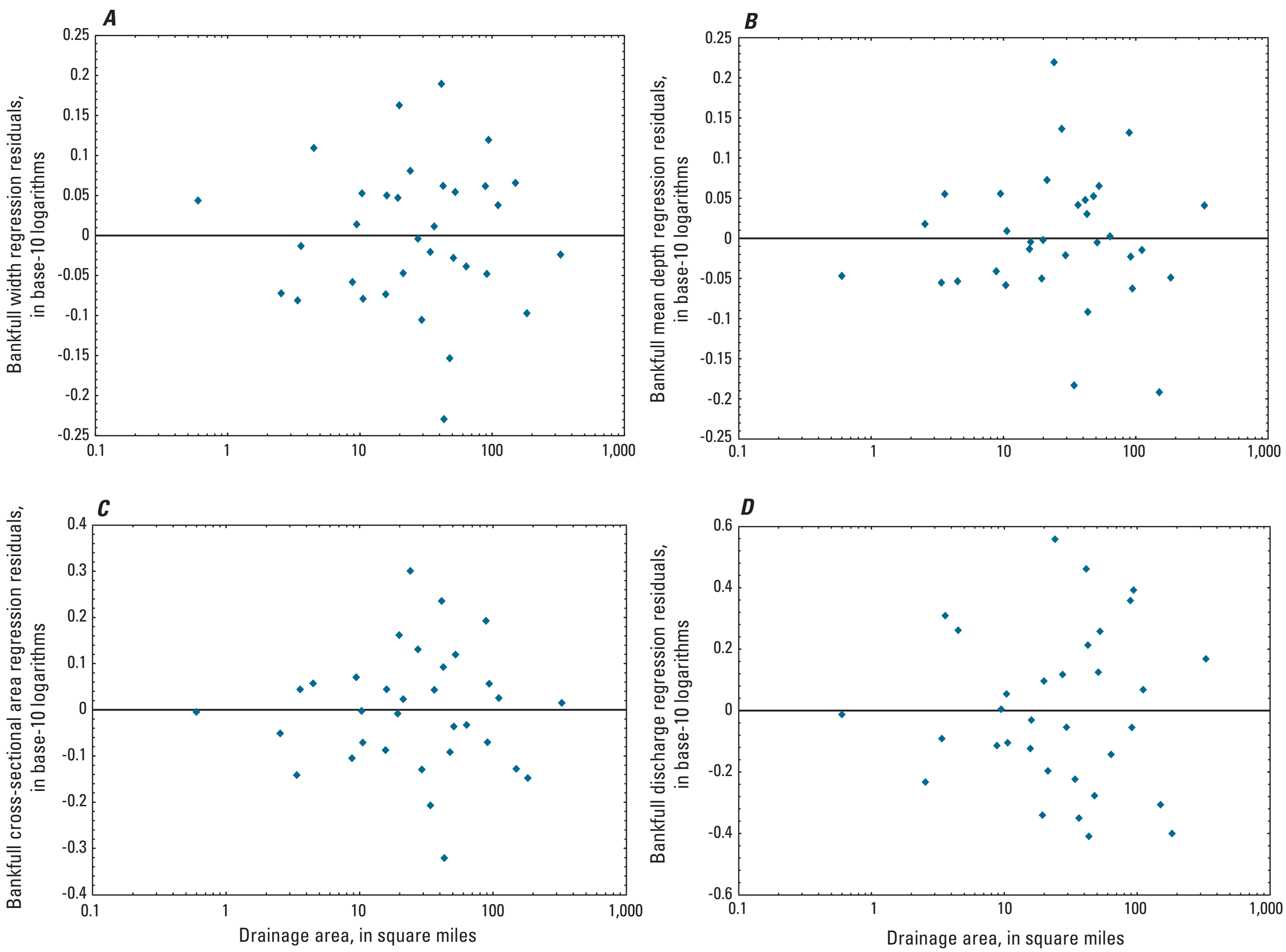


Figure 3. Simple regression equation residuals in relation to drainage area for bankfull: *A,* width, *B,* mean depth, *C,* cross-sectional area, and *D,* discharge for streams in and near Massachusetts.

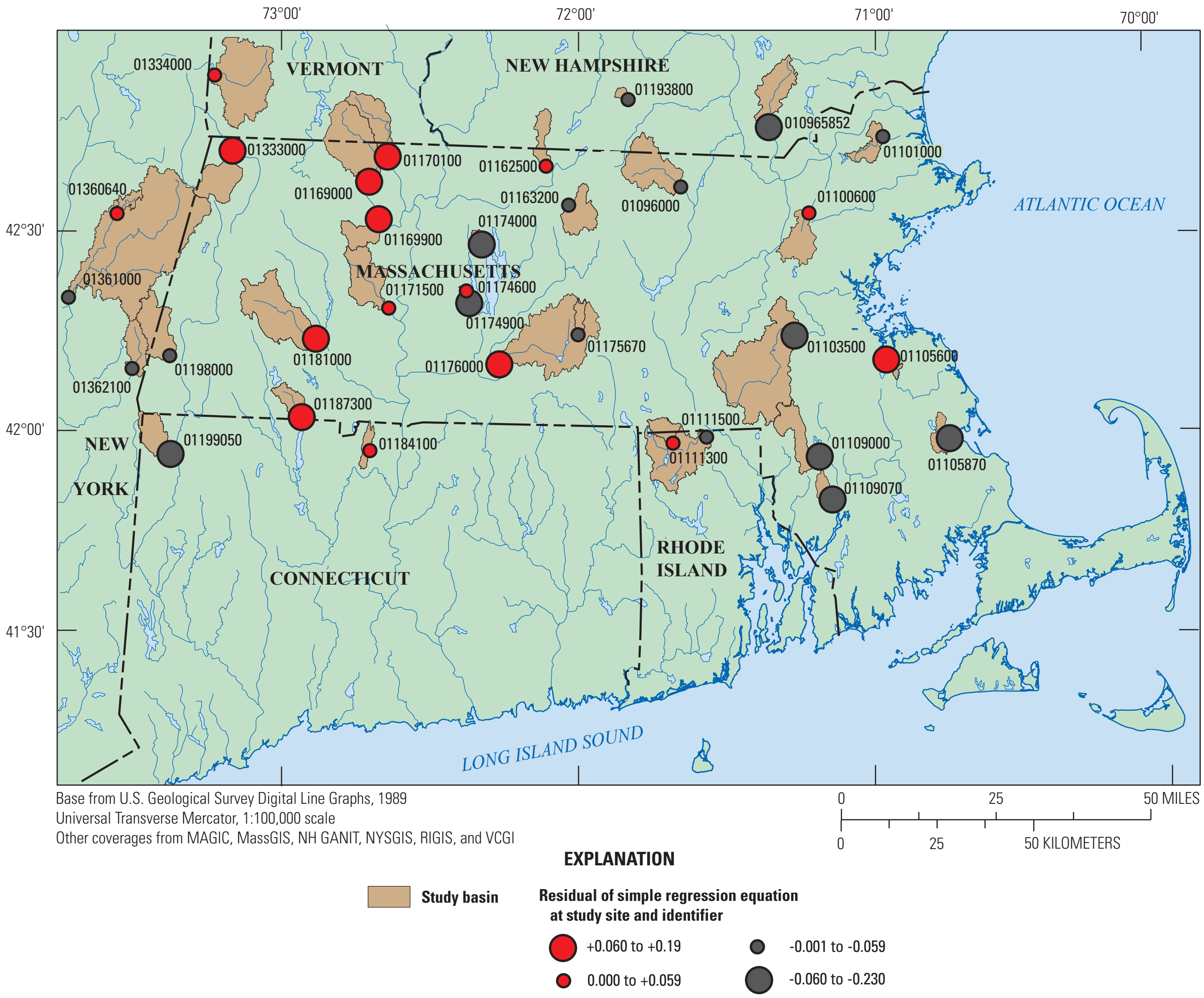
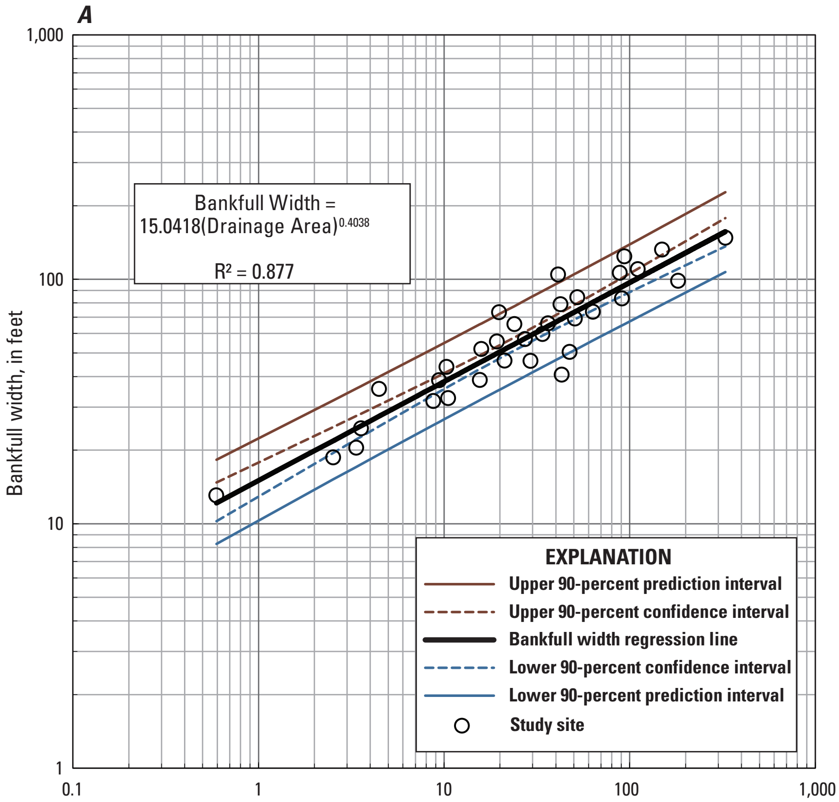


Figure 4. Geographic distribution of bankfull width simple regression equation residuals for study sites in and near Massachusetts.



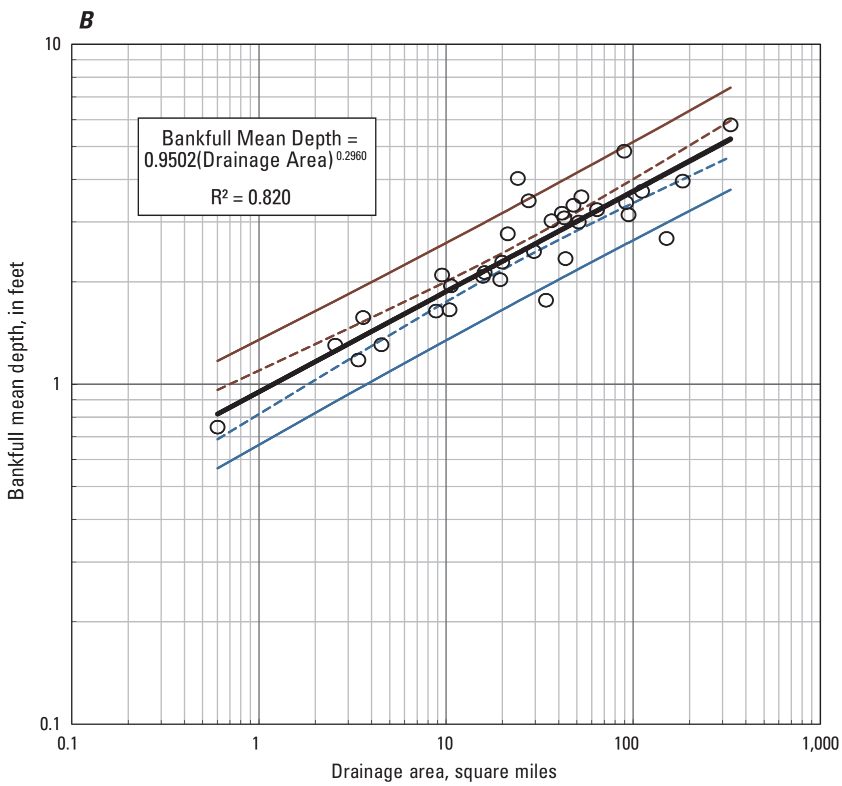


Figure 5. Regional curves of the relation between bankfull: *A,* width, *B,* mean depth, *C,* cross-sectional area, and *D,* discharge and drainage area for streams in and near Massachusetts.

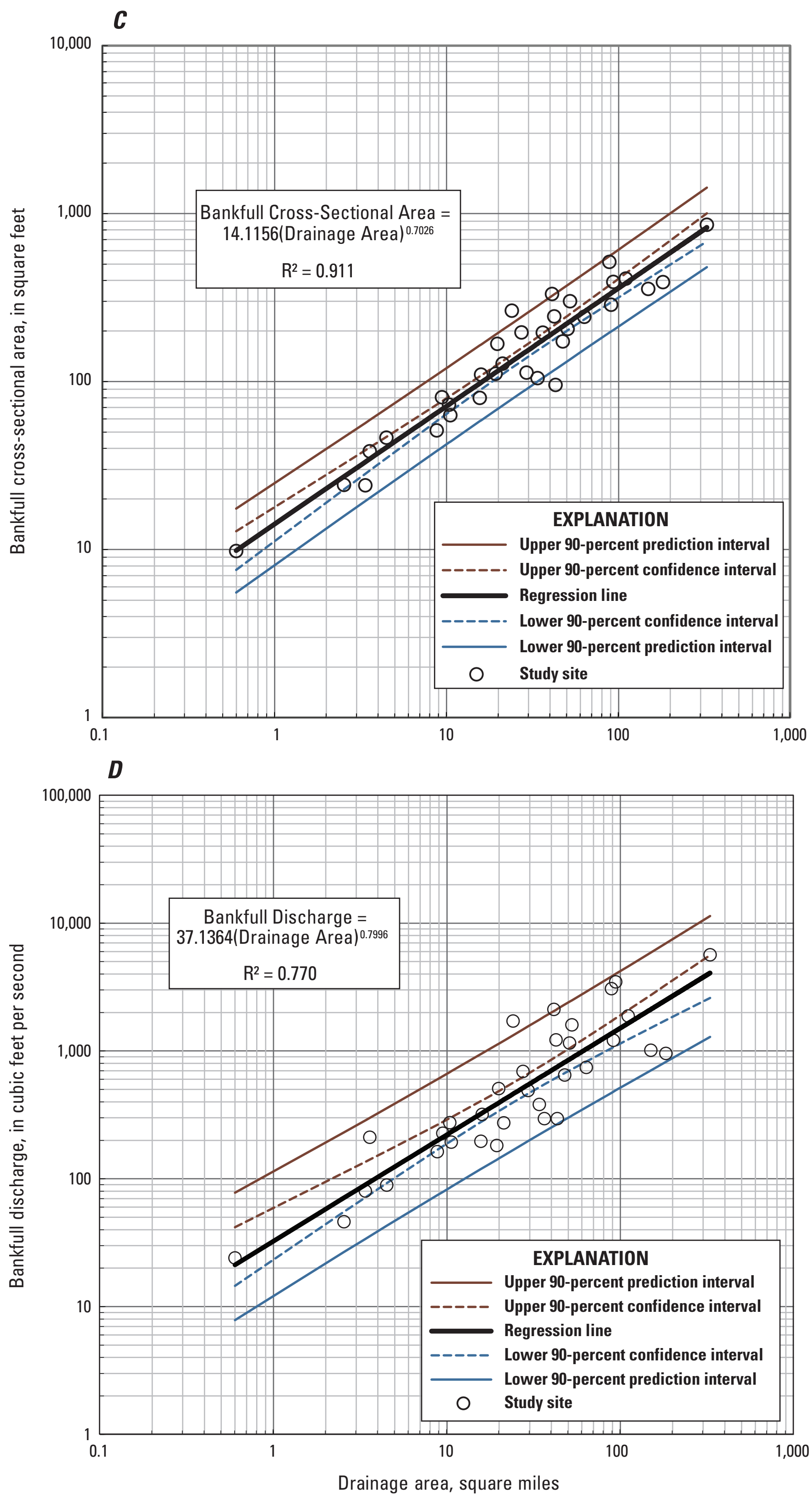


Figure 5. Regional curves of the relation between bankfull: *A,* width, *B,* mean depth, *C,* cross-sectional area, and *D,* discharge and drainage area for streams in and near Massachusetts.—Continued

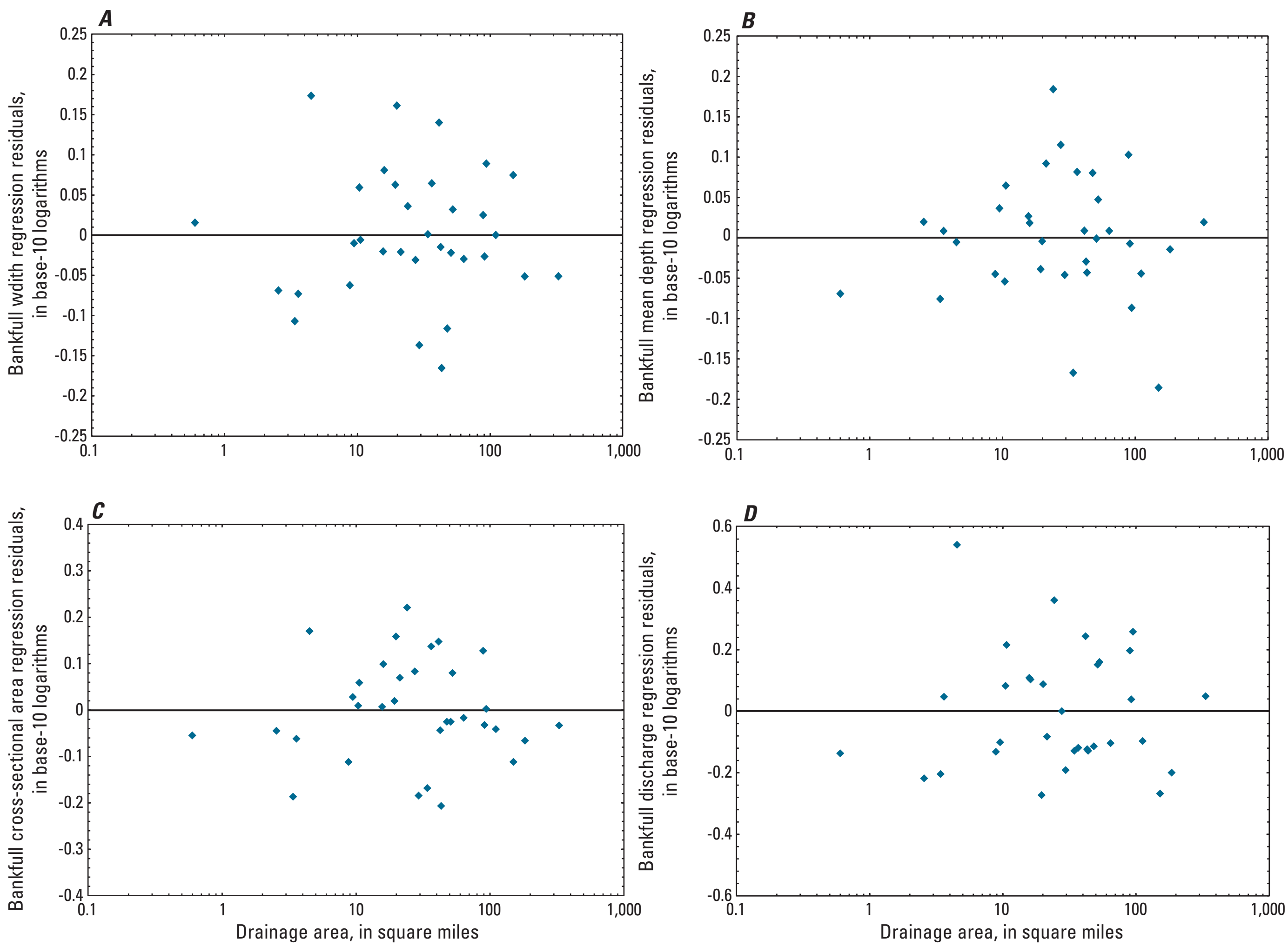


Figure 6. Multiple regression equation residuals in relation to drainage area for bankfull: *A,* width, *B,* mean depth, *C,* cross-sectional area, and *D,* discharge and in relation to mean basin slope for bankfull: *E,* width, *F,* mean depth, *G,* cross-sectional area, and *H,* discharge for streams in and near Massachusetts.

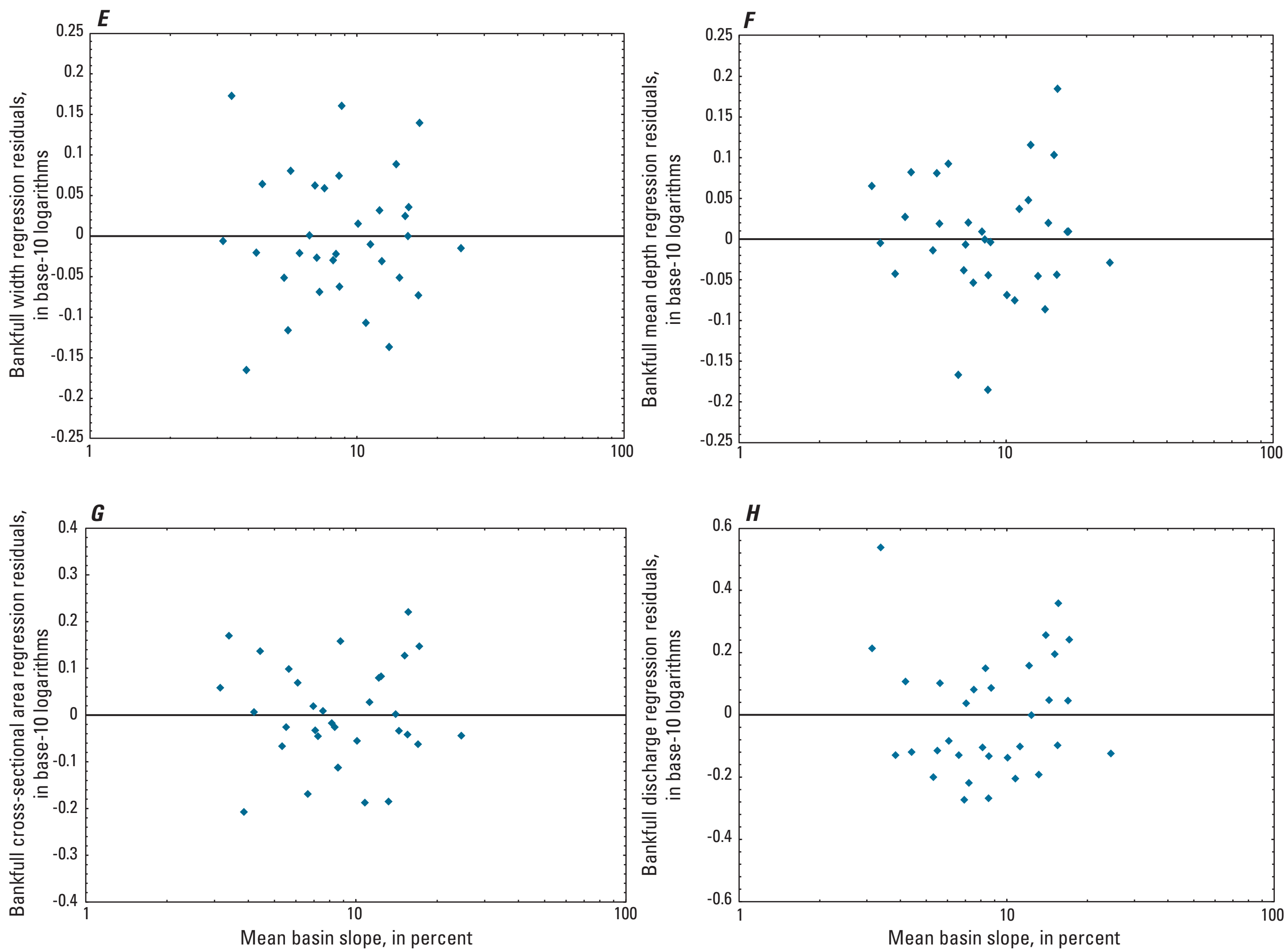


Figure 6. Multiple regression equation residuals in relation to drainage area for bankfull: *A,* width, *B,* mean depth, *C,* cross-sectional area, and *D,* discharge and in relation to mean basin slope for bankfull: *E,* width, *F,* mean depth, *G,* cross-sectional area, and *H,* discharge for streams in and near Massachusetts.—Continued

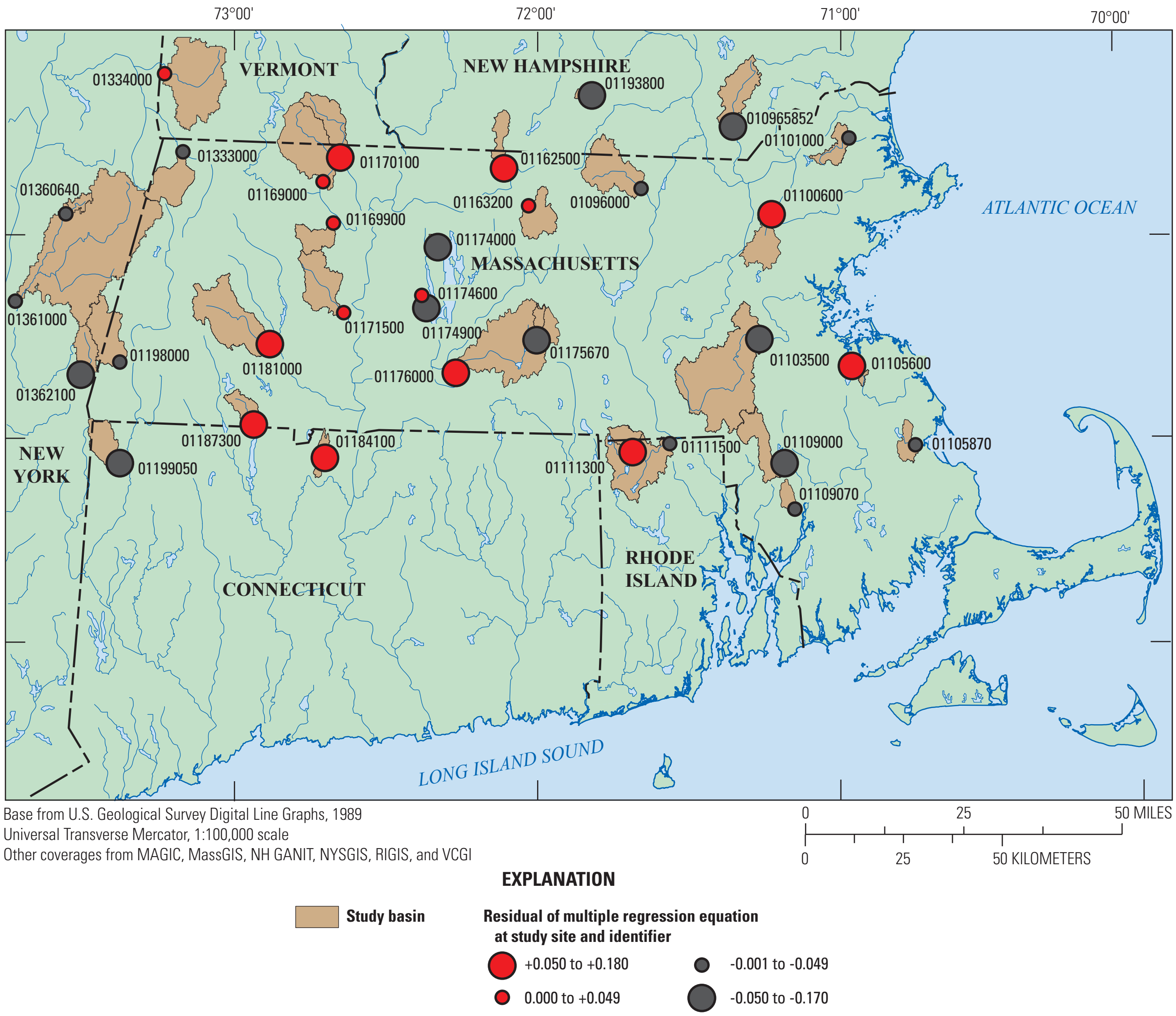


Figure 7. Geographic distribution of bankfull width multiple regression equation residuals for study sites in and near Massachusetts.

Confidence- and Prediction-Interval Estimation

An important adjunct to the estimation of bankfull discharge and channel geometry using the equations is the estimation of the confidence and prediction intervals of each value. The confidence interval provides an estimate for the mean of the response variable "*y*" (bankfull channel geometry and discharge) given any value of the independent explanatory variable "*x*" (drainage area and mean basin slope) (Helsel and Hirsch, 2002, p. 240–241, 300). The confidence intervals provide estimates of the lower and upper limits for the estimates of the bankfull channel geometry and discharge from the equations. For example, the 90-percent confidence interval for an estimated value (mean) of the response variable ("*y*" or bankfull channel geometry and discharge) defines the lower and upper limits between which the true estimate has a 90-percent chance of being found. In contrast, the prediction interval provides the confidence interval for an estimate of an individual response variable "*y*" (not the mean of the response variable "*y*") (Helsel and Hirsch, 2002, p. 241–242, 300). The prediction interval is different from the confidence interval in that it incorporates an additional term for the unexplained variability of the estimate and the slope and intercept of the equation. The lower and upper 90-percent confidence and prediction intervals are included on the plots of the regression equations (figs. 5A–D). The prediction interval is much wider than the confidence interval, and the lines appear to be parallel to the simple regression line, whereas the confidence interval is bowed.

Equations 16–19 were used to calculate the lower and upper 90-percent confidence and prediction intervals for the simple and multiple regression equations. These equations could be easily modified to calculate confidence and prediction intervals at different levels of significance; for example, to calculate 95-percent confidence and prediction intervals, an alpha value (α) of 0.05 would be used instead of the 90-percent confidence interval and prediction interval alpha value (α) of 0.10. For the simple and multiple regression equations, the lower and upper confidence and prediction interval equations are

$$Lower\ CI = \widehat{y_0} - \left(t_{n-p,\frac{\propto}{2}} \times s \times \sqrt{\left(x_0' \left(X'X \right)^{-1} x_0 \right)} \right), \quad (16)$$

$$Upper\ CI = \widehat{y_0} + \left(t_{n-p,\frac{\propto}{2}} \times s \times \sqrt{\left(x_0' \left(X'X \right)^{-1} x_0 \right)} \right), \quad (17)$$

$$Lower\ PI = \widehat{y_0} - \left(t_{n-p,\frac{\propto}{2}} \times s \times \sqrt{\left(1 + x_0' \left(X'X \right)^{-1} x_0 \right)} \right), \quad (18)$$

$$Upper\ PI = \widehat{y_0} + \left(t_{n-p,\frac{\propto}{2}} \times s \times \sqrt{\left(1 + x_0' \left(X'X \right)^{-1} x_0 \right)} \right), \quad (19)$$

where

CI = confidence interval;

PI = prediction interval;

$\widehat{y_0}$ = estimated bankfull width, mean depth, cross-sectional area, or discharge from equations 8–15 (table 6);

$t_{n-p,\frac{\propto}{2}}$ = the quartile of the student's t-distribution having n-p degrees of freedom with a probability of exceedance of $\frac{\propto}{2}$;

n = number of observations, 33 for this study;

p = number of parameters in the regression equation, 2 for the simple regression equations and 3 for the multiple regression equations (includes the intercept);

α = 0.10 for the 90-percent confidence and prediction intervals (0.05 for the 95-percent confidence and prediction intervals);

s = root mean square error;

$$x_0' = \begin{bmatrix} 1 \\ log_{10}\left(drainage\,area\right) \end{bmatrix} \text{ for the simple regression equations;}$$

$$x_0' = \begin{bmatrix} 1 \\ log_{10}\left(drainage\,area\right) \\ log_{10}\left(mean\,basin\,slope\right) \end{bmatrix} \text{ for the multiple regression equations;}$$

$$\left(X'X\right)^{-1} = \text{covariance matrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \text{ for simple regression equations;}$$

$$(X'X)^{-1} = \text{covariance matrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \text{ for multiple regression equations;}$$

$$x_0 = \begin{bmatrix} 1 & log_{10}(drainage\,area) \end{bmatrix} \text{ for simple regression equations; and}$$

$$x_0 = \begin{bmatrix} 1 & log_{10}(drainage\,area) & log_{10}(mean\,basin\,slope) \end{bmatrix} \text{ for multiple regression equations.}$$

Parameters of the confidence and prediction interval equations 16–19 for the simple and multiple regression equations are listed in table 7.

Application

Example calculations of the bankfull width are presented for the simple and multiple regression equations with the 90-percent confidence and prediction intervals. The example stream site used is USGS streamgage Green River near Great Barrington, Mass. (01198000), which has a drainage area of 51.0 mi^2 and a mean basin slope of 8.336 percent (table 5).

For the example calculations of bankfull width, equations 8 (simple regression) and 12 (multiple regression) (table 6) are used for the lower and upper 90-percent confidence and prediction intervals. Statistical data needed to compute the 90-percent lower and upper confidence and prediction intervals are in table 7.

Using the simple regression equation (equation 8, table 6),

Bankfull width = 15.0418 $(51.0)^{0.4038}$ = 73.59 ft.

To calculate the associated confidence and prediction intervals for the simple regression equation, the following matrix is computed:

$$x_0' = \begin{bmatrix} 1 \\ log_{10}(drainage\,area) \end{bmatrix} = \begin{bmatrix} 1 \\ log_{10}(51.0) \end{bmatrix} \begin{bmatrix} 1 \\ 1.7076 \end{bmatrix}$$

$$(X'X)^{-1} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} = \begin{bmatrix} 0.208608 & -0.127177 \\ -0.127177 & 0.090709 \end{bmatrix}$$

$$x_0 = \begin{bmatrix} 1 & log_{10}(drainage\,area) \end{bmatrix} = \begin{bmatrix} 1 & log_{10}(51.0) \end{bmatrix} = \begin{bmatrix} 1 & 1.7076 \end{bmatrix}$$

$$x_0' \times (X'X)^{-1} = \begin{bmatrix} (1 \times 0.208608) + (1.7076 \times -0.127177) \\ (1 \times -0.127177) + (1.7076 \times 0.090709) \end{bmatrix} = \begin{bmatrix} -0.008559 \\ 0.027718 \end{bmatrix}$$

$$x_0' \times (X'X)^{-1} \times x_0 = \begin{bmatrix} (-0.008559 \times 1) + (0.027718 \times 1.7076) \end{bmatrix} = 0.038772 \text{ .}$$

Table 7. Simple and multiple regression equation confidence and prediction interval parameters for estimating the bankfull width, mean depth, cross-sectional area, and discharge for streams in and near Massachusetts.

[t-90, the quartile of the student's t-distribution having either n-2 (simple regression) or n-p (multiple regression, p is the number of explanatory variable including the intercept, p = 3 for this study) degrees of freedom with a probability of exceedance of 0.05; t-95, the quartile of the student's t-distribution having either n-2 or n-p degrees of freedom with a probability of exceedance of 0.025; s, root mean square error; n, number of data points; $(X'X)^{-1}$, covariance matrix]

Bankfull equation	t-90	t-95	s	n	$(X'X)^{-1}$		
			Simple regression equations				
Width	1.696	2.040	0.0903	33	0.208608	-0.127177	
					-0.127177	0.090709	
Mean depth	1.696	2.040	0.0826	33	0.208608	-0.127177	
					-0.127177	0.090709	
Cross-sectional area	1.696	2.040	0.1308	33	0.208608	-0.127177	
					-0.127177	0.090709	
Discharge	1.696	2.040	0.2608	33	0.208608	-0.127177	
					-0.127177	0.090709	
			Multiple regression equations				
Width	1.697	2.042	0.0825	33	0.669743	-0.095301	-0.540629
					-0.095301	0.092912	-0.037371
					-0.540629	-0.037371	0.633828
Mean depth	1.697	2.042	0.0781	33	0.669743	-0.095301	-0.540629
					-0.095301	0.092912	-0.037371
					-0.540629	-0.037371	0.633828
Cross-sectional area	1.697	2.042	0.1123	33	0.669743	-0.095301	-0.540629
					-0.095301	0.092912	-0.037371
					-0.540629	-0.037371	0.633828
Discharge	1.697	2.042	0.1986	33	0.669743	-0.095301	-0.540629
					-0.095301	0.092912	-0.037371
					-0.540629	-0.037371	0.633828

The associated confidence and prediction intervals are

$$Lower\,CI = 10^{\hat{y}_0 - \left(t_{n-p,\frac{\alpha}{2}} \times s \times \sqrt{\left(x_0'(X'X)^{-1}x_0\right)}\right)} = 10^{1.8672 - 1.696 \times 0.0903 \times \sqrt{0.038772}} = 68.65 \text{ ft}$$

$$Upper\,CI = 10^{\hat{y}_0 + \left(t_{n-p,\frac{\alpha}{2}} \times s \times \sqrt{\left(x_0'(X'X)^{-1}x_0\right)}\right)} = 10^{1.8672 + 1.696 \times 0.0903 \times \sqrt{0.038772}} = 78.88 \text{ ft}$$

$$Lower\,PI = 10^{\hat{y}_0 - \left(t_{n-p,\frac{\alpha}{2}} \times s \times \sqrt{\left(1 + x_0'(X'X)^{-1}x_0\right)}\right)} = 10^{1.8672 - 1.696 \times 0.0903 \times \sqrt{1 + 0.038772}} = 51.37 \text{ ft}$$

$$Upper\,PI = 10^{\hat{y}_0 + \left(t_{n-p,\frac{\alpha}{2}} \times s \times \sqrt{\left(1 + x_0'(X'X)^{-1}x_0\right)}\right)} = 10^{1.8672 + 1.696 \times 0.0903 \times \sqrt{1 + 0.038772}} = 105.42 \text{ ft}.$$

Using the multiple regression equation (equation 12, table 6),

Bankfull width = 10.6640 $(51.0)^{0.3935}$ $(8.336)^{0.1751}$ = 72.63 ft.

To calculate the associated confidence and prediction intervals for the multiple regression equation, the following matrix is computed:

$$x_0' = \begin{bmatrix} 1 \\ log_{10}(drainage\,area) \\ log_{10}(mean\,basin\,slope) \end{bmatrix} = \begin{bmatrix} 1 \\ log_{10}(51.0) \\ log_{10}(8.336) \end{bmatrix} = \begin{bmatrix} 1 \\ 1.7076 \\ 0.9210 \end{bmatrix}$$

$$(X'X) = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} = \begin{bmatrix} 0.669743 & -0.095301 & -0.540629 \\ -0.095301 & 0.092912 & -0.037371 \\ -0.540629 & -0.037371 & 0.633828 \end{bmatrix}$$

$$x_0 = \begin{bmatrix} 1 & log_{10}(drainage\,area) & log_{10}(mean\,basin\,slope) \end{bmatrix} = \begin{bmatrix} 1 & log_{10}(51.0) & log_{10}(8.336) \end{bmatrix} = \begin{bmatrix} 1 & 1.7076 & 0.9210 \end{bmatrix}$$

$$x_0' \times (X'X)^{-1} = \begin{bmatrix} (1 \times 0.669743) + (1.7076 \times -0.095301) + (0.9210 \times -0.540629) \\ (1 \times -0.095301) + (1.7076 \times 0.092912) + (0.9210 \times -0.037371) \\ (1 \times -0.540629) + (1.7076 \times -0.037371) + (0.9210 \times 0.633828) \end{bmatrix} = \begin{bmatrix} 0.009088 \\ 0.028938 \\ -0.020688 \end{bmatrix}$$

$$x_0' \times (X'X)^{-1} \times x_0 = \left[(0.009088 \times 1) + (0.028938 \times 1.7076) + (-0.020688 \times 0.9210)\right] = 0.039448 \,.$$

The associated confidence and prediction intervals are

$$Lower\ CI = 10^{\widehat{y_0} - \left(t_{n-p,\frac{\propto}{2}} \times s \times \sqrt{\left(x_0'(X'X)^{-1} x_0\right)}\right)} = 10^{1.8800 - 1.697 \times 0.0825 \times \sqrt{0.039448}} = 68.12 \text{ ft}$$

$$Upper\ CI = 10^{\widehat{y_0} + \left(t_{n-p,\frac{\propto}{2}} \times s \times \sqrt{\left(x_0'(X'X)^{-1} x_0\right)}\right)} = 10^{1.8800 + 1.697 \times 0.0825 \times \sqrt{0.039448}} = 77.43 \text{ ft}$$

$$Lower\ PI = 10^{\widehat{y_0} - \left(t_{n-p,\frac{\propto}{2}} \times s \times \sqrt{\left(1 + x_0'(X'X)^{-1} x_0\right)}\right)} = 10^{1.8800 - 1.697 \times 0.0825 \times \sqrt{1 + 0.039448}} = 52.28 \text{ ft}$$

$$Upper\ PI = 10^{\widehat{y_0} + \left(t_{n-p,\frac{\propto}{2}} \times s \times \sqrt{\left(1 + x_0'(X'X)^{-1} x_0\right)}\right)} = 10^{1.8800 + 1.697 \times 0.0825 \times \sqrt{1 + 0.039448}} = 100.89 \text{ ft.}$$

The use of the multiple regression equation not only improves the estimated values of the bankfull width, but also results in narrower confidence and prediction intervals compared to those that result from the simple regression equations. This improvement in confidence intervals and prediction intervals also results when the multiple regression equations are used instead of the simple regression equations for bankfull cross-sectional area and discharge.

Comparison to Other Studies in the Eastern United States and Southeastern Canada

Several studies have been done to develop regional curves, simple regression equations, and multiple regression equations for areas of the eastern United States and southeastern Canada (table 8). Studies in Indiana, Maryland, Michigan, New York, North Carolina, Ohio, Pennsylvania, Vermont, Virginia, and southeastern Ontario used field methods consistent with those used in this study to develop regional curves and simple regression equations relating bankfull width, mean depth, cross-sectional area, and discharge. In most of these studies, the intercepts and slopes of the regional equations that include bankfull width, mean depth, cross-sectional area, and discharge regional equations generally are similar to those of this study (table 8). Additionally, median bankfull discharge recurrence intervals for all of these studies range from 1 to 2 years.

Several recent studies have shown that the coefficients of simple regression equations, using drainage area as the sole explanatory variable to predict bankfull geometry and discharge, do not differ substantially within the large areas of northeastern United States. Bent (2006) determined that several bankfull studies (table 8) in the Northeast generally could be represented with one equation for bankfull width, mean depth, cross-sectional area, and discharge. But, two studies had at least one bankfull equation that was significantly different from the northeastern United States set of equations—one study in the Coastal Plain physiographic province and one study in the Piedmont physiographic province. A similar study by Johnson and Fecko (2008) for the eastern United States, which used a different dataset than Bent (2006) but included data from several of the studies in table 8, determined that the Appalachian Plateau, New England, and Valley and Ridge physiographic provinces could be represented by one equation for bankfull width. They also found that bankfull width equations for the the Piedmont and Coastal Plain physiographic provinces were significantly different from equations for the other physiographic provinces. Faustini and others (2009) grouped bankfull width study sites in the northeastern United States into three major ecoregions (constructed by aggregating USEPA Level III ecoregions): the northern Appalachians, southern Appalachians, and Coastal Plains. The Faustini and others (2009) study did not include data from any bankfull studies listed in table 8. On the basis of these three regional studies, the Coastal Plain physiographic province in the northeastern United States likely is best represented by its own set of bankfull equations.

Table 8. Equation parameters used for estimating bankfull channel geometry and discharge by drainage area for selected hydrologic

[ft, foot; ft^2, square foot; ft^3/s, cubic foot per second; No., number; mi^2, square mile; R^2, coefficient of determination; --, no data; <, less than; ~, approximately; settings and 1 site from White (2001) in the carbonate settings. Cinotto (2003) includes 6 sites from White (2001). Chaplin (2005) includes 5 sites from White only 37 and 3 sites for Regions A and B, respectively, for the bankfull discharge equations. McCandless (2003b) used 9 sites for the eastern Coastal Plain bankfull in Virginia and the 14 sites used by McCandless (2003) for the Coastal Plain of Maryland and Delaware. R^2 values for Massachusetts (this study) and Ohio

State or area of United States	Hydrologic or physiographic region(s)	Reference	No. of sites	Drainage area range (mi^2)	Width (ft)		
					Intercept	Slope	R^2
Indiana	Northern Moraine and Lake Region	Robinson, 2013	25	0.26–941	13.4	0.318	0.92
	Central Till Plain Region		31	0.04–812	18.2	0.327	0.94
	Southern Hills and Lowlands Region		26	0.06–186	27.2	0.286	0.94
Maryland[1]	Allegheny Plateau/Valley and Ridge	McCandless, 2003a	14	0.2–73.1	13.87	0.44	0.92
Maryland	Coastal Plain	McCandless, 2003b	14	0.3–113	10.3	0.38	0.8
Maryland[1]	Piedmont	McCandless and Everett, 2002	23	1.47–102	14.78	0.39	0.83
Maine	Coastal and central	Dudley, 2004	15	2.92–298	7.67	0.52	0.82
Massachusetts[1]	Statewide	This study	33	0.60–329	15.0418	0.4038	0.88
Michigan	Southern Lower Michigan Ecoregion	Rachol and Boley-Morse, 2009	28	20.9–385	8.19	0.44	0.69
New Hampshire[1]	Statewide	Shane Csiiki, NH Department of Environmental Services, written commun., 2013	20	2.94–385	12.335	0.4832	0.79
New York[1]	Hydrologic region 4/4a	Miller and Davis, 2003	18	3.72–332	12.51	0.51	0.88
New York[1]	Hydrologic region 5	Westergard and others, 2005	16	0.7–332	13.2	0.459	0.9
New York[1]	Hydrologic region 6	Mulvihill and others, 2005	14	1.02–290	16.9	0.419	0.79
New York[1]	Hydrologic region 7	Mulvihill and others, 2006	10	1.07–349	10.8	0.458	0.89
New York[1]	Hydrologic region 3	Mulvihill and Baldigo, 2007	12	0.42–329	24	0.292	0.85
New York[1]	Hydrologic region 1 and 2	Mulvihill and others, 2007	16	0.52–396	21.5	0.362	0.89
North Carolina	Coastal Plain	Sweet and Geratz, 2003	22	0.6–182	9.64	0.38	0.95
North Carolina	Mountains	Harman and others, 2000	12	2.0–126	19.9	0.36	0.81
North Carolina	Piedmont-rural	Harman and others, 1999	13	0.2–128	11.89	0.43	0.81
North Carolina	Piedmont-urban	Doll and others, 2002	17	0.2–42.6	24.39	0.33	0.88
Ohio	Region A	Sherwood and Huitger, 2005	45	0.29–685	18	0.356	0.91
Ohio	Region B	Sherwood and Huitger, 2005	5	0.55–387	32	0.356	0.91
Pennsylvania	Piedmont	White, 2001	6	2.57–102	14.8	0.4613	0.79

regions or physiographic provinces and states in the eastern United States and southeastern Canada.

Note: Cinotto (2003) includes 6 sites from White (2001). Chaplin (2005) includes 5 sites from White (2001) and 8 sites from Cinotto (2003) in the non-carbonate (2001) and 8 sites from Cinotto (2003) in the non-carbonate settings and 1 site from White (2001) in the carbonate settings. Sherwood and Huitger (2005) used discharge equation and 5 sites for the western Coastal Plain bankfull discharge equation. Krstolic and Chaplin (2007) used 6 Coastal Plain sites from their study (Sherwood and Huitger, 2005) equations are the adjusted R^2. Annable (1996a and b) does not include sites for which bankfull discharge was not determined]

Mean depth (ft)			Cross-sectional area (ft^2)			Discharge (ft^3/s)			Remarks	Range of recurrence intervals for bankfull discharge (years)	Median bankfull recurrence interval
Intercept	Slope	R^2	Intercept	Slope	R^2	Intercept	Slope	R^2			
1.3	0.176	0.75	17.0	0.495	0.92	--	--	--		--	--
1.6	0.159	0.56	28.8	0.487	0.88	--	--	--		--	--
1.9	0.183	0.58	50.9	0.468	0.87	--	--	--		--	--
0.95	0.31	0.91	13.17	0.75	0.93	34.02	0.94	0.99		1.05–1.8	1.51
1.01	0.32	0.87	10.34	0.7	0.96	14.65	0.76	0.97	Eastern Coastal Plain	1.04–1.37	1.14
						31.35	0.73	0.98	Western Coastal Plain		
1.18	0.34	0.86	17.42	0.73	0.95	84.56	0.76	0.93		1.26–1.75	1.5
0.594	0.34	0.76	4.55	0.86	0.82	5.19	1.05	0.88		<1.0	<1.0
0.9502	0.296	0.82	14.1156	0.7026	0.91	37.1364	0.7996	0.77		1.03–3.52	1.39
0.67	0.27	0.28	4.38	0.74	0.59	4.05	0.95	0.6		<1.005–10	1.25
1.2277	0.2803	0.8	15.028	0.7649	0.85	41.448	0.9191	0.8		--	--
1.01	0.31	0.85	12.67	0.81	0.9	62.96	0.87	0.81		1.2–2.7	1.42
0.802	0.367	0.91	10.6	0.826	0.98	45.5	0.84	0.94		1.11–6.00	1.39
1.04	0.244	0.64	17.6	0.662	0.89	48	0.842	0.9		1.01–2.35	1.52
1.47	0.199	0.52	15.9	0.656	0.96	37.1	0.765	0.94		1.05–3.60	1.78
1.66	0.21	0.77	39.8	0.503	0.92	83.8	0.679	0.93		1.16–3.35	2
1.06	0.329	0.89	22.3	0.694	0.97	49.6	0.849	0.95		1.01–3.80	1.95
0.98	0.36	0.92	9.43	0.74	0.96	8.79	0.76	0.92		<1.0–1.1	<1.0
1.1	0.31	0.79	22.1	0.67	0.88	115.7	0.73	0.88		1.10–1.90	1.59
1.5	0.32	0.88	21.43	0.68	0.95	89.04	0.72	0.97		1.1–1.8	1.4
2.43	0.33	0.87	60.34	0.65	0.95	306.8	0.63	0.94		1.1–1.5	1.3
1.52	0.265	0.88	27.1	0.621	0.95	93.3	0.637	0.82		1.01–9.65	1.36
2.02	0.265	0.88	64.5	0.621	0.95	230	0.637	0.82		1.26–5.55	1.78
0.7804	0.3919	0.84	11.69	0.8517	0.98	69.6	0.793	0.98		1.2–1.5	1.4

Table 8. Equation parameters used for estimating bankfull channel geometry and discharge by drainage area for selected hydrologic

[ft, foot; ft^2, square foot; ft^3/s, cubic foot per second; No., number; mi^2, square mile; R^2, coefficient of determination; --, no data; <, less than; ~, approximately; settings and 1 site from White (2001) in the carbonate settings. Cinotto (2003) includes 6 sites from White (2001). Chaplin (2005) includes 5 sites from White only 37 and 3 sites for Regions A and B, respectively, for the bankfull discharge equations. McCandless (2003b) used 9 sites for the eastern Coastal Plain bankfull in Virginia and the 14 sites used by McCandless (2003) for the Coastal Plain of Maryland and Delaware. R^2 values for Massachusetts (this study) and Ohio

State or area of United States	Hydrologic or physiographic region(s)	Reference	No. of sites	Drainage area range (mi^2)	Width (ft)		
					Intercept	Slope	R^2
Pennsylvania	Piedmont	Cinotto, 2003	14	2.57–102	13.6	0.469	0.8
Pennsylvania[1]	Non-carbonate areas	Chaplin, 2005	55	3.45–214	14.65	0.449	0.81
Pennsylvania[1]	Carbonate areas	Chaplin, 2005	11	2.57–216	9.83	0.449	0.81
Vermont[1]	Statewide	Jaquith and Kline, 2001	14	8.9–139	10.18	0.5	0.78
Virginia, Maryland, and West Virginia[1]	Valley and Ridge	Keaton and others, 2005	41	0.1–247	12.445	0.4362	0.89
Virginia and Maryland	Coastal Plain	Krstolic and Chaplin, 2007	20	0.28–113	11.9899	0.63803	0.94
Virginia[1]	Piedmont	Lotspeich, 2009	17	0.29–111	12.964	0.3721	0.913
West Virginia	Eastern region (Valley and Ridge)	Messinger and Wiley, 2004	11–18	46.5–1,619	8.76	0.503	0.54
	Western region (Appalachian Plateau)		36–56	2.78–1,354	16	0.423	0.84
West Virginia[1]	Appalachian Plateau	Messinger, 2009	37	0.76–205	20.4865	0.7133	0.9492
Ontario, Canada	Southern	Annable, 1996a and b	47	7.3–456	9.4571	0.442	0.58
Northeast	Appalachian Plateau, Coastal Plain, New England, Piedmont, and Valley and Ridge	Bent, 2006	204	0.20–332	13.2635	0.4459	0.82
Eastern	Eastern Highlands	Faustini and others, 2009	275	~0.4–730	12.62	0.38	0.75
Northeast	Northern Appalachians	Faustini and others, 2009	87	~1–250	12.13	0.39	0.72
Eastern	Southern Appalachians	Faustini and others, 2009	188	~0.4–730	12.69	0.37	0.77
Northeast	New England	Faustini and others, 2009	45	~1–250	13.02	0.37	0.60
Northeast	Mid-Atlantic	Faustini and others, 2009	77	~1–250	12.11	0.38	0.75
Eastern	Appalachian Plateau, New England, and Valley and Ridge	Johnson and Fecko, 2008	154	~0.2–350	13.34	0.45	--
Eastern	Piedmont	Johnson and Fecko, 2008	36	~0.3–200	13.98	0.39	--
Eastern	Coastal Plain	Johnson and Fecko, 2008	68	~0.3–420	10.41	0.38	--
Northeast	Appalachian Plateau, New England, Piedmont, and Valley and Ridge	This study	334	0.1–396	15.1988	0.4190	0.86

[1]Study used in northeastern United States bankfull width regression equation covering the Appalachian Plateau, New England, Piedmont, and Valley and Ridge

regions or physiographic provinces and states in the eastern United States and southeastern Canada.—Continued

Note: Cinotto (2003) includes 6 sites from White (2001). Chaplin (2005) includes 5 sites from White (2001) and 8 sites from Cinotto (2003) in the non-carbonate (2001) and 8 sites from Cinotto (2003) in the non-carbonate settings and 1 site from White (2001) in the carbonate settings. Sherwood and Huitger (2005) used discharge equation and 5 sites for the western Coastal Plain bankfull discharge equation. Krstolic and Chaplin (2007) used 6 Coastal Plain sites from their study (Sherwood and Huitger, 2005) equations are the adjusted R^2. Annable (1996a and b) does not include sites for which bankfull discharge was not determined]

Mean depth (ft)			Cross-sectional area (ft^2)			Discharge (ft^3/s)			Remarks	Range of recurrence intervals for bankfull discharge (years)	Median bankfull recurrence interval
Intercept	Slope	R^2	Intercept	Slope	R^2	Intercept	Slope	R^2			
0.912	0.339	0.72	12.4	0.81	0.94	53.1	0.842	0.93		1–1.5	1.3
0.875	0.33	0.72	12.04	0.797	0.92	43.21	0.867	0.92		1.0–1.9	1.4
0.894	0.284	0.76	8.62	0.734	0.88	44.29	0.634	0.73		1.2–2.3	1.5
1.22	0.25	0.59	12.21	0.75	0.85	17.69	1.07	0.81		1.12–1.86	1.5
1.001	0.2881	0.87	12.595	0.7221	0.94	43.249	0.7938	0.91		<1.1–2.3	1.3
1.145	0.27345	0.87	10.4459	0.36543	0.89	28.3076	0.59834	0.79		<1–2.1	1.15
0.892	0.3721	0.915	11.636	0.7981	0.95	43.895	0.9472	0.949		1–4.3	1.5
0.59	0.411	0.72	5.48	0.917	0.9	--	--	--		--	--
1.32	0.351	0.71	18.2	0.797	0.93	--	--	--		--	--
1.067	0.3128	0.8783	20.4865	0.7133	0.9767	59.81	0.8538	0.9592		1.1–3	1.4
1.2033	0.2345	0.31	3.4685	0.6765	0.7	41.662	0.7217	0.63		--	--
0.9951	0.3012	0.76	12.8552	0.7537	0.90	40.9545	0.8448	0.80		--	--
--	--	--	--	--	--	--	--	--		--	--
--	--	--	--	--	--	--	--	--		--	--
--	--	--	--	--	--	--	--	--		--	--
--	--	--	--	--	--	--	--	--		--	--
--	--	--	--	--	--	--	--	--		--	--
--	--	--	--	--	--	--	--	--		--	--
--	--	--	--	--	--	--	--	--		--	--
--	--	--	--	--	--	--	--	--		--	--
1.0377	0.2989	0.80	15.5826	0.7198	0.92	49.4778	0.8206	0.88		--	--

physiographic provinces, and shown in figure 8.

The equations and data for bankfull width developed for Massachusetts in the present study are compared in figure 8 to the equations and data for bankfull width developed by the previous 15 studies listed in table 8 that were located in the northeastern United States. The 15 previous studies in the northeastern United States studies addressed in figure 8 include studies in Maryland (two physiographic provinces), New Hampshire (statewide), New York (six hydrologic regions), Pennsylvania (carbonate and non-carbonate regions), Vermont (statewide), Virginia (two physiographic provinces), and West Virginia (one physiographic province). The earlier Pennsylvania studies by White (2001) and Cinotto (2003) were included, although they are listed as not being included in table 8) because their data are in the statewide Pennsylvania study by Chaplin (2005). The Coastal Plain physiographic province studies in Maryland (McCandless, 2003b) and Virginia (Krstolic and Chaplin, 2007) were not included because their equations did not compare well with those of the other 15 studies and the present study for Massachusetts. The study in Maine (Dudley, 2004) and the earlier study in West Virginia (Messinger and Wiley, 2004) are not included in figure 8; the equations from these studies were not considered comparable because they were developed using office records of data obtained during discharge measurements rather than data from field surveys of stream reaches specifically conducted for bankfull studies. The studies in table 8 from Indiana, Michigan, North Carolina, Ohio, and southern Ontario, Canada, were excluded because they were not considered part of the Northeast. Thus, the 15 previous studies and the present study for Massachusetts included in figure 8 represent the Appalachian Plateau, New England, Piedmont, and Valley and Ridge physiographic provinces in the northeastern United States.

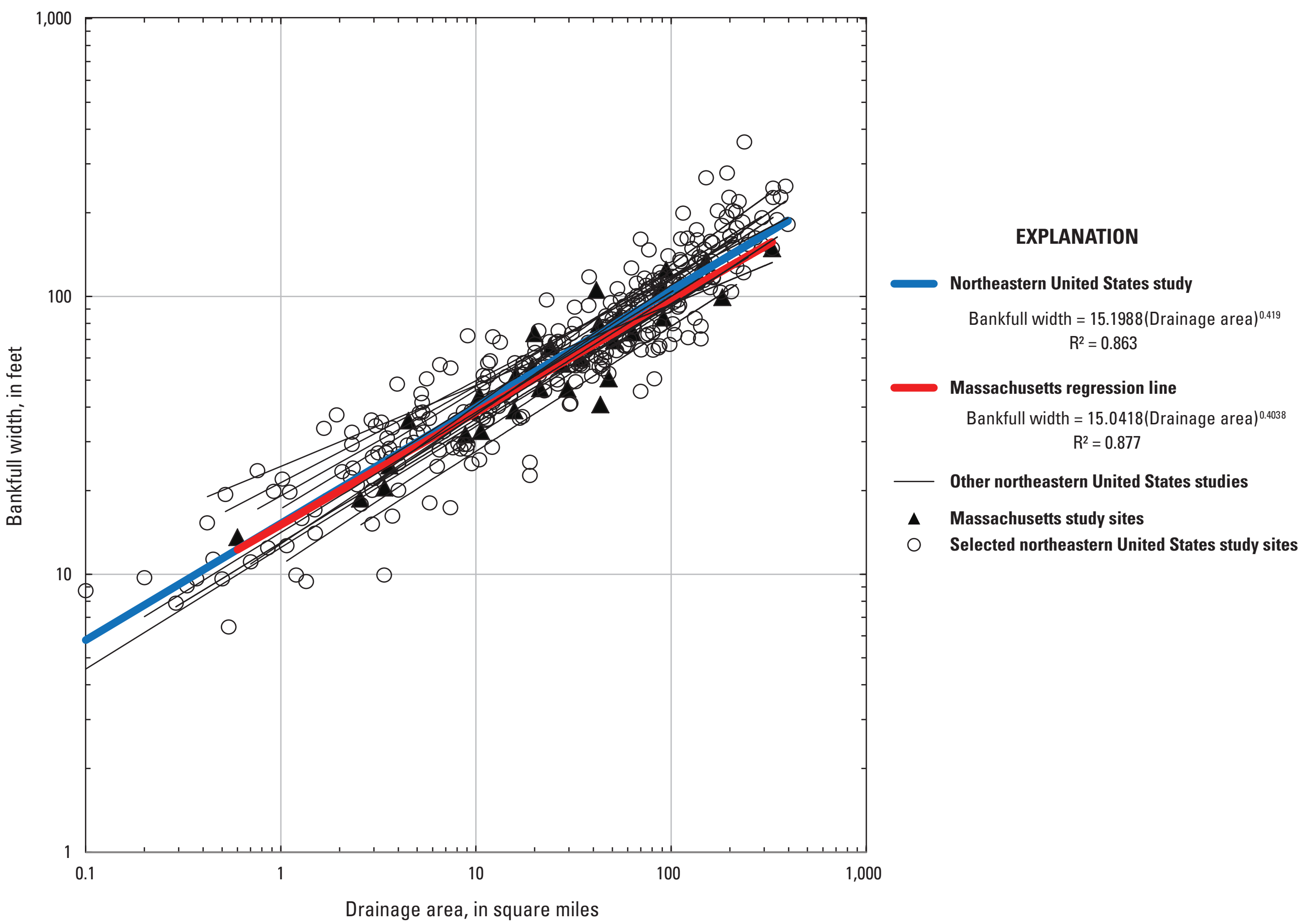


Figure 8. Regression lines for bankfull width in relation to drainage area for selected studies in the northeastern United States.

For the 16 bankfull width equations (15 previous studies and the present study for Massachusetts) shown in figure 8, the y-intercepts ranged from 9.83 to 24 with a median of 13.87, and the slopes ranged from 0.292 to 0.7133 with a median of 0.44 (table 8). A regression equation that would represent the 334 study sites for these 16 bankfull width equations across the northeastern United States would have a y-intercept of 15.1988 and a slope of 0.4190 with a predicted R^2 of 0.8607. This general equation for bankfull width for the northeastern United States is similar to equations published by Bent (2006) for the Northeast, by Johnson and Fecko (2008) for the Piedmont and Appalachian-New England-Valley and Ridge physiographic provinces, and by Faustini and others (2009) for the northern and southern Appalachian and New England and Mid-Atlantic water-resources regions (table 8). Bankfull equations for mean depth, cross-sectional area, and discharge for these 334 study sites (from the 15 previous studies and the present study) for the northeastern United States (Appalachian, New England, Piedmont, and Valley and Ridge physiographic provinces) are also listed in table 8. The regression summary statistics and analyses results for these northeastern United States bankfull channel geometry and discharge equations are in appendix 4.

Several studies in other states determined multiple regression equations to estimate more accurately bankfull characteristics. In Ohio, Sherwood and Huitger (2005) determined that bankfull characteristics could be estimated better with multiple regression equations than with simple regression equations that use drainage area as the sole explanatory variable. They found that main-channel slope and mean main-channel elevation (measured using geographic information systems) were significant variables, in addition to drainage area, and that local channel slope and bed-material size were significant variables if they could be field measured at the site of interest. In Virginia, Keaton and others (2005) also determined that bankfull characteristics could be estimated better with multiple regression equations than with simple regression equations using drainage area. They found that the percentage of carbonate bedrock underlying the basin was a significant explanatory variable in addition to drainage area in estimating bankfull width, cross-sectional area, and discharge.

Limitations of the Regional Curves and Regression Equations and Areas for Further Study

The bankfull channel geometry and discharge regional curves and equations are applicable for stream sites with drainage areas of 0.60 to 329 mi^2 and mean basin slopes of 2.2 to 23.9 percent (range of these basin characteristics for the stream sites used to develop the regional curves and equations). The equations, which are based on data from streams without regulated peak flows, most likely are applicable to all streams without flood control structures, such as dams, levees, diversions, and so forth. If a stream site has regulated peak flows, the regional curves and equations estimate the bankfull channel geometry and discharge as if the stream were naturally flowing.

The bankfull channel geometry and discharge regional curves and equations may not be applicable in areas of Massachusetts where basin, land use, or climatic conditions are appreciably different from those of the sites used to develop the curves and equations. For example, the equations might not apply to streams with drainage basins in which the urban land use (commercial, industrial, transportation, and high-density residential) is greater than about 25 percent of the total land area. In basins with more urban land, runoff peaks can be greatly increased in magnitude. This may affect the bankfull channel forming discharges, which may in turn affect the bankfull channel geometry characteristics. Basins with more urban land also may have stream channels that have been altered by development, which may result in unnatural bankfull channel geometry characteristics. Additionally, the regional curves and equations may not be applicable for streams in basins where the surficial geology is almost entirely stratified deposits. Stratified deposits are present mainly on Cape Cod and the Islands and in southeastern Massachusetts close to Cape Cod (area labeled as USEPA Level III ecoregion, Atlantic Coastal Pine Barrens in fig. 2). In these areas, precipitation mainly percolates into the soil and through the unsaturated zone to the groundwater table (reducing surface runoff) and later discharges to the stream as base flow. Thus, runoff peaks can be greatly diminished in magnitude, which may affect the bankfull channel forming discharges. The equations also may not be applicable where streams flow through extensive wetlands.

The accuracy of the regional curves and regression equations are a function of the quality of the data used in their development. These data include identification of the bankfull stage indicators, measurement of the bankfull channel geometry characteristics, the occurrence of unknown regulation that might affect peak flows upstream from a site, and the measured basin characteristics. Basin characteristics of the stream sites used in the development of the regional curves and regression equations are limited by the accuracy of the digital data layers used. Digital data layers [such as digital elevation models (DEMs) (U.S. Geological Survey, 2007a), hydrography (U.S. Geological Survey, 2007b), wetlands (MassGIS, 2011), surficial geology (MassGIS, 2007), soils (U.S. Department of Agriculture, Natural Resources Conservation Service, Soil Survey Division, 2004; MassGIS, 2012), and land use (MassGIS, 2009)] in the future will likely become available at scales with better spatial resolutions than are currently (2013) available. These digital data layers likely would improve the accuracy of the measured basin characteristics used as explanatory variables to predict bankfull channel geometry and discharge, but re-examination of the regression equations would be required. Digital data layers that might improve the equation include

(1) county-level soil-survey maps referred to as Soil Survey Geographic (SSURGO) database (U.S. Department of Agriculture, Natural Resources Conservation Service, Soil Survey Division, 2004; MassGIS, 2012); (2) 1970–2000 climate data available through the Parameter-elevation Regressions on Independent Slopes Model (PRISM) climate-mapping system of Spatial Climate Analysis Service at Oregon State University (http://www.ocs.oregonstate.edu/prism/); and (3) statewide wetlands (1:12,000 scale) interpreted from stereo color-infrared photography (MassGIS, 2011).

The regression equations could be incorporated into a Web-based application of the USGS STREAMSTATS Program (http://water.usgs.gov/osw/programs/streamstats.html). A map-based interface is used in the Web-based application that allows a user to point and click on any stream site, and the application will calculate selected streamflow statistics for an ungaged site, or the user can view available selected streamflow statistics for a gaged site. In a similar manner, a user could click on any stream site in Massachusetts, and the appropriate equation will estimate the bankfull width, mean depth, cross-sectional area, and discharge with the 90-percent prediction intervals.

Summary and Conclusions

Regional curves, simple regression equations, and multiple regression equations were developed for estimating bankfull width, mean depth, cross-sectional area, and discharge for streams in Massachusetts. The curves and equations provide water-resource and conservation managers with methods for estimating bankfull characteristics at a specific stream site in Massachusetts. This information will assist the environmental agencies that administer the Commonwealth of Massachusetts Rivers Protection Act of 1996, which establishes a 200-foot-wide protected riverfront area extending from the mean-annual high-water line (bankfull) along each side of a perennial stream, with exceptions for some densely developed areas (25-foot wide). Additionally, information on bankfull channel geometry and discharge are important to Federal, State, and local governments and private organizations involved in stream assessment and restoration projects.

The regional curves and equations were developed from stream surveys at 33 U.S. Geological Survey streamgages in and near Massachusetts. Drainage areas of the 33 sites ranged from 0.60 to 329 square miles (mi^2). The surveys included identification of bankfull stage at 14 to 25 locations about a bankfull width apart along the stream reach at each of the 27 sites. At 2 of these locations at each of the 27 sites, a detailed cross section was surveyed to determine the bankfull width, mean depth, and cross-sectional area and to characterize the streambed material, using 50-point pebble count of the intermediate particle-size diameter. Bankfull discharge and the associated recurrence interval were estimated at each of the 33 sites. The average and median recurrence intervals of bankfull discharge in and near Massachusetts were estimated to be 1.53 and 1.34 years, respectively.

Regional curves and simple regression equations developed for bankfull width, mean depth, cross-sectional area, and discharge used drainage area as the sole explanatory variable. Drainage area is the most significant explanatory variable in estimating these bankfull characteristics, and it is also the most commonly used variable for estimation of these bankfull characteristics. Additionally, statistical analyses determined that estimation of bankfull characteristics could be improved with multiple regression equations, which include the explanatory variable mean basin slope in addition to the drainage area. Results of simple regression equations using drainage area were compared to results from other bankfull studies in the northeastern United States. The Massachusetts bankfull characteristics curves and equations compared well with similar studies in areas of Maryland, New Hampshire, New York, Pennsylvania, Vermont, and Virginia, excluding the Coastal Plain physiographic province in Maryland and Virginia. The curves and equations also compared well with those developed for the northeastern United States (excluding the Coastal Plain phyiographic province) using data from the previous studies in these states.

Limitations associated with site selection and development of the regression equations result in some constraints for the application of equations presented in this report. These equations apply only to streams within the study area having (1) a basin area that contains less than about 25 percent urban area; (2) little to no streamflow regulation, especially by flood-control structures; (3) drainage areas greater than 0.60 mi^2 and less than 329 mi^2, and (4) a mean basin slope greater than 2.2 percent and less than about 23.9 percent. The equations may not be applicable for streams in basins where the surficial geology is almost entirely stratified deposits. These stratified deposits are present mainly on Cape Cod and the Islands and in southeastern Massachusetts close to Cape Cod. The equations also may not be applicable where streams flow through extensive wetlands. Regardless of the setting, the regional curves presented in this report are not intended for use as the sole method for estimating bankfull characteristics; however, they may supplement field identification of the bankfull channel when used in conjunction with field-verified bankfull indicators, flood-frequency analysis, or other supporting evidence.

References Cited

Ahearn, E.A., 2004, Regression equations for estimating flood flows for the 2-, 10-, 25, 50-, 100-, and 500-year recurrence intervals in Connecticut: U.S. Geological Survey Scientific Investigations Report 2004–5160, 68 p., http://pubs.usgs.gov/sir/2004/5160/pdf/sir2004-5160.pdf.

Annable, W.K., 1996a, Database of morphologic characteristics of watercourses in southern Ontario: Credit Valley Conservation Authority and the Ontario Ministry of Natural Resources, Watershed Science Centre, Trent University, 212 p.

Annable, W.K., 1996b, Morphologic relationships of rural watercourses in southern Ontario and selected field methods in fluvial geomorphology: Credit Valley Conservation Authority and the Ontario Ministry of Natural Resources, Watershed Science Centre, Trent University, 92 p.

Armstrong, D.S., Parker, G.W., and Richards, T.A., 2008, Characteristics and classification of least altered streamflows in Massachusetts: U.S. Geological Survey Scientific Investigations Report 2007–5291, 113 p., plus CD–ROM, http://pubs.usgs.gov/sir/2007/5291/.

Bent, G.C., 2006, Equations for estimating bankfull channel geometry and discharge for streams in the northeastern United States [abs.]: Proceedings of the Eighth Interagency Sedimentation Conference, Reno, Nevada, April 2–6, 2006, p. 1026, accessed April 16, 2013, http://pubs.usgs.gov/misc_reports/FISC_1947-2006/pdf/1st-7thFISCs-CD/8thFISC/Poster_Bent_AbstractOnly.pdf.

Chaplin, J.J., 2005, Development of regional curves relating bankfull channel geometry and discharge to drainage area for streams in Pennsylvania and selected areas of Maryland: U.S. Geological Survey Scientific Investigations Report 2005–5147, 34 p., http://pubs.usgs.gov/sir/2005/5147/SIR2005-5147.pdf.

Cinotto, P.J., 2003, Development of regional curves of bankfull channel geometry and discharge for streams in non-urban Piedmont Physiographic Province, Pennsylvania and Maryland: U.S. Geological Survey Water-Resources Investigations Report 03–4014, 27 p., http://pa.water.usgs.gov/reports/wrir03-4014.pdf.

Denny, C.S., 1982, Geomorphology of New England: U.S. Geological Survey Professional Paper 1208, 18 p., 1 pl.

Doll, B.A., Wise-Frederick, D.E., Buckner, C.M., Wilkerson, S.D., Harman, W.A., Smith, R.E., and Spooner, Jean, 2002, Hydraulic geometry relationships for urban stream throughout the Piedmont of North Carolina: Journal of the American Water Resources Association, v. 38, no. 3, p. 641–651.

Dudley, R.W., 2004, Hydraulic geometry relations for rivers in coastal and central Maine: U.S. Geological Survey Scientific Investigations Report 2004–5042, 30 p., http://water.usgs.gov/pubs/sir/2004/5042/.

Dunne, T., and Leopold, L.B., 1978, Water in environmental planning: San Francisco, Calif., W.H. Freeman, 818 p.

Emmett, W.W., 2004, A historical perspective on regional channel geometry curves: Stream Notes, January 2004, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Stream Technology Center, p. 5–6, accessed April 16, 2013, http://stream.fs.fed.us/news/streamnt/pdf/jan04.pdf.

Falcone, J.A., 2011, GAGES-II: Geospatial Attributes of Gages for Evaluating Streamflow [digital spatial dataset], accessed May 28, 2012, at http://water.usgs.gov/GIS/metadata/usgswrd/XML/gagesII_Sept2011.xml.

Faustini, J.M., Kaufmann, P.R., and Herlihy, A.T., 2009, Downstream variation in bankfull width of wadeable streams across the conterminous United States: Geomorphology, v. 108, p. 292–311.

Harman, W.A., Wise, D.E., Walker, M.A., Morris, R., Cantrell, M.A., Clemmons, M., Jennings, G.D., Clinton, D., and Patterson, J.M., 2000, Bankfull regional curves for North Carolina mountain streams, *in* Kane, D.L., ed., American Water Resources Association, Water Resources in Extreme Environments Symposium, AWRA TPS-00-1, p. 185–190.

Harman, W.H., Jennings, G.D., Patterson, J.M., Clinton, D.R., Slate, L.O., Jessup, A.G., Everhart, J.R., and Smith, R.E., 1999, Bankfull hydraulic geometry relationships for North Carolina streams, *in* Olsen, D.S., and Potyondy, J.P., eds., American Water Resources Association, Wildland Hydrology Symposium, Proceedings: Bozeman, Montana, Summer Symposium June 30–July 2, 1999, AWRA TPS-99-3, p. 401–408.

Harrelson, C.C., Rawlins C.L., and Potyondy, J.P., 1994, Stream channel reference sites: an illustrated guide to field technique: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, General Technical Report RM-245, 61 p., accessed April 16, 2013, http://www.fs.fed.us/rm/pubs_rm/rm_gtr245.pdf.

Helsel, D.R., and Hirsch, R.M., 2002, Statistical methods in water resources: U.S. Geological Survey Techniques of Water-Resources Investigations, book 4, Hydrologic analysis and interpretation, chap. A3, 510 p., http://pubs.usgs.gov/twri/twri4a3/pdf/twri4a3-new.pdf.

Hodgkins, Glenn, 1999, Estimating the magnitude of peak flows for streams in Maine for selected recurrence intervals: U.S. Geological Survey Water-Resources Investigations Report 99–4008, 49 p., http://me.water.usgs.gov/99-4008.pdf.

Interagency Advisory Committee on Water Data, 1982, Guidelines for determining flood-flow frequency: U.S. Geological Survey, Bulletin 17B of the Hydrology Subcommittee, Office of Water Data Coordination, 183 p., http://water.usgs.gov/osw/bulletin17b/dl_flow.pdf.

Jaquith, S., and Kline, M., 2006, Vermont regional hydraulic geometry curves: Vermont Department of Environmental Conservation, Water Quality Division, River Management Program, 12 p., accessed November 18, 2008, at http://www.vtwaterquality.org/rivers/docs/rv_hydraulicgeo-curves.pdf.

Jarrett, R.D., 1984, Hydraulics of high-gradient streams: Journal of Hydraulic Engineering, American Society of Civil Engineers, v. 105, no. 11, p. 1519–1539.

Jarrett, R.D., 1986, Evaluation of the slope-area method for computing peak discharge: U.S. Geological Survey Water-Supply Paper 2310, p. 13–24, http://pubs.usgs.gov/wsp/2310/report.pdf.

Johnson, P.A., and Fecko, B.J., 2008, Regional channel geometry equations: a statistical comparison for physiographic provinces in the eastern U.S.: River Research and Applications, v. 24, p. 823–834.

Keaton, J.N., Messinger, Terence, and Doheny, E.J., 2005, Development and analysis of regional curves for streams in the non-urban valley and Ridge physiographic provinces, Maryland, Virginia, and West Virginia: U.S. Geological Survey Scientific Investigations Report 2005–5076, 116 p., http://pubs.usgs.gov/sir/2005/5076/sir05_5076.pdf.

Krstolic, J.L., and Chaplin, J.J., 2007, Bankfull regional curves for streams in the non-urban, non-tidal Coastal Plain Physiographic Province, Virginia and Maryland: U.S. Geological Survey Scientific Investigations Report 2007–5162, 48 p., http://pubs.usgs.gov/sir/2007/5162/pdf/SIR2007-5162.pdf.

Leopold, L.B., 1994, A view of the river: Harvard University Press, Cambridge, Mass., Harvard University, 298 p.

Limerinos, J.T., 1970, Determination of the Manning coefficient from measured bed roughness in natural channels: U.S. Geological Survey Water-Supply Paper 1898–B, 47 p., http://pubs.usgs.gov/wsp/1898b/report.pdf.

Lotspeich, R.R., 2009, Regional curves of bankfull channel geometry for non-urban streams in the Piedmont Physiographic Province, Virginia: U.S. Geological Survey Scientific Investigations Report 2009–5206, 51 p., http://pubs.usgs.gov/sir/2009/5206/pdf/sir2009-5206.pdf.

Lumia, Richard, Freehafer, D.A., and Smith, M.J., 2006, Magnitude and frequency of floods in New York: U.S. Geological Survey Scientific Investigations Report 2006–5112, 152 p., http://pubs.usgs.gov/sir/2006/5112/SIR2006-5112.pdf.

Massachusetts Department of Transportation, 2010, Design of bridges and culverts for wildlife passage at freshwater streams: MassDOT, Highway Division, 294 p., accessed April 16, 2013, http://www.mhd.state.ma.us/downloads/projDev/Design_Bridges_Culverts_Wildlife_Passage_122710.pdf.

Massachusetts Executive Office of Energy and Environmental Affairs, Department of Fish and Game, Division of Ecological Restoration, 2012, Massachusetts stream crossing handbook (2d ed.), 13 p., accessed April 16, 2013, http://www.mass.gov/eea/docs/dfg/der/pdf/stream-crossings-handbook.pdf.

MassGIS, 2007, Surficial geology 1:24,000, accessed October, 1, 2007, at http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/datalayers/sg24k.html.

MassGIS, 2009, Land use (2005)–June 2009, accessed April 3, 2013, at http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/datalayers/lus2005.html.

MassGIS, 2011, DEP wetlands (1:12,000) Change–August 2011, accessed April 3, 2013, at http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/datalayers/wetchange.html.

MassGIS, 2012, NRCS SSURGO–Certified Soils–November 2012, accessed April 3, 2013, at http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/datalayers/soi.html.

McCandless, T.L., 2003a, Maryland stream survey: bankfull discharge and channel characteristics of streams in the Allegheny Plateau and the Valley and Ridge hydrologic region: U.S. Fish and Wildlife Service, Annapolis, Md., CBFO-S03-01, 92 p., accessed April 16, 2013, http://www.fws.gov/chesapeakebay/pdf/Plateau.pdf.

McCandless, T.L., 2003b, Maryland stream survey: bankfull discharge and channel characteristics of streams in the Coastal Plain hydrologic region: Annapolis, Md., U.S. Fish and Wildlife Service, CBFO-S03-02, 89 p., accessed April 16, 2013, http://www.fws.gov/chesapeakebay/pdf/plain.pdf.

McCandless, T.L., and Everett, R.A., 2002, Maryland stream survey: bankfull discharge and channel characteristics of streams in the Piedmont hydrologic region: Annapolis, Md., U.S. Fish and Wildlife Service, CBFO-S02-01, 163 p., accessed April 16, 2013, http://www.fws.gov/chesapeake-bay/pdf/Piedmont.pdf.

Messinger, Terence, 2009, Regional curves for bankfull channel characteristics in the Appalachian Plateaus, West Virginia: U.S. Geological Survey Scientific Investigations Report 2009–5242, 43 p., http://pubs.usgs.gov/sir/2009/5242/pdf/sir2009-5242.pdf.

Messinger, Terence, and Wiley, J.B., 2004, Regional relations in bankfull channel characteristics determined from flow measurements at selected stream-gaging stations in West Virginia, 1911–2002: U.S. Geological Survey Water-Resources Investigations Report 03–4276, 43 p., http://pubs.usgs.gov/wri/wri034276/pdf/wri03-4276.pdf.

Miller, Sarah, and Davis, Daniel, 2003, Optimizing Catskill Mountain regional bankfull discharge and hydraulic geometry relationships: Proceedings of the American Water Resources Association, 2003 International Congress, Watershed management for water supply systems, New York City, N.Y., June 29–July 2, 2003, 10 p., accessed April 3, 2013, at http://www.nyc.gov/html/dep/pdf/resources/smp.pdf.

Minitab, Inc., 2003, Meet Minitab, Release 14 for Windows: Minitab, Inc., 138 p.

Mulvihill, C.I., and Baldigo, B.P., 2007, Regionalized equations for bankfull discharge and channel characteristics of streams in New York state—hydrologic region 3 east of the Hudson River: U.S. Geological Survey Scientific Investigations Report 2007–5227, 15 p., http://pubs.usgs.gov/sir/2007/5227/pdf/SIR2007-5227.pdf.

Mulvihill, C.I., Ernst, A.G., and Baldigo, B.P., 2005, Regionalized equations for bankfull discharge and channel characteristics of streams in New York state: Hydrologic region 6 in the southern tier of New York: U.S. Geological Survey Scientific Investigations Report 2005–5100, 21 p., http://ny.water.usgs.gov/pubs/wri/sir055100/sir2005-5100.pdf.

Mulvihill, C.I., Ernst, A.G., and Baldigo, B.P., 2006, Regionalized equations for bankfull discharge and channel characteristics of streams in New York state: Hydrologic region 7 in western New York: U.S. Geological Survey Scientific Investigations Report 2006–5075, 14 p., http://ny.water.usgs.gov/pubs/wri/sir065075/sir2006-5075.pdf.

Mulvihill, C.I., Filopowicz, Amy, Coleman, Arthur, and Baldigo, B.P., 2007, Regionalized equations for bankfull discharge and channel characteristics of streams in New York state—hydrologic region 1 and 2 in the Adirondack Region of northern New York: U.S. Geological Survey Scientific Investigations Report 2007–5189, 18 p., at http://pubs.usgs.gov/sir/2007/5189/.

Murphy, P.J., 2001, Estimating equation for mixed populations of floods in Massachusetts: Journal of Hydrologic Engineering, v. 6, no.1, p. 72–74.

Olson, S.A., 2002, Flow-frequency characteristics of Vermont streams: U.S. Geological Survey Water-Resources Investigations Report 02–4238, 47 p., http://pubs.usgs.gov/wri/wrir02-4238/wrir02-4238.pdf.

Olson, S.A., 2009, Estimation of flood discharges at selected recurrence intervals for streams in New Hampshire: U.S. Geological Survey Scientific Investigations Report 2008–5206, 57 p., http://pubs.usgs.gov/sir/2008/5206/pdf/sir2008-5206.pdf.

Powell, R.O., Miller, S.J., Westergard, B.E., Mulvihill, C.I., Baldigo, B.P., Gallagher, A.S., and Starr, R.R., 2004, Guidelines for surveying bankfull channel geometry and developing regional hydraulic-geometry relations for streams in New York state: U.S. Geological Survey Open-File Report 03–92, 20 p., http://ny.water.usgs.gov/pubs/of/of03092/of03-092.pdf.

Rachol, C.M., and Boley-Morse, Kristine, 2009, Estimated bankfull discharge for selected Michigan rivers and regional hydraulic geometry curves for estimating bankfull characteristics in southern Michigan rivers: U.S. Geological Survey Scientific Investigations Report 2009–5133, 300 p., http://pubs.usgs.gov/sir/2009/5133/pdf/sir2009-5133_web.pdf.

River and Stream Continuity Partnership, 2011, Massachusetts river and stream crossing standards: 26 p., accessed April 16, 2013, http://www.streamcontinuity.org/pdf_files/MA%20Crossing%20Stds%203-1-11%20corrected%203-8-12.pdf.

Robinson, B.A., 2013, Regional bankfull-channel dimensions of non-urban wadeable streams in Indiana: U.S. Geological Survey Scientific Investigations Report 2013-5078, 33 p., http://pubs.usgs.gov/sir/2013/5078/pdf/sir2013-5078.pdf.

Rosgen, D.L., 1994, A classification of natural rivers: Catena, v. 22, p. 169–199.

Rosgen, D.L., 1996, Applied river morphology (2d ed.): Pagosa Springs, Colo., Wildland Hydrology, 388 p.

Sherwood, J.M., and Huitger, C.A., 2005, Bankfull characteristics of Ohio streams and their relation to peak streamflows: U.S. Geological Survey Scientific Investigations Report 2005–5153, 38 p., http://pubs.usgs.gov/sir/2005/5153/pdf/Bankfull_book.pdf.

Simcox, A.C., 1992, Water resources of Massachusetts: U.S. Geological Survey Water-Resources Investigations Report 90–4144, 94 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.

The Commonwealth of Massachusetts, 2009, Wetlands protection act regulations, 310 CMR10.00, accessed March 23, 2013, at http://www.mass.gov/eea/agencies/massdep/water/regulations/310-cmr-10-00-wetlands-protection-act-regulations.html.

U.S. Department of Agriculture, Forest Service, 1995, A guide for field identification of bankfull stage in the western United States: Rocky Mountain Research Station, Stream Systems Technology Center, video.

U.S. Department of Agriculture, Forest Service, 2003, Identifying bankfull stage in forested streams in the eastern United States: Rocky Mountain Research Station, Stream Systems Technology Center, video.

U.S. Department of Agriculture, Forest Service, 2004, Guide to identification of bankfull stage in the northeastern United States: Rocky Mountain Research Station, Stream Systems Technology Center, General Technical Report RMRS-GTR-133-CD, 4 CDs.

U.S. Department of Agriculture, Natural Resources Conservation Service, Soil Survey Division, 2004, National SSURGO database—data, accessed April 29, 2004, at http://www.ftw.nrcs.usda.gov/ssur_data.html.

U.S. Environmental Protection Agency, 2006, Level III ecoregions, accessed February 26, 2006, at http://www.epa.gov/wed/pages/ecoregions/level_iii.htm.

U.S. Geological Survey, 2007a, National elevation dataset, accessed June 8, 2007, at http://ned.usgs.gov/.

U.S. Geological Survey, 2007b, National hydrography dataset, accessed June 8, 2007, at http://nhd.usgs.gov/index.html.

Wandle, S.W., Jr., 1983, Estimating peak discharges of small, rural streams in Massachusetts: U.S. Geological Survey Water-Supply Paper 2214, 26 p.

Westergard, B.E., Mulvihill, C.I., Ernst, A.G., and Baldigo, B.P., 2005, Regional equations for bankfull discharge and channel characteristics of stream in New York State–hydrologic region 5 in central New York: U.S. Geological Survey Scientific Investigations Report 2004–5247, 16 p., http://ny.water.usgs.gov/pubs/wri/sir045247/.

White, K.E., 2001, Regional curve development and selection of a references 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., http://pa.water.usgs.gov/reports/wrir01-4146.pdf.

Wolman, M.G., 1954, A method of sampling coarse river-bed material: Transactions of American Geophysical Union, v. 25, p. 951–956.

Zarriello, P.J., Ahearn, E.A., and Levin, S.B., 2012, Magnitude of flood flows for selected annual exceedance probabilities in Rhode Island through 2010: U.S. Geological Survey Scientific Investigations Report 2012–5109, 81 p., http://pubs.usgs.gov/sir/2012/5109/.

Zarriello, P.J., and Socolow, R.S., 2003, The U.S. Geological Survey streamflow and observation-well network in Massachusetts and Rhode Island: U.S. Geological Survey Open-File Report 03–277, 114 p., http://pubs.usgs.gov/of/2003/ofr03277/pdfs/ofr03277all.pdf.

Appendixes 1–4

Appendix 1. Information on the starting and ending locations of surveyed stream reaches and locations of the two surveyed cross sections for study sites in and near Massachusetts.

[USGS station no.: Streamgages shown in figure 1 and described in table 1. USGS, U.S. Geological Survey; no., number; ft, foot; CT, Connecticut; MA, Massachusetts; NH, New Hampshire; RI, Rhode Island; °, degrees; ′, minutes; ″, seconds; --, no data]

USGS station no.	Station name	Stream-gage latitude	Stream-gage longitude	Start distance of survey upstream from outside gage (ft)	Starting and ending location no., where bankfull was identified	Distance upstream in survey for starting and ending location, where bankfull was identified (ft)	Starting and ending location where bankfull was identified (latitude)	Starting and ending location where bankfull was identified (longitude)	Cross-section no.	Distance upstream in survey of cross section (ft)	Cross-section latitude	Cross-section longitude
01093800	Stony Brook Tributary near Temple, NH	42° 51′ 36″	71° 50′ 0″	526	1	62	--	--	9	326	--	--
					22	742	--	--	17	595	--	--
01096000	Squannacook River near West Groton, MA	42° 38′ 3″	71° 39′ 30″	936	1	16	42° 38.101′	71° 39.626′	3	197	42° 38.078′	71° 39.608′
					18	1,585	42° 37.956′	71° 39.404′	16	1,439	42° 37.97′	71° 39.428′
010965852	Beaver Brook at North Pelham, NH	42° 46′ 58″	71° 21′ 15″	776	1	92	42° 47.057′	71° 21.342′	3	230	42° 47.047′	71° 21.317′
					21	1,428	42° 46.917′	71° 21.194′	14	1,035	42° 46.983′	71° 21.17′
01100600	Shawsheen River near Wilmington, MA	42° 34′ 5″	71° 12′ 55″	124	1	3	42° 34.065′	71° 12.905′	6	516	42° 34.149′	71° 12.926′
					20	1,660	42° 34.281′	71° 12.821′	10	746	42° 34.185′	71° 12.908′
01101000	Parker River at Byfield, MA	42° 45′ 10″	70° 56′ 46″	1,068	1	7	42° 45.26′	70° 56.752′	1	7	42° 45.26′	70° 56.752′
					18	1,065	42° 45.154′	70° 56.734′	2	54	42° 45.256′	70° 56.744′
01103500	Charles River at Dover, MA	42° 15′ 22″	71° 15′ 38″	708	1	40	42° 15.446′	71° 15.703′	11	1,301	42° 15.333′	71° 15.478′
					20	2,358	42° 15.316′	71° 15.271′	17	2,065	42° 15.318′	71° 15.339′
01105600	Old Swamp River near South Weymouth, MA	42° 11′ 25″	70° 56′ 43″	589	1	7	42° 11.408′	70° 56.552′	8	281	42° 11.401′	70° 56.605′
					21	779	42° 11.444′	70° 56.706′	14	523	42° 11.425′	70° 56.655′
01105870	Jones River at Kingston, MA	41° 59′ 27″	70° 44′ 3″	30	1	41	41° 59.456′	70° 44.043′	6	339	41° 59.449′	70° 43.981′
					18	917	41° 59.4′	70° 43.89′	13	680	41° 59.434′	70° 43.943′
01109000	Wading River near Norton, MA	41° 56′ 51″	71° 10′ 38″	79	1	3	41° 56.852′	71° 10.594′	5	240	41° 56.889′	71° 10.548′
					16	996	41° 56.959′	71° 10.522′	10	554	41° 56.938′	71° 10.539′
01109070	Segreganset River at Dighton, MA	41° 50′ 25″	71° 8′ 36″	12	1	23	41° 50.412′	71° 8.569′	8	490	41° 50.351′	71° 8.572′
					16	895	41° 50.292′	71° 8.548′	14	784	41° 50.309′	71° 8.55′

Appendix 1. Information on the starting and ending locations of surveyed stream reaches and locations of the two surveyed cross sections for study sites in and near Massachusetts.—Continued

[USGS station no.: Streamgages shown in figure 1 and described in table 1. USGS, U.S. Geological Survey; no., number; ft, foot; CT, Connecticut; MA, Massachusetts; NH, New Hampshire; RI, Rhode Island; °, degrees; ′, minutes; ″, seconds; --, no data]

USGS station no.	Station name	Stream-gage latitude	Stream-gage longitude	Start distance of survey upstream from outside gage (ft)	Starting and ending location no., where bankfull was identified	Distance upstream in survey for starting and ending location, where bankfull was identified (ft)	Starting and ending location where bankfull was identified (latitude)	Starting and ending location where bankfull was identified (longitude)	Cross-section no.	Distance upstream in survey of cross section (ft)	Cross-section latitude	Cross-section longitude
01111300	Nipmuc River near Harrisville, RI	41° 58′ 52″	71° 41′ 11″	358	1	5	41° 58.914′	71° 41.185′	9	422	41° 58.897′	71° 41.159′
					23	1,167	41° 58.778′	71° 41.22′	13	658	41° 58.846′	71° 41.164′
01111500	Branch River at Forestdale, RI	41° 59′ 47″	71° 33′ 47″	113	1	63	41° 59.806′	71° 33.732′	7	510	41° 59.789′	71° 33.663′
					15	1,025	41° 59.788′	71° 33.558′	9	658	41° 59.776′	71° 33.624′
01162500	Priest Brook near Winchendon, MA	42° 40′ 57″	72° 6′ 56″	113	1	49	42° 40.984′	72° 6.865′	6	371	42° 40.924′	72° 6.862′
					22	1,443	42° 40.852′	72° 6.82′	9	554	42° 40.887′	72° 6.859′
01163200	Otter River at Otter River, MA	42° 35′ 18″	72° 2′ 29″	89	1	33	42° 35.307′	72° 2.457′	6	562	42° 35.357′	72° 2.52′
					14	1,146	42° 35.45′	72° 2.514′	13	1,101	42° 35.445′	72° 2.504′
01169000	North River at Shattuckville, MA	42° 38′ 18″	72° 43′ 32″	2,450	1	24	42° 38.547′	72° 43.124′	2	140	42° 38.536′	72° 43.144′
					21	2,423	42° 38.311′	72° 43.501′	17	1,937	42° 38.375′	72° 43.45′
01169900	South River near Conway, MA	42° 32′ 31″	72° 41′ 39″	520	1	23	42° 32.463′	72° 41.733′	9	524	42° 32.511′	72° 41.644′
					20	1,230	42° 32.574′	72° 41.509′	18	1,088	42° 32.578′	72° 41.535′
01170100	Green River near Colrain, MA	42° 42′ 12″	72° 40′ 16″	965	1	15	42° 42.344′	72° 40.236′	3	184	42° 42.308′	72° 40.244′
					20	1,710	42° 42.124′	72° 40.077′	15	1,237	42° 42.158′	72° 40.176′
01171500	Mill River at Northampton, MA	42° 19′ 5″	72° 39′ 21″	926	1	5	42° 19.29′	72° 39.974′	2	62	42° 19.262′	72° 40.014′
					21	1,339	42° 19.107′	72° 39.829′	6	346	42° 19.228′	72° 39.966′
01174900	Cadwell Creek near Belchertown, MA	42° 20′ 8″	72° 22′ 12″	552	1	33	42° 20.183′	72° 22.167′	6	202	42° 20.16′	72° 22.169′
					20	552	42° 20.1′	72° 22.188′	11	344	42° 20.135′	72° 22.173′
01175670	Sevenmile River near Spencer, MA	42° 15′ 54″	72° 0′ 19″	664	1	19	42° 15.968′	72° 0.359′	20	19	42° 15.968′	72° 0.359′
					19	1,137	42° 15.82′	72° 0.296′	13	518	42° 15.904′	72° 0.311′

Appendix 1. Information on the starting and ending locations of surveyed stream reaches and locations of the two surveyed cross sections for study sites in and near Massachusetts.—Continued

[USGS station no.: Streamgages shown in figure 1 and described in table 1. USGS, U.S. Geological Survey; no., number; ft, foot; CT, Connecticut; MA, Massachusetts; NH, New Hampshire; RI, Rhode Island; °, degrees; ′, minutes; ″, seconds; --, no data]

USGS station no.	Station name	Streamgage latitude	Streamgage longitude	Start distance of survey upstream from outside gage (ft)	Starting and ending location no., where bankfull was identified	Distance upstream in survey for starting and ending location, where bankfull was identified (ft)	Starting and ending location where bankfull was identified (latitude)	Starting and ending location where bankfull was identified (longitude)	Cross-section no.	Distance upstream in survey of cross section (ft)	Cross-section latitude	Cross-section longitude
01176000	Quaboag River at West Brimfield, MA	42° 10′ 56″	72° 15′ 51″	1,470	1	30	42° 11.119′	72° 15.846′	4	513	42° 11.036′	72° 15.846′
					22	2,661	42° 10.719′	72° 15.762′	20	2,380	42° 10.709′	72° 15.721′
01181000	West Branch Westfield River at Huntington, MA	42° 14′ 14″	72° 53′ 46″	1,747	1	21	42° 14.277′	72° 54.098′	2	112	42° 14.293′	72° 54.073′
					21	2,265	42° 14.159′	72° 53.665′	11	1,040	42° 14.255′	72° 53.874′
01184100	Stony Brook near West Suffield, CT	41° 57′ 38″	72° 42′ 39″	373	1	6	41° 57.616′	72° 42.675′	18	560	41° 57.648′	72° 42.587′
					25	792	41° 57.627′	72° 42.546′	22	665	41° 57.63′	72° 42.581′
01187300	Hubbard River near West Hartland, CT	42° 2′ 14″	72° 56′ 22″	910	1	30	42° 2.323′	72° 56.52′	6	399	42° 2.297′	72° 56.453′
					20	1,480	42° 2.155′	72° 56.329′	16	1,195	42° 2.205′	72° 56.334′
01198000	Green River near Great Barrington, MA	42° 11′ 31″	73° 23′ 28″	1,165	1	29	42° 11.735′	73° 23.573′	7	613	42° 11.649′	73° 23.513′
					20	1,925	42° 11.466′	73° 23.379′	20	1,925	42° 11.466′	73° 23.379′
01199050	Salmon Creek at Lime Rock, CT	41° 56′ 32″	73° 23′ 29″	890	1	28	41° 56.67′	73° 23.436′	14	681	41° 56.584′	73° 23.453′
					22	1,095	41° 56.516′	73° 23.445′	21	1,033	41° 56.523′	73° 23.454′
01333000	Green River at Williamstown, MA	42° 42′ 32″	73° 11′ 50″	1,225	1	17	42° 42.591′	73° 11.986′	8	566	42° 42.527′	73° 11.912′
					20	1,560	42° 42.564′	73° 11.726′	15	1,115	42° 42.55′	73° 11.812′

Appendix 2. Bankfull data collected at the two surveyed cross sections and stream reach for study sites in and near Massachusetts.

[USGS station no.: Streamgages shown in figure 1 and described in table 1. USGS, U.S. Geological Survey; no., number; mi^2, square mile; ft, foot; ft^2, square foot; mm, millimeter; d_w, weighted particle-size distribution—equation 2 in report (Limerinos, 1970); ft^3/sec, cubic feet per second; CT, Connecticut; MA, Massachusetts; NH, New Hampshire; RI, Rhode Island]

USGS station no.	Station name	Drainage area (mi^2)	Cross-section data						
			Cross-section no.	Entrenchment ratio	Width-to-depth ratio	Water-surface slope (ft/ft)	Wetted perimeter (ft)	Hydraulic radius (ft)	Cross-sectional area (ft^2)
01093800	Stony Brook Tributary near Temple, NH	3.60	9	3.07	14.55	0.0145	25.08	1.58	39.54
			17	2.34	16.67	0.0064	24.40	1.53	37.42
01096000	Squannacook River near West Groton, MA	63.7	3	1.82	23.15	0.0067	89.03	3.22	286.89
			16	1.74	21.89	0.0214	65.53	3.03	198.36
010965852	Beaver Brook at North Pelham, NH	47.8	3	2.22	14.58	0.0004	58.41	3.82	223.05
			14	1.76	15.53	0.0043	43.73	2.82	123.47
01100600	Shawsheen River near Wilmington, MA	36.5	6	5.74	16.10	0.0003	60.76	3.41	207.46
			10	5.78	30.08	0.0003	76.02	2.42	183.59
01101000	Parker River at Byfield, MA	21.3	1	3.06	14.12	0.0002	45.67	2.93	133.79
			2	2.91	20.00	0.0002	48.23	2.53	121.93
01103500	Charles River at Dover, MA	183	11	3.41	24.87	0.0007	100.65	3.87	390.01
			17	5.23	24.89	0.0010	100.89	3.89	392.00
01105600	Old Swamp River near South Weymouth, MA	4.50	8	3.46	31.48	0.0088	41.36	1.24	51.47
			14	4.05	22.99	0.0052	31.93	1.29	41.29
01105870	Jones River at Kingston, MA	15.7	6	3.59	21.25	0.0014	44.08	1.93	85.00
			13	2.80	16.11	0.0021	36.43	2.06	75.05
01109000	Wading River near Norton, MA	43.3	5	7.15	18.78	0.0033	40.30	2.11	85.06
			10	4.49	16.13	0.0014	39.74	2.66	105.60
01109070	Segreganset River at Dighton, MA	10.6	8	5.31	13.73	0.0079	32.67	2.19	71.42
			14	3.37	20.86	0.0142	35.76	1.53	54.66
01111300	Nipmuc River near Harrisville, RI	16.0	9	3.78	20.54	0.0053	46.58	2.21	103.07
			13	3.46	28.33	0.0007	56.14	2.08	116.63

Appendix 2. Bankfull data collected at the two surveyed cross sections and stream reach for study sites in and near Massachusetts.—Continued

[USGS station no.: Streamgages shown in figure 1 and described in table 1. USGS, U.S. Geological Survey; no., number; mi², square mile; ft, foot; ft², square foot; mm, millimeter; d_w, weighted particle-size distribution—equation 2 in report (Limerinos, 1970); ft³/sec, cubic feet per second; CT, Connecticut; MA, Massachusetts; NH, New Hampshire; RI, Rhode Island]

USGS station no.	Station name	Drainage area (mi²)	Cross-section data						
			Cross-section no.	Entrenchment ratio	Width-to-depth ratio	Water-surface slope (ft/ft)	Wetted perimeter (ft)	Hydraulic radius (ft)	Cross-sectional area (ft²)
01111500	Branch River at Forestdale, RI	91.2	7	2.49	23.71	0.0033	86.23	3.71	319.58
			9	2.29	25.09	0.0031	76.46	3.31	253.39
01162500	Priest Brook near Winchendon, MA	19.4	6	2.90	37.48	0.0036	62.26	1.53	94.98
			9	3.52	20.77	0.0009	49.81	2.57	127.82
01163200	Otter River at Otter River, MA	34.1	6	2.16	41.30	0.0070	70.11	1.53	107.34
			13	1.74	27.39	0.0088	52.55	1.94	102.18
01169000	North River at Shattuckville, MA	89.0	2	7.14	22.16	0.0023	112.39	4.75	534.10
			17	1.53	21.63	0.0091	110.80	4.49	497.87
01169900	South River near Conway, MA	24.1	9	1.62	14.94	0.0059	63.53	3.93	249.68
			18	1.27	17.59	0.0044	81.94	3.40	278.68
01170100	Green River near Colrain, MA	41.4	3	1.16	38.11	0.0086	107.24	2.91	311.70
			15	1.12	28.55	0.0061	106.69	3.31	353.37
01171500	Mill River at Northampton, MA	52.6	2	1.58	24.36	0.0051	88.72	3.42	303.51
			6	1.36	23.06	0.0059	97.90	3.05	298.96
01174900	Cadwell Creek near Belchertown, MA	2.55	6	1.42	15.86	0.0240	21.86	1.19	26.05
			11	1.46	12.71	0.0256	18.43	1.22	22.48
01175670	Sevenmile River near Spencer, MA	8.81	20	2.66	25.44	0.0056	40.15	1.41	56.43
			13	7.09	14.17	0.0018	25.23	1.82	45.99
01176000	Quaboag River at West Brimfield, MA	150	4	1.18	53.90	0.0023	141.04	2.73	384.51
			20	1.37	44.65	0.0048	119.55	2.74	327.46
01181000	West Branch Westfield River at Huntington, MA	94.0	2	1.89	35.83	0.0130	115.14	3.07	353.66
			11	2.80	42.84	0.0110	165.83	2.59	430.09

Appendix 2. Bankfull data collected at the two surveyed cross sections and stream reach for study sites in and near Massachusetts.—Continued

[USGS station no.: Streamgages shown in figure 1 and described in table 1. USGS, U.S. Geological Survey; no., number; mi², square mile; ft, foot; ft², square foot; mm, millimeter; d_w, weighted particle-size distribution—equation 2 in report (Limerinos, 1970); ft³/sec, cubic feet per second; CT, Connecticut; MA, Massachusetts; NH, New Hampshire; RI, Rhode Island]

USGS station no.	Station name	Drainage area (mi²)	Cross-section data						
			Cross-section no.	Entrenchment ratio	Width-to-depth ratio	Water-surface slope (ft/ft)	Wetted perimeter (ft)	Hydraulic radius (ft)	Cross-sectional area (ft²)
01184100	Stony Brook near West Suffield, CT	10.4	18	1.30	27.59	0.0133	49.27	1.69	83.40
			22	1.32	25.00	0.0124	40.00	1.56	62.26
01187300	Hubbard River near West Hartland, CT	19.9	6	1.87	30.25	0.0364	81.62	2.10	171.40
			16	1.15	33.86	0.0202	91.27	1.80	164.03
01198000	Green River near Great Barrington, MA	51.0	7	6.94	27.28	0.0010	81.83	2.54	207.61
			20	2.69	19.32	0.0019	67.81	3.01	204.40
01199050	Salmon Creek at Lime Rock, CT	29.4	14	1.22	22.90	0.0092	50.86	2.06	104.75
			21	1.31	15.65	0.0066	52.21	2.32	121.03
01333000	Green River at Williamstown, MA	42.6	8	1.17	29.58	0.0120	89.45	2.70	241.38
			15	1.49	22.16	0.0049	95.7	2.58	246.86

Appendix 2. Bankfull data collected at the two surveyed cross sections and stream reach for study sites in and near Massachusetts.—Continued

[USGS station no.: Streamgages shown in figure 1 and described in table 1. USGS, U.S. Geological Survey; no., number; mi^2, square mile; ft, foot; ft^2, square foot; mm, millimeter; d_w, weighted particle-size distribution—equation 2 in report (Limerinos, 1970); ft^3/sec, cubic feet per second; CT, Connecticut; MA, Massachusetts; NH, New Hampshire; RI, Rhode Island]

USGS station no.	Station name	Cross-section no.	Limerios (1970) equation											
			Particle size d_{16} (mm)	Particle size d_{50} (mm)	Particle size d_{84} (mm)	Particle size d_w (mm)	Roughness coefficient (based on d_{16})	Roughness coefficient (based on d_{50})	Roughness coefficient (based on d_{84})	Roughness coefficient (based on d_w)	Discharge (ft^3/s) (based on d_{16})	Discharge (ft^3/s) (based on d_{50})	Discharge (ft^3/s) (based on d_{84})	Discharge (ft^3/s) (based on d_w)
01093800	Stony Brook Tributary near Temple, NH	9	29.78	71.86	135.63	105.91	0.0301	0.0499	0.0442	0.0451	319	192	217	213
		17	18.63	38.07	62.70	50.90	0.0269	0.0393	0.0342	0.0352	221	151	173	169
01096000	Squannacook River near West Groton, MA	3	2.52	141.66	618.54	413.87	0.0185	0.0554	0.0721	0.0682	4,125	1,378	1,059	1,120
		16	2.16	140.07	287.44	214.70	0.0181	0.0560	0.0513	0.0514	5,005	1,614	1,765	1,760
010965852	Beaver Brook at North Pelham, NH	3	0.69	9.16	21.25	15.57	0.0157	0.0254	0.0250	0.0249	1,032	639	650	652
		14	25.79	58.15	116.30	89.80	0.0279	0.0409	0.0380	0.0385	864	589	634	627
01100600	Shawsheen River near Wilmington, MA	6	0.79	5.61	22.13	15.04	0.0159	0.0233	0.0252	0.0248	763	522	481	489
		10	0.74	1.89	6.93	4.80	0.0156	0.0194	0.0206	0.0203	548	440	414	419
01101000	Parker River at Byfield, MA	1	0.67	4.00	29.78	19.14	0.0155	0.0219	0.0269	0.0261	373	263	214	221
		2	0.64	3.17	192.00	116.22	0.0153	0.0211	0.0457	0.0425	312	226	104	112
01103500	Charles River at Dover, MA	11	3.17	17.71	89.73	59.47	0.0192	0.0290	0.0341	0.0332	1,975	1,307	1,111	1,143
		17	19.60	112.64	186.52	147.66	0.0260	0.0485	0.0420	0.0429	1,754	941	1,087	1,065
01105600	Old Swamp River near South Weymouth, MA	8	6.00	49.76	103.16	77.42	0.0213	0.0454	0.0419	0.0421	390	183	199	198
		14	4.00	51.58	83.86	66.19	0.0198	0.0457	0.0386	0.0395	266	115	136	133
01105870	Jones River at Kingston, MA	6	1.74	9.52	26.42	18.88	0.0173	0.0263	0.0268	0.0266	423	279	274	276
		13	2.00	12.00	40.81	28.29	0.0177	0.0276	0.0296	0.0291	468	301	281	285
01109000	Wading River near Norton, MA	5	1.78	32.00	70.83	52.28	0.0174	0.0355	0.0341	0.0340	687	338	351	352
		10	2.38	28.29	55.43	41.98	0.0183	0.0334	0.0312	0.0314	618	338	362	360
01109070	Segreganset River at Dighton, MA	8	3.03	55.43	422.65	270.52	0.0189	0.0420	0.0678	0.0627	843	379	235	254
		14	[1]29.40	[1]96.00	[1]221.10	[1]164.40	[1]0.0301	[1]0.0577	[1]0.0550	[1]0.0551	[1]428	[1]223	[1]234	[1]234

Appendix 2. Bankfull data collected at the two surveyed cross sections and stream reach for study sites in and near Massachusetts.—Continued

[USGS station no.: Streamgages shown in figure 1 and described in table 1. USGS, U.S. Geological Survey; no., number; mi^2, square mile; ft, foot; ft^2, square foot; mm, millimeter; d_w, weighted particle-size distribution—equation 2 in report (Limerinos, 1970); ft^3/sec, cubic feet per second; CT, Connecticut; MA, Massachusetts; NH, New Hampshire; RI, Rhode Island]

USGS station no.	Station name	Cross-section no.	Particle size d_{16} (mm)	Particle size d_{50} (mm)	Particle size d_{84} (mm)	Particle size d_w (mm)	Limerios (1970) equation: Roughness coefficient (based on d_{16})	Roughness coefficient (based on d_{50})	Roughness coefficient (based on d_{84})	Roughness coefficient (based on d_w)	Discharge (ft^3/s) (based on d_{16})	Discharge (ft^3/s) (based on d_{50})	Discharge (ft^3/s) (based on d_{84})	Discharge (ft^3/s) (based on d_w)
01111300	Nipmuc River near Harrisville, RI	9	4.00	37.25	82.46	61.05	0.0197	0.0369	0.0354	0.0354	962	515	536	536
		13	0.69	2.52	14.89	9.76	0.0153	0.0203	0.0237	0.0231	488	369	316	324
01111500	Branch River at Forestdale, RI	7	10.20	53.47	163.25	115.01	0.0231	0.0384	0.0406	0.0399	2,837	1,706	1,615	1,640
		9	[2]6.30	[2]15.40	[2]83.60	[2]55.41	[2]0.0213	[2]0.0284	[2]0.0371	[2]0.0330	[2]2,194	[2]1,646	[2]1,261	[2]1,414
01162500	Priest Brook near Winchendon, MA	6	1.08	8.68	32.00	21.91	0.0161	0.0361	0.0385	0.0280	699	312	292	402
		9	0.79	13.86	43.37	30.26	0.0157	0.0381	0.0395	0.0291	681	281	271	368
01163200	Otter River at Otter River, MA	6	13.21	73.26	156.77	117.36	0.0249	0.0508	0.0472	0.0474	715	350	377	375
		13	0.87	26.93	119.12	79.64	0.0158	0.0341	0.0405	0.0391	1,412	653	549	569
01169000	North River at Shattuckville, MA	2	25.18	44.26	110.85	82.31	0.0272	0.0355	0.0354	0.0354	3,971	3,037	3,048	3,047
		17	0.93	73.26	476.47	307.95	0.0164	0.0411	0.0573	0.0542	11,722	4,687	3,365	3,558
01169900	South River near Conway, MA	9	0.83	44.26	146.52	101.27	0.0161	0.0362	0.0390	0.0382	4,416	1,967	1,826	1,863
		18	0.71	48.00	138.81	97.76	0.0157	0.0376	0.0391	0.0385	3,965	1,656	1,594	1,619
01170100	Green River near Colrain, MA	3	33.91	76.15	181.19	134.95	0.0296	0.0446	0.0436	0.0436	2,961	1,968	2,013	2,010
		15	16.00	71.86	192.00	138.36	0.0251	0.0427	0.0435	0.0430	3,637	2,138	2,103	2,123
01171500	Mill River at Northampton, MA	2	1.15	24.00	88.52	60.43	0.0167	0.0313	0.0344	0.0337	4,396	2,339	2,130	2,176
		6	8.00	76.95	156.77	117.95	0.0222	0.0443	0.0412	0.0414	3,249	1,624	1,748	1,740
01174900	Cadwell Creek near Belchertown, MA	6	10.84	50.58	122.01	89.46	0.0241	0.0462	0.0452	0.0450	280	146	149	150
		11	6.00	30.50	128.00	86.55	0.0213	0.0380	0.0459	0.0442	287	161	133	138
01175670	Sevenmile River near Spencer, MA	20	8.00	99.12	184.37	141.16	0.0225	0.0604	0.0518	0.0526	351	131	152	150
		13	4.00	29.78	105.66	72.73	0.0197	0.0354	0.0393	0.0384	220	123	110	113

Appendix 2. Bankfull data collected at the two surveyed cross sections and stream reach for study sites in and near Massachusetts.—Continued

[USGS station no.: Streamgages shown in figure 1 and described in table 1. USGS, U.S. Geological Survey; no., number; mi^2, square mile; ft, foot; ft^2, square foot; mm, millimeter; d_w, weighted particle-size distribution—equation 2 in report (Limerinos, 1970); ft^3/sec, cubic feet per second; CT, Connecticut; MA, Massachusetts; NH, New Hampshire; RI, Rhode Island]

USGS station no.	Station name	Cross-section no.	Limerios (1970) equation											
			Particle size d_{16} (mm)	Particle size d_{50} (mm)	Particle size d_{84} (mm)	Particle size d_w (mm)	Roughness coefficient (based on d_{16})	Roughness coefficient (based on d_{50})	Roughness coefficient (based on d_{84})	Roughness coefficient (based on d_w)	Discharge (ft^3/s) (based on d_{16})	Discharge (ft^3/s) (based on d_{50})	Discharge (ft^3/s) (based on d_{84})	Discharge (ft^3/s) (based on d_w)
01176000	Quaboag River at West Brimfield, MA	4	1.12	48.00	117.90	85.25	0.0165	0.0387	0.0383	0.0380	3,253	1,385	1,399	1,410
		20	1.78	64.00	143.72	105.61	0.0175	0.0424	0.0407	0.0406	3,771	1,559	1,624	1,629
01181000	West Branch Westfield River at Huntington, MA	2	32.00	116.30	245.69	185.50	0.0291	0.0516	0.0481	0.0484	4,358	2,458	2,640	2,622
		11	76.16	164.28	273.90	221.24	0.0370	0.0633	0.0522	0.0541	3,428	2,004	2,432	2,345
01184100	Stony Brook near West Suffield, CT	18	[3]1.00	[3]110.90	[3]301.10	[3]214.03	[3]0.0160	[3]0.0600	[3]0.0621	[3]0.0607	[3]1,274	[3]339	[3]328	[3]335
		22	[3]11.50	[3]64.00	[3]446.00	[3]287.95	[3]0.0241	[3]0.0477	[3]0.0821	[3]0.0747	[3]575	[3]291	[3]169	[3]186
01187300	Hubbard River near West Hartland, CT	6	32.00	156.77	367.08	270.48	0.0299	0.0667	0.0638	0.0636	2,670	1,199	1,253	1,257
		16	19.60	146.52	430.83	304.41	0.0269	0.0683	0.0746	0.0724	1,907	752	688	709
01198000	Green River near Great Barrington, MA	7	0.65	4.00	32.00	20.47	0.0153	0.0220	0.0275	0.0267	1,186	828	661	682
		20	2.83	12.00	43.37	29.91	0.0188	0.0270	0.0292	0.0287	1,474	1,025	949	964
01199050	Salmon Creek at Lime Rock, CT	14	4.00	96.00	256.00	182.80	0.0197	0.0527	0.0539	0.0530	1,228	460	450	457
		21	[4]18.90	[4]156.80	[4]855.10	[4]561.99	[4]0.0263	[4]0.0643	[4]0.10714	[4]0.0969	[4]974	[4]399	[4]240	[4]265
01333000	Green River at Williamstown, MA	8	2.83	43.37	141.66	98.29	0.0188	0.0380	0.0410	0.0398	4,072	2,031	1,879	1,919
		15	0.71	19.60	128.00	82.75	0.0155	0.0305	0.0396	0.0380	3,121	1,588	1,222	1,275

Appendix 2. Bankfull data collected at the two surveyed cross sections and stream reach for study sites in and near Massachusetts.—Continued

[USGS station no.: Streamgages shown in figure 1 and described in table 1. USGS, U.S. Geological Survey; no., number; mi^2, square mile; ft, foot; ft^2, square foot; mm, millimeter; d_w, weighted particle-size distribution—equation 2 in report (Limerinos, 1970); ft^3/sec, cubic feet per second; CT, Connecticut; MA, Massachusetts; NH, New Hampshire; RI, Rhode Island]

USGS station no.	Station name	Cross-section no.	Jarrett (1984) equation			Channel material		Stream-reach data					
			Water-surface slope is less than 0.002 ft/ft	Roughness coefficient (based on equation)	Discharge (ft^3/s)	Particle size d_{50} (mm)	Particle-size classification (based on d_{50})	Average entrenchment ratio	Average width-to-depth ratio	Sinuosity (ft/ft)	Water-surface slope (ft/ft)	Particle size d_{50} (mm)	Particle-size classification (based on d_{50})
01093800	Stony Brook Tributary near Temple, NH	9	No	0.0726	133	71.86	Small cobble	2.71	15.61	1.15	0.0096	57.64	Very coarse gravel
		17	No	0.0534	111	38.07	Very coarse gravel						
01096000	Squannacook River near West Groton, MA	3	No	0.0483	1,588	141.66	Large cobble	1.78	22.52	1.26	0.0046	118.55	Small cobble
		16	No	0.0758	1,198	140.07	Large cobble						
010965852	Beaver Brook at North Pelham, NH	3	Yes	0.0161	1,013	9.16	Medium gravel	1.99	15.05	1.30	0.0013	19.6	Coarse gravel
		14	No	0.0417	581	58.15	Very coarse gravel						
01100600	Shawsheen River near Wilmington, MA	6	Yes	0.0147	830	5.61	Fine gravel	5.76	23.09	1.21	0.0011	4.18	Fine gravel
		10	Yes	0.0155	551	1.89	Very coarse sand						
01101000	Parker River at Byfield, MA	1	Yes	0.0129	449	4.00	Very fine gravel	2.99	17.06	1.64	0.0002	0.9	Coarse sand
		2	Yes	0.0132	362	3.17	Very fine gravel						
01103500	Charles River at Dover, MA	11	Yes	0.0199	1,918	17.71	Coarse gravel	4.32	24.88	1.08	0.0008	18.13	Coarse gravel
		17	Yes	0.0227	2,017	112.64	Small cobble						
01105600	Old Swamp River near South Weymouth, MA	8	No	0.0623	134	49.76	Very coarse gravel	3.76	27.23	1.04	0.0046	50.01	Very coarse gravel
		14	No	0.0507	104	51.58	Very coarse gravel						
01105870	Jones River at Kingston, MA	6	Yes	0.0289	255	9.52	Medium gravel	3.20	18.68	1.08	0.0024	13.68	Medium gravel
		13	No	0.0334	249	12.00	Medium gravel						
01109000	Wading River near Norton, MA	5	No	0.0395	304	32.00	Coarse gravel	5.82	17.46	1.40	0.0024	29.64	Coarse gravel
		10	Yes	0.0275	413	28.29	Coarse gravel						

Appendix 2. Bankfull data collected at the two surveyed cross sections and stream reach for study sites in and near Massachusetts.—Continued

[USGS station no.: Streamgages shown in figure 1 and described in table 1. USGS, U.S. Geological Survey; no., number; mi^2, square mile; ft, foot; ft^2, square foot; mm, millimeter; d_w, weighted particle-size distribution—equation 2 in report (Limerinos, 1970); ft^3/sec, cubic feet per second; CT, Connecticut; MA, Massachusetts; NH, New Hampshire; RI, Rhode Island]

			Jarrett (1984) equation			Channel material		Stream-reach data					
USGS station no.	Station name	Cross-section no.	Water-surface slope is less than 0.002 ft/ft	Roughness coefficient (based on equation)	Discharge (ft^3/s)	Particle size d_{50} (mm)	Particle-size classification (based on d_{50})	Average entrenchment ratio	Average width-to-depth ratio	Sinuosity (ft/ft)	Water-surface slope (ft/ft)	Particle size d_{50} (mm)	Particle-size classification (based on d_{50})
01109070	Segreganset River at Dighton, MA	8	No	0.0547	292	55.43	Very coarse gravel	4.34	17.30	1.22	0.013	101.69	Small cobble
		14	No	0.0724	178	141.66	Large cobble						
01111300	Nipmuc River near Harrisville, RI	9	No	0.0469	406	37.25	Very coarse gravel	3.62	24.43	1.14	0.0021	12.44	Medium gravel
		13	Yes	0.0219	342	2.52	Very fine gravel						
01111500	Branch River at Forestdale, RI	7	No	0.0361	1,824	53.47	Very coarse gravel	2.39	24.40	1.00	0.0022	65.88	Small cobble
		9	No	0.0359	1,308	2,155.90	Bedrock						
01162500	Priest Brook near Winchendon, MA	6	No	0.0430	262	8.68	Medium gravel	3.21	29.13	1.73	0.002	18.32	Coarse gravel
		9	Yes	0.0233	460	13.86	Medium gravel						
01163200	Otter River at Otter River, MA	6	No	0.0553	322	73.26	Small cobble	1.95	34.35	1.12	0.0049	48	Very coarse gravel
		13	No	0.0580	384	26.93	Coarse gravel						
01169000	North River at Shattuckville, MA	2	No	0.0302	3,589	44.26	Very coarse gravel	4.34	21.89	1.09	0.0052	66.95	Small cobble
		17	No	0.0514	3,767	73.26	Small cobble						
01169900	South River near Conway, MA	9	No	0.0446	1,605	44.26	Very coarse gravel	1.45	16.26	1.00	0.0052	30.21	Coarse gravel
		18	No	0.0408	1,533	48.00	Very coarse gravel						
01170100	Green River near Colrain, MA	3	No	0.0540	1,632	76.15	Small cobble	1.14	33.33	1.09	0.0075	92.81	Small cobble
		15	No	0.0464	1,978	71.86	Small cobble						
01171500	Mill River at Northampton, MA	2	No	0.0431	1,708	24.00	Coarse gravel	1.47	23.71	1.11	0.0038	16.95	Coarse gravel
		6	No	0.0464	1,558	76.95	Small cobble						
01174900	Cadwell Creek near Belchertown, MA	6	No	0.0919	74	50.58	Very coarse gravel	1.44	14.28	1.19	0.0267	51.17	Very coarse gravel
		11	No	0.0938	65	30.50	Coarse gravel						

Appendix 2. Bankfull data collected at the two surveyed cross sections and stream reach for study sites in and near Massachusetts.—Continued

[USGS station no.: Streamgages shown in figure 1 and described in table 1. USGS, U.S. Geological Survey; no., number; mi^2, square mile; ft, foot; ft^2, square foot; mm, millimeter; d_w, weighted particle-size distribution—equation 2 in report (Limerinos, 1970); ft^3/sec, cubic feet per second; CT, Connecticut; MA, Massachusetts; NH, New Hampshire; RI, Rhode Island]

			Jarrett (1984) equation			Channel material		Stream-reach data					
USGS station no.	Station name	Cross-section no.	Water-surface slope is less than 0.002 ft/ft	Roughness coefficient (based on equation)	Discharge (ft^3/s)	Particle size d_{50} (mm)	Particle-size classification (based on d_{50})	Average entrenchment ratio	Average width-to-depth ratio	Sinuosity (ft/ft)	Water-surface slope (ft/ft)	Particle size d_{50} (mm)	Particle-size classification (based on d_{50})
01175670	Sevenmile River near Spencer, MA	20	No	0.0515	154	99.12	Small cobble	4.88	19.80	1.20	0.0053	38.07	Very coarse gravel
		13	Yes	0.0321	135	29.78	Coarse gravel						
01176000	Quaboag River at West Brimfield, MA	4	No	0.0330	1,629	48.00	Very coarse gravel	1.28	49.27	1.07	0.0025	76.15	Small cobble
		20	No	0.0436	1,521	64.00	Very coarse gravel						
01181000	West Branch Westfield River at Huntington, MA	2	No	0.0626	2,037	116.30	Small cobble	2.35	39.33	1.10	0.0066	128	Small cobble
		11	No	0.0603	2,110	164.28	Large cobble						
01184100	Stony Brook near West Suffield, CT	18	No	0.0694	294	2,298.80	Bedrock	1.31	26.29	1.33	0.0064	70.83	Small cobble
		22	No	0.0685	203	2,762.61	Bedrock						
01187300	Hubbard River near West Hartland, CT	6	No	0.0983	815	156.77	Large cobble	1.51	32.06	1.05	0.0236	179.45	Large cobble
		16	No	0.0806	638	146.52	Large cobble						
01198000	Green River near Great Barrington, MA	7	Yes	0.0243	750	4.00	Very fine gravel	4.82	23.30	1.05	0.0011	12.39	Medium gravel
		20	Yes	0.0302	920	12.00	Medium gravel						
01199050	Salmon Creek at Lime Rock, CT	14	No	0.0585	415	96.00	Small cobble	1.27	19.27	1.13	0.0034	119.12	Small cobble
		21	No	0.0506	509	192.00	Large cobble						
01333000	Green River at Williamstown, MA	8	No	0.0620	1,236	43.37	Very coarse gravel	1.33	25.87	1.36	0.0107	59.56	Very coarse gravel
		15	No	0.0444	1,094	19.60	Coarse gravel						

[1]For cross-section 14 at streamgage 01109070 Segreganset River at Dighton, MA, 12 of 50 Wolman (1954) pebble count samples were classified as bedrock and not used in calculation of the Manning's roughness coefficient (Limerinos, 1970) using the d_w, d_{16}, d_{50}, and d_{84} (equations 2, 3, 4, 5, and 6 in this report).

[2]For cross-section 9 at streamgage 01111500 Branch River at Forestdale, RI, 27 of 50 Wolman (1954) pebble count samples were classified as bedrock and not used in calculation of the Manning's roughness coefficient (Limerinos, 1970) using the d_w, d_{16}, d_{50}, and d_{84} (equations 2, 3, 4, 5, and 6 in this report).

[3]For cross-sections 18 and 22 at streamgage 01184100 Stony Brook near West Suffield, CT, 30 of 50 and 44 of 50, respectively, Wolman (1954) pebble count samples were classified as bedrock and not used in calculation of the Manning's roughness coefficient (Limerinos, 1970) using the d_w, d_{16}, d_{50}, and d_{84} (equations 2, 3, 4, 5, and 6 in this report).

[4]For cross-section 21 at streamgage 01199050 Salmon Creek at Lime Rock, CT, 3 of 50 Wolman (1954) pebble count samples were classified as bedrock and not used in calculation of the Manning's roughness coefficient (Limerinos, 1970) using the d_w, d_{16}, d_{50}, and d_{84} (equations 2, 3, 4, 5, and 6 in this report).

Appendix 3. Results of analyses of simple and multiple regression equations to estimate bankfull width, mean depth, cross-sectional area, and discharge for streams in and near Massachusetts.

[DF, degrees of freedom associated with each independent variable; <, less than; log, base-10 logarithm]

Variable	DF	Parameter estimate	Standard error	t-value	p-value
Simple regression					
Log bankfull width					
Intercept	1	1.17730	0.04124	28.54	0.000
Log drainage area	1	0.40382	0.02720	14.85	0.000
Log mean depth					
Intercept	1	-0.02217	0.03774	-0.59	0.561
Log drainage area	1	0.29598	0.02488	11.89	0.000
Log cross-sectional area					
Intercept	1	1.14970	0.05974	19.25	0.000
Log drainage area	1	0.70255	0.03939	17.83	0.000
Log discharge					
Intercept	1	1.56980	0.11910	13.18	0.000
Log drainage area	1	0.79964	0.07855	10.18	0.000
Multiple regression					
Log bankfull width					
Intercept	1	1.02792	0.06755	15.22	0.000
Log drainage area	1	0.39350	0.02516	15.64	0.000
Log mean basin slope	1	0.17514	0.06572	2.67	0.012
Log mean depth					
Intercept	1	-0.13700	0.06392	-2.14	0.040
Log drainage area	1	0.28804	0.02381	12.10	0.000
Log mean basin slope	1	0.13463	0.06219	2.16	0.038
Log cross-sectional area					
Intercept	1	0.88486	0.09189	9.63	0.000
Log drainage area	1	0.68424	0.03423	19.99	0.000
Log mean basin slope	1	0.31050	0.08939	3.47	0.002
Log discharge					
Intercept	1	0.91640	0.16250	5.64	0.00
Log drainage area	1	0.75447	0.06052	12.47	0.00
Log mean basin slope	1	0.76590	0.15810	4.85	0.00

Appendix 4. Summary statistics, confidence and prediction interval parameters, and results of analyses of simple regression equations for estimating the bankfull width, mean depth, cross-sectional area, and discharge for streams in the northeastern United States.

[R^2, coefficient of determination; S_e, standard error of the estimate; S_p, standard error of the prediction; t-90, the quartile of the student's t-distribution having n-2 (simple regression) degrees of freedom with a probability of exceedance of 0.05; t-95, the quartile of the student's t-distribution having n-2 degrees of freedom with a probability of exceedance of 0.025; n, number of data points; s, root mean square error; $(X'X)^{-1}$, covariance matrix; DF, degrees of freedom associated with each independent variable; log, base-10 logarithm]

Bankfull equation	Summary statistics							Confidence and prediction interval parameters					
	R^2	Adjusted R^2	Predicted R^2	S_e (log)	S_e (%)	S_p (log)	S_p (%)	t-90	t-95	s	n	$(X'X)^{-1}$	
Bankfull Width (ft)= 15.1988 [Drainage Area (mi^2)]$^{0.4190}$	0.863	0.862	0.8607	0.1198	28.12	0.1206	28.31	1.650	1.968	0.1198	334	0.014888427	-0.008356732
												-0.008356732	0.005871240
Bankfull Mean Depth (ft) = 1.0377 [Drainage Area (mi^2)]$^{0.2989}$	0.804	0.803	0.8013	0.1057	24.70	0.1064	24.88	1.650	1.968	0.1057	334	0.014888427	-0.008356732
												-0.008356732	0.005871240
Bankfull Cross-Sectional Area (ft^2) = 15.5826 [Drainage Area (mi^2)]$^{0.7198}$	0.915	0.914	0.9134	0.1547	36.78	0.1586	37.77	1.650	1.968	0.1547	334	0.014888427	-0.008356732
												-0.008356732	0.005871240
Bankfull Discharge (ft^3/s) = 49.4778 [Drainage Area (mi^2)]$^{0.8208}$	0.878	0.877	0.8762	0.2195	53.95	0.2208	54.31	1.650	1.968	0.2195	334	0.014888427	-0.008356732
												-0.008356732	0.005871240

Results of analyses

Variable	DF	Parameter estimate	Standard error	t-value	p-value
Log bankfull width					
Intercept	1	1.18181	0.01462	80.86	0.000
Log drainage area	1	0.41901	0.00918	45.65	0.000
Log mean depth					
Intercept	1	0.01607	0.01290	1.25	0.214
Log drainage area	1	0.29886	0.00810	36.88	0.000
Log cross-sectional area					
Intercept	1	1.19264	0.01921	62.07	0.000
Log drainage area	1	0.71983	0.01207	59.66	0.000
Log discharge					
Intercept	1	1.69441	0.02678	63.26	0.000
Log drainage area	1	0.82085	0.01682	48.81	0.000

Prepared by the Pembroke and West Trenton
Publishing Service Centers.

For more information concerning this report, contact:

Office Chief
U.S. Geological Survey
New England Water Science Center
Massachusetts-Rhode Island Office
10 Bearfoot Road
Northborough, MA 01532
dc_ma@usgs.gov

or visit our Web site at:
http://ma.water.usgs.gov

USGS

Bent and Waite—**Equations for Estimating Bankfull Channel Geometry and Discharge for Streams in Massachusetts**—Scientific Investigations Report 2013–5155

Printed on recycled paper

ISSN 2328-031X (print)
ISSN 2328-0328 (online)
http://dx.doi.org/10.3133/sir20135155

ISBN 978-1-4113-3693-3