Comparison of Methods for Determining Streamflow Requirements for Aquatic Habitat Protection at Selected Sites on the Assabet and Charles Rivers, Eastern Massachusetts, 2000–02

By Gene W. Parker, David S. Armstrong (U.S. Geological Survey), and
Todd A. Richards (Massachusetts Division of Fisheries and Wildlife)

In cooperation with the
Massachusetts Executive Office of Environmental Affairs, Department of Conservation and Recreation, Town of Hudson, and Massachusetts Division of Fisheries and Wildlife

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile ($ft^3/s/mi^2$)	0.01093	cubic meter per second per square kilometer ($m^3/s/km^2$)
foot (ft)	0.3048	meter (m)
foot per second (ft/s)	0.3048	meter per second (m/s)
mile (mi)	1.609	kilometer (km)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	259	hectare
square mile (mi^2)	2.590	square kilometer (km^2)

Local datums used in this report were arbitrarily set at the time of the fieldwork and are not referenced to any National Geodetic Vertical Datum.

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Abstract

Four methods used to determine streamflow requirements for habitat protection at nine critical riffle reaches in the Assabet River and Charles River Basins were compared. The methods include three standard setting techniques—R2Cross, Wetted Perimeter, and Tennant—and a diagnostic method, the Range of Variability Approach. One study reach is on the main stem of the Assabet River, four reaches are on tributaries to the Assabet River (Cold Harbor Brook, Danforth Brook, Fort Meadow Brook, and Elizabeth Brook), three are on the main stem of the Charles River, and one is on a tributary to the Charles River (Mine Brook). The strength of the R2Cross and Wetted-Perimeter methods is that they may be applied at ungaged locations whereas the Tennant method and the Range of Variability Approach require a period of streamflow record for analysis.

Fish community assessments conducted at or near riffle sites in flowing reaches of the Assabet River and Charles River Basins were used to indicate ecological conditions. The fish communities in the main stem and tributary reaches of both the Assabet and Charles River Basins indicated degraded aquatic ecosystems. However, the degree of degradation differs between the two basins. The extreme predominance of tolerant, generalist species in the Charles River fish community demonstrates the cumulative impacts of flow, habitat, and water-chemistry degradation, combined with the effects of nearby impoundments and changing land use.

The range of discharges for nine ungaged riffle reaches defined by the median R2Cross 3-of-3 criteria, R2Cross 2-of-3 criteria, and Wetted-Perimeter streamflow requirements, was 0.86 cubic foot per second per square mile, 0.18 cubic foot per second per square mile, and 0.23 cubic foot per second per square mile, respectively. Application of R2Cross and Wetted-Perimeter methods to sites with altered streamflows or at sites that are riffles only at low to moderate flows can result in a greater variability of streamflow requirements than would result if the methods were applied to riffles on natural channels with unaltered streamflows. The R2Cross 2-of-3 criteria and the Wetted-Perimeter streamflow requirements for the Assabet and Charles River sites show narrower interquartile ranges and lower median streamflow requirements than for 10 index streamflow-gaging stations in southern New England. This is especially evident for the R2Cross 2-of-3 criteria and Wetted-Perimeter results that were close to half of the flow requirements determined at the 10 southern New England stations.

The R2Cross and Wetted-Perimeter methods were also compared to the Range of Variability Approach analysis and the Tennant Method. The median R2Cross 3-of-3 criteria streamflow requirement for the nine riffles is close to the 75th percentile of the monthly mean flows during the summer low-flow period from six streamflow-gaging stations near the Assabet and Charles River Basins having mostly unaltered flow. This streamflow requirement is close to the median Tennant 40-percent-flow requirement for good habitat condition for the same six nearby stations. The R2Cross 2-of-3 criteria and Wetted-Perimeter results were less than the 25th-percentile of monthly mean flows during the summer months for the six stations. These streamflow requirements are in the poor habitat range as indicated by a Tennant analysis of the same six stations. These comparisons indicate that the R2Cross and Wetted-Perimeter methods underestimate streamflow requirements when applied to sites in smaller drainage areas and channels that are runs at higher flows.

Introduction

During the summer (July through September), when water levels are naturally low and the demand for water is high, water users are in competition for a limited supply of water. Federal, State and local agencies, as well as private citizens' groups, are concerned that streamflows altered by water withdrawals and returns could reduce the quality and quantity of the habitat that supports the biological integrity of the Assabet River and Charles River systems in eastern Massachusetts (fig. 1).

It is generally recognized that the quantity and quality of available water may not be sufficient to meet all needs and interests of area stakeholders. The Massachusetts Department of Conservation and Recreation (MADCR) determined that the Assabet River and Charles River Basins could serve as pilot areas in which to test methods for determining streamflow requirements for habitat protection. The U.S. Geological Survey (USGS), in cooperation with the Massachusetts Executive Office of Environmental Affairs (EOEA) Watershed Initiative Program and MADCR, began a habitat assessment in 2001 to determine the streamflow requirements in the Assabet and Charles River Basins.

In addition, the USGS coordinated its work with fish-assessment studies conducted by the Massachusetts Division of Fish and Wildlife to evaluate the current (1999–2002) fish population in the Assabet and Charles River Basins. Armstrong and others (2001) and Bain and Meixler (2000) have documented the utility of using fish to document flow-altered conditions in the Northeast. In 2002, a project was started by the USGS in cooperation with the Town of Hudson, MA, and in collaboration with the Organization of the Assabet River, to study additional riffle reaches in the Assabet River Basin. The USGS, in cooperation with the MADCR, coordinated the habitat project with a ground-water modeling project for the Assabet River Basin. The results from the modeling simulations will help to quantify the effects of water-use practices on streamflow and habitat in the Assabet River Basin.

Techniques for assessing streamflows for habitat protection can generally be categorized in three ways: standard-setting, incremental, and diagnostic methods (Instream Flow Council, 2002). Standard-setting methods use predetermined decision-making formulas or criteria to yield a single streamflow value. Incremental methods involve the analysis of habitat conditions at a specific site in relation to multiple decision variables for the exploration of different flow-management alternatives. Diagnostic methods consist of the examination of streamflow records over time for the identification of any changing conditions. The selection of a flow to protect habitat is based on the results of the different flow-management alternatives tested. Incremental methods were not used in this project due to their site-specific application.

The R2Cross (Nehring, 1979; Espegren, 1996, 1998) and Wetted-Perimeter (Nelson, 1984; Leathe and Nelson, 1986) methods are standard-setting, in-stream flow methods that require site-specific physical and hydraulic data. Cross-section data, and measurements of water depths in a riffle for a range of discharges are used to develop and calibrate a step-backwater flow model of a riffle habitat. The flow model is then used to simulate the physical and hydraulic data used in the R2Cross and Wetted-Perimeter methods. An advantage of the R2Cross and Wetted-Perimeter methods is that they are based upon results from a hydraulic model calibrated to field observations and do not require streamflow records; thus, the streamflow requirements obtained by these methods can be applied in hydrologically disturbed drainage basins and at gaged or ungaged sites.

The Tennant standard-setting method (Tennant, 1976) is based on a percentage of the average annual discharge for the period of streamflow records at a site. Specified percentages of the average annual discharge for a site correspond to specified levels of quality of habitat protection (excellent to poor). The limitation of the method is the requirement of having a continuous streamflow record to analyze. Application of the Tennant method to streamflow records at sites with altered flow conditions would influence subsequent calculations and results.

The Range of Variability Approach (RVA) (Richter and others, 1997), which is a diagnostic method, identifies and diagnoses an appropriate range of variation in 33 indicators of hydrologic alterations (IHA) parameters for a period of streamflow record at a site. The range of variation in these indicators is used to identify initial streamflow targets for flow management and habitat protection. As with the Tennant method, application of the method to streamflow records at sites with altered flow conditions would influence subsequent calculations and results.

Parker and Armstrong (2001) presented preliminary results of the R2Cross and Wetted-Perimeter analyses for five riffle reaches in the Assabet and Charles River Basins to estimate streamflow requirements for habitat protection. The results were considered preliminary because the flow conditions were generally too low for model calibration in the flow range of interest due to the dry weather prior to December 2001. Since the publication of the Parker and Armstrong (2001) report, study of the original five riffle reaches has been completed and five new reaches have been analyzed.

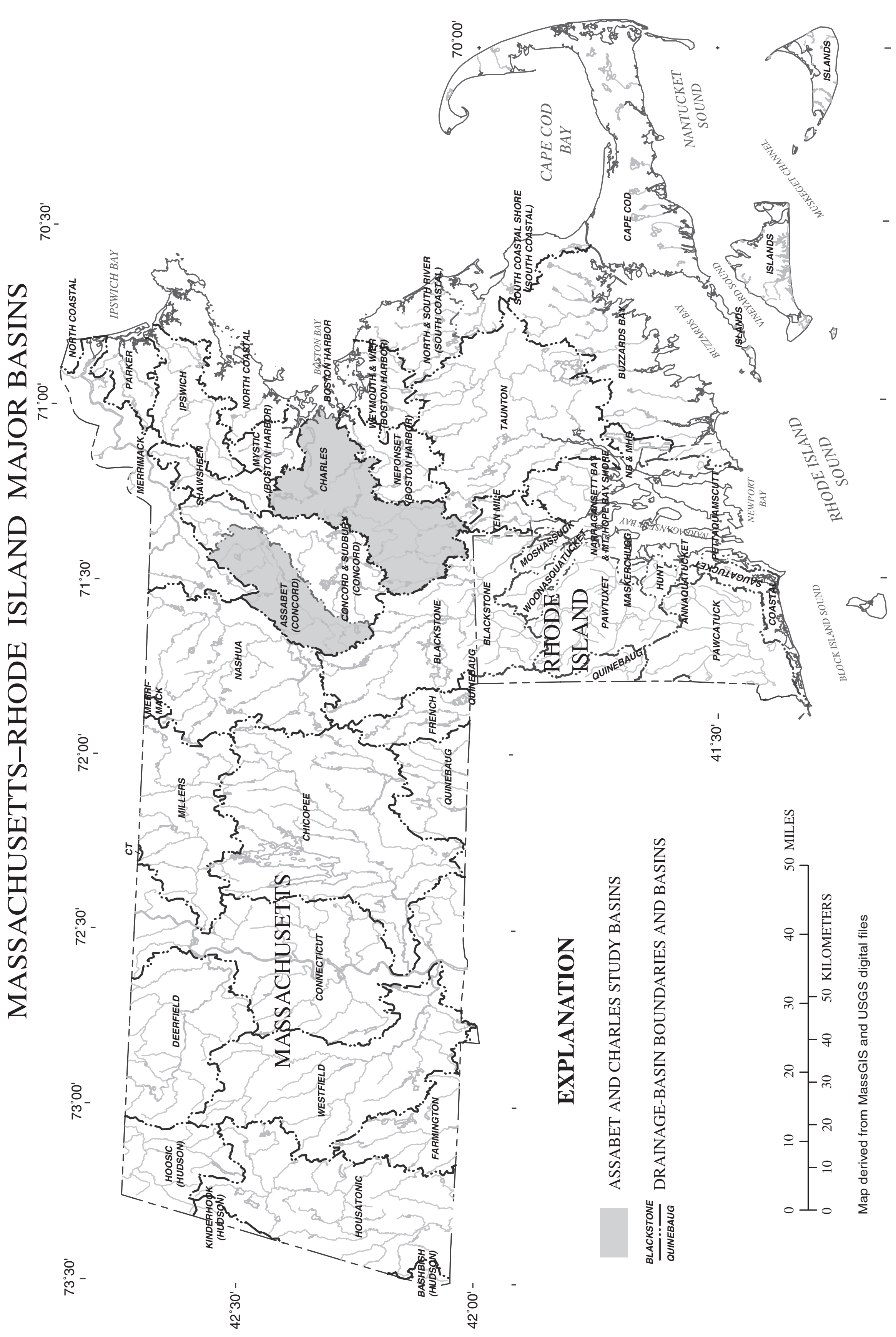

Figure 1. Location of major river basins in Massachusetts.

Purpose and Scope

This report compares three standard-setting methods and a diagnostic method for estimating the flow necessary to maintain aquatic habitat in the Assabet and Charles Rivers. The study area includes riffle reaches of the main stem Charles and Assabet Rivers and riffle reaches on tributaries to the Assabet and Charles Rivers in Massachusetts. The report describes streamflow requirements determined by means of the R2Cross (Nehring, 1979; Espegren, 1996, 1998), Wetted-Perimeter (Nelson, 1984; Leathe and Nelson, 1986), Tennant methods (Tennant, 1976), and by the RVA (Richter and others, 1997). Incremental methods were not used in this project because of their site-specific application. Streamflow requirements for aquatic habitat protection were determined from data collected in 2001 and 2002 at 10 sites: 3 sites on the main stem Charles River, 1 site on the main stem of the Assabet River, and 1 site each on Mine Brook in the Charles River Basin and Nashoba Brook, Elizabeth Brook, Danforth Brook, Fort Meadow Brook, and Cold Harbor Brook in the Assabet River Basin. Streamflow requirements for aquatic habitat protection were determined by the R2Cross and Wetted-Perimeter methods at 9 of the 10 riffle sites in the Charles and Assabet River Basins. These requirements were compared with average monthly discharges determined by using the RVA method and with streamflow requirements determined by using the Tennant method for six nearby streamflow-gaging stations.

The report also describes the fish communities at or near riffle sites in the Assabet and Charles River Basin study areas. The report evaluates the health of the habitat in relation to the fish population. The evaluation is based on the results of fish-population surveys conducted in the study basins during 2000–02. In addition, the report relates the results to analysis of the target fish community determined for the Quinebaug River Basin, MA.

Description of Study Sites

The Assabet and Charles Rivers are in nearby drainage basins in eastern Massachusetts (fig. 1). The Assabet River is a subbasin of the Concord River and is bounded by the Nashua and Blackstone River Basins to the west and the Sudbury River Basin to the east and south. The Charles River drains into Boston Harbor and is bounded by the Blackstone River Basin to the west, the Sudbury River to the North, and Taunton and Neponset River Basins to the south.

The main-stem study site in the headwaters of the Assabet River is a riffle near Westborough, MA (fig. 2). Five tributary study sites are on riffles on Nashoba Brook, Elizabeth Brook, Danforth Brook, Fort Meadow Brook, and Cold Harbor Brook (table 1). The Assabet River study site is about 100 ft downstream of the bridge over Fisher Street in Westborough, MA. The Nashoba Brook study site is about 110 ft downstream of Commonwealth Avenue in West Concord, MA, and about 950 ft upstream of the brook’s mouth at the Assabet River. The Elizabeth Brook study site is just downstream of a ford on an unnamed road in Stow, MA, and about 0.72 mi upstream of the brook’s mouth at the Assabet River. The Fort Meadow Brook study site is in Hudson, MA, about 1.5 mi upstream from the brook’s mouth at the Assabet River. The Danforth Brook study site is in Hudson, MA, about 1.35 mi upstream of the brook’s mouth at the Assabet River. The Cold Harbor Brook study site is in Northborough, MA, about 2.9 mi upstream of the brook’s mouth at the Assabet River.

The two main-stem Charles River study sites are riffles upstream of the Walker Street Bridge and the streamflow-gaging station on the Charles River at Medway (01103200). An additional main-stem study site is in the headwaters of the Charles River on a riffle in Hopkinton, MA, about 300 ft downstream of Echo Lake and about 3,450 ft upstream of the State Route 85 culvert in Milford, MA. The Mine Brook study site is at a riffle about 800 ft east of the intersection of Routes 140 and I-495 in Franklin, MA (table 1).

Methods for Determining Streamflow Requirements for Aquatic Habitat Protection

Two standard-setting methods, the R2Cross method (Espegren, 1996, 1998; Nehring, 1979) and the Wetted-Perimeter method (Nelson, 1984; Leathe and Nelson, 1986), were applied at 10 riffle study sites in the Assabet and Charles River Basins for the evaluation of streamflow requirements for aquatic habitat protection. For comparison purposes, the Tennant method (Tennant, 1976), a standard-setting method, and the RVA method (Richter and others, 1996), a diagnostic method, were applied to records from six streamflow-gaging stations at sites with relatively unaltered streamflows and within 30 mi of the ten riffle study sites. The results of the comparison indicate the minimal streamflows that could protect aquatic habitat in relatively unaltered-flow basins in the region around the Assabet and Charles River Basins.

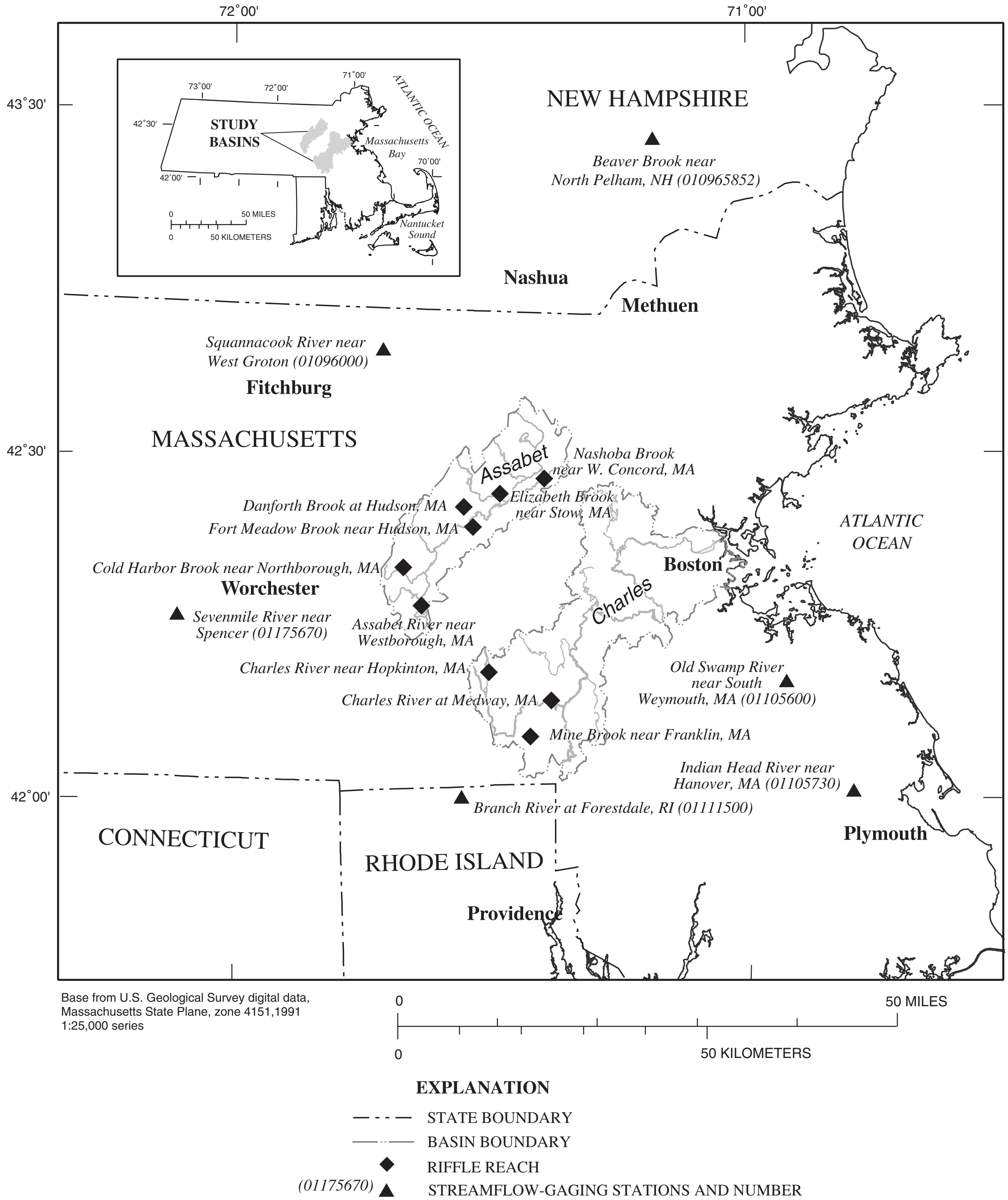

Figure 2. Location of study sites and six streamflow-gaging stations near the Charles and Assabet River Basins, Massachusetts.

Table 1. Locations and characteristics of riffle reaches, Assabet and Charles Rivers, Massachusetts.

[ft, foot; mi^2, square mile]

River basin	Stream name	Town	Riffle location	Approximate riffle length (ft)	Drainage area (mi^2)
Assabet River	Assabet River	Westborough	100 ft downstream of Fisher Street Bridge	100	6.79
	Cold Harbor Brook	Northborough	250 ft downstream of Cherry Street culvert	60	5.06
	Danforth Brook	Hudson	300 ft upstream of Route 85 culvert	80	5.12
	Fort Meadow Brook	Hudson	1,350 ft upstream of Shay Street culvert	90	4.85
	Elizabeth Brook	Stow	1,060 ft south of White Pond Road	70	18.7
	Nashoba Brook	West Concord	110 ft downstream of Commonwealth Avenue Bridge	130	48.01
Charles River	Charles River	Hopkinton	3,450 ft upstream of State Route 85 culvert in Milford	90	1.58
	Mine Brook	Franklin	680 ft upstream of Route 140 culvert	87	10.0
	Charles River	Medway	1,480 ft upstream of Walker Street Bridge	30	65.7
	Charles River	Medway	600 ft upstream of Walker Street Bridge	110	65.7

Application of the R2Cross and Wetted-Perimeter methods requires careful selection of study sites in riffle habitats. A riffle is a section of channel, usually between pools, that has gravel-to-cobble-sized bed material. The water surface is turbulent with little or no whitewater and average velocities are in the range of 0.6 ft/s to 1.6 ft/s (Bain and Stevenson, 1999). Appropriate riffles for application of the R2Cross and Wetted-Perimeter methods extend across the entire channel, are fairly stable, and maintain hydraulic control over a range of low to moderate flows. Differences in channel geometry among riffles can create variability in the determined streamflow requirements. For example, reaches that have large boulders or woody debris in the channel or altered streambeds or banks should be avoided. If possible, riffle sites are chosen that represent natural riffle conditions. The methods work best in riffles in alluvial channels that adjust their width and depth to accommodate higher flows. Alterations to channels can have a direct effect on streamflow recommendations generated by these methods. The artificial widening or narrowing of the stream channel at a site can affect wetted perimeter, average velocity, and average depth. The reinforcement of stream banks and streambeds with riprap prevents natural width and depth adjustments. Consequently, streamflow requirements determined for natural riffle sites may not be sufficient to protect habitat at sites in a widened channel and may be excessive at sites in an artificially restricted channel; conversely, flow requirements estimated at sites with a narrowed channel may not provide sufficient flows for habitat protection in unaltered stream reaches.

Water-Surface-Profile Modeling

A water-surface-profile model, the U.S. Army Corps of Engineers Hydrologic Engineering Center's River Analysis System (HEC-RAS; Brunner, 2001), was used in this study to simulate the water-surface profile for each riffle site and to determine the hydraulic parameters required for application of both the R2Cross and Wetted-Perimeter methods. HEC-RAS is designed to perform one-dimensional hydraulic calculations for a network of natural or constructed channels under steady or gradually varying flow. The computational procedure is based on the solution of the one-dimensional energy equation from one stream section to the next. Energy losses are evaluated by friction (Manning's equation) and channel contraction or expansion (Brunner, 2001). Once calibrated, the HEC-RAS model is used to simulate hydraulic parameters for a wide range of discharges. R2Cross streamflow requirements are determined from a staging table of discharges, water-surface altitudes, stream-top width, average depth, average velocity, and percentage of bankfull wetted perimeter. Wetted-perimeter streamflow requirements are determined from plots of wetted perimeter and discharge, wetted perimeter and water-surface altitude, and stream cross section.

R2Cross Method

The R2Cross method requires selection of a critical riffle along a stream and is based on the assumption that a discharge chosen to maintain habitat in the riffle is sufficient to maintain habitat for fish in nearby pools and runs for most life stages of fish and aquatic invertebrates (Nehring, 1979). As can be seen in figure 3, the flow conditions at a pooled reach include slower velocities, greater depths, and greater wetted perimeters than the flow conditions found at an adjacent riffle reach for the same discharge. Streamflow requirements for habitat protection in riffles are based on minimum flows that meet or exceed criteria for three hydraulic parameters: average depth, percent of bankfull wetted perimeter, and average water velocity (table 2). Criteria for these hydraulic variables were developed in Colorado to quantify the amount of streamflow required for "preserving the natural environment to a reasonable degree" (Espegren, 1996).

A.

B.

Figure 3. *A*, Riffle and *B*, pooled reaches on the Charles River at Medway, Massachusetts, on August 1, 2001, during a period of low flow.

Table 2. R2Cross criteria for four hydraulic parameters for protection of aquatic habitat.

[Source: Modified from Espegren, 1996. ft, foot; ft/s, foot per second; ≥, greater than or equal to]

Stream top width (ft)	Average depth (ft)	Bankfull wetted perimeter (percent)	Average velocity (ft/s)
1–20	0.2	50	1.0
21–50	0.2–0.5	50	1.0
51–60	0.5–0.6	50–60	1.0
61–100	0.6–1.0	≥70	1.0

To account for seasonal streamflow variability, the R2Cross method establishes different streamflow requirements for the summer and winter seasons. Initial streamflow recommendations in Colorado are based upon the minimal streamflows that meet or exceed all three hydraulic criteria during the high-flow period in summer and any two of the three hydraulic criteria during its low-flow period in winter (table 2). In contrast to Colorado, Massachusetts's flows are generally lowest in mid summer and early fall (July through September). For this study, R2Cross streamflow recommendations were determined by the methods based on 3-of-3 and 2-of-3 hydraulic criteria. The criteria are scaled to each channel on the basis of the bankfull channel width and wetted perimeter.

Streamflow requirements for habitat protection in riffles determined by using the R2Cross methodology usually involve the calculation of the energy loss in the form of friction (Manning's equation) for a single cross section in a study riffle. HEC-RAS was used to simulate the water-surface profile for each riffle site. Use of multiple cross-sections and the HEC-RAS model provides improved simulations of the hydraulic conditions expected in riffles in comparison to conditions simulated by modeling an individual cross section.

Wetted-Perimeter Method

The Wetted-Perimeter method is based on the assumption that there is a direct relation between the wetted perimeter in a riffle and fish habitat in streams (Annear and Conder, 1984; Lohr, 1993). The wetted perimeter of a stream, defined as the width of the streambed and stream banks in contact with water for an individual cross section, is used as a measure of the availability of aquatic habitat over a range of discharges (Annear and Conder, 1984; Nelson, 1984). A plot of the relation between wetted perimeter and discharge indicates the discharge that fully wets the bottom of the channel bed (fig. 4). These plots generally have a characteristic shape—steeper at low discharges and flatter at high discharges. Initially, as the channel fills with water, the wetted perimeter increases sharply for each unit increase in discharge. Once the water rises above the bottom of the bank, the rate of increase of wetted perimeter for each unit increase of discharge abruptly decreases. This abrupt decrease is indicated by the curves breakpoint. The breakpoint is used to determine the streamflow required for habitat protection. On a stream cross section, this point theoretically corresponds to the break in slope at the bottom of a stream bank where the water surface would begin to rise up the banks when flows increase, or recede in a more horizontal direction from the stream banks when flows decrease.

The Wetted-Perimeter method should be applied only to cross sections in riffle habitats. The method should not be applied in other habitats such as pools or runs. The Wetted-Perimeter method is best applied to rectangular or trapezoidal cross sections within riffles on straight reaches. The shape of the relation between wetted perimeter and discharge is largely a function of channel geometry. The bottom of the bank is most readily identified in the field in channels with rectangular or trapezoidal cross sections, which produce a more defined breakpoint than triangular or bowl-shaped cross-sections (Gippel and Stewardson, 1998). In practice, there is seldom a single break in slope in the wetted-perimeter-to-discharge relation. The slope of the stream banks, the presence of bars or boulders, or other irregularities in the streambed or banks can contribute to the lack of a distinct breakpoint or multiple breaks in slope. Less well-defined breakpoints may also be a function of the number, density, and location of points surveyed along a cross section.

The Wetted-Perimeter method is best applied in alluvial channels that can naturally adjust their depth and width. Application of the method to disturbed channels (widened or narrowed) or channels with hardened stream banks (rip-rap or a stone wall) will likely increase the variability of streamflow requirements determined by the method. Cross sections should be selected to avoid woody debris, large rocks, or other obstructions that extend above the water surface. Cross sections on bends where the channel has a deep thalweg against the bank on outside of the bend, and a point bar on the inside of the bend, should also be avoided where possible. Cross sections at transitions between the riffle itself and other habitats at the upstream or downstream ends of the riffle should also be avoided.

For this study, several detailed cross sections were surveyed at each riffle site. Points that corresponded to changes in slope of the streambeds and banks were surveyed along the cross section. The altitudes of the bottoms of the stream banks that corresponded to a fully wetted channel were determined during surveying. These surveyed bottom-of-the-bank altitudes were used to determine of Wetted-Perimeter streamflow requirements. In cross sections where the transition between streambed and bank is gradual, several points defining the transition were surveyed along with points that defined the channel width.

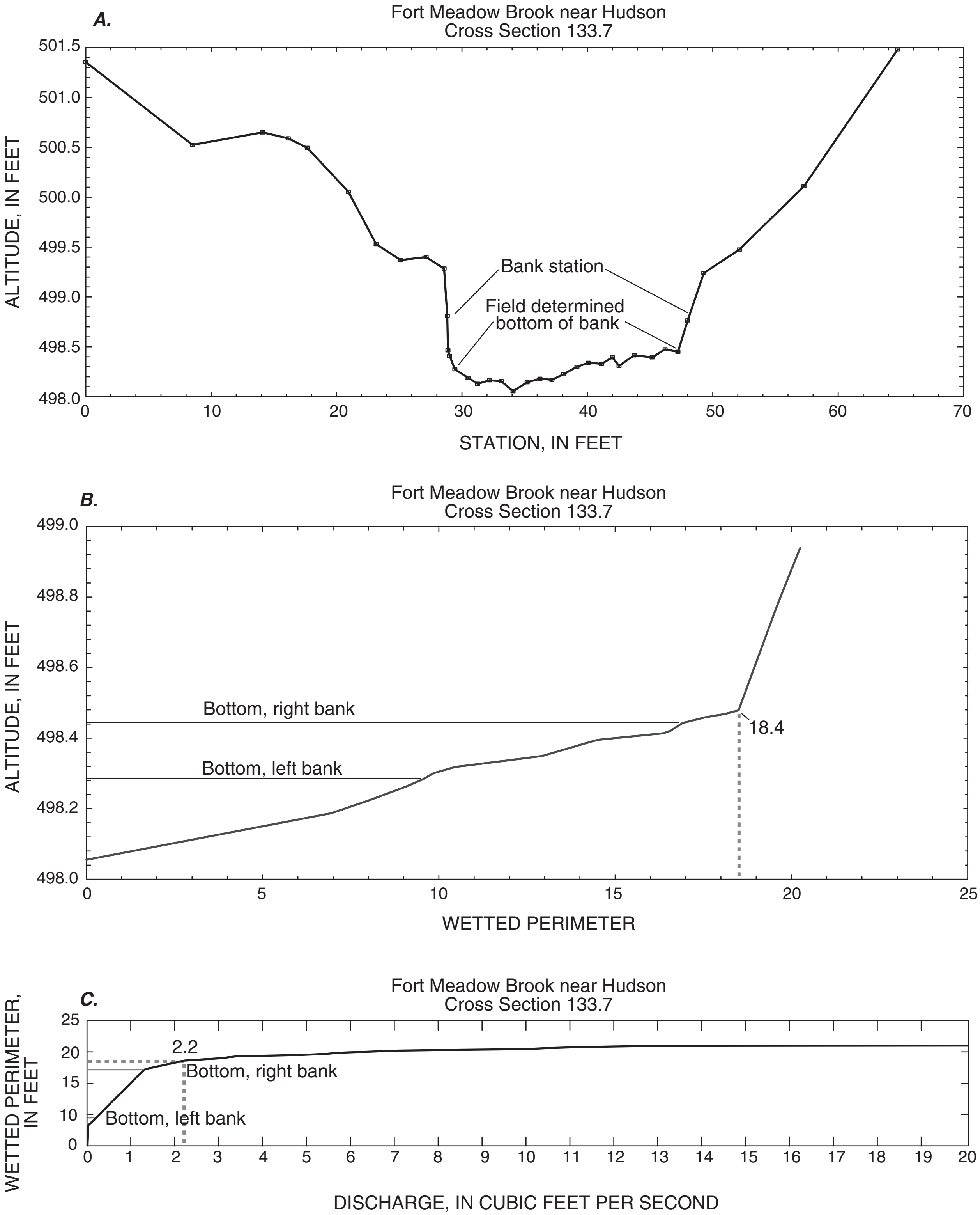

Figure 4. *A*, Stream channel for River Station 133.7; *B*, graph of relation between altitude and wetted perimeter; and *C*, graph of relation between wetted perimeter and discharge at Fort Meadow Brook near Hudson, Massachusetts.

Plots of water-surface altitude and wetted perimeter were also used in this study to identify breakpoints due to changes in channel geometry. In a rectangular or trapezoidal channel with steep banks, the altitudes of the bottoms of the left and right banks define a narrow range of elevations that corresponds with a break in slope. If the breakpoint on the plot of wetted perimeter and discharge was not associated with the altitudes of the bottoms of banks or if there were multiple breakpoints, the breakpoint on the plot of wetted perimeter and water-surface altitude plot that most closely corresponds with the elevations of the left and right bottoms of bank is used to determine the streamflow requirement. In a triangular or bowl-shaped channel, or trapezoid-shaped channel where one or both banks have a shallow slope, the surveyed bottoms of banks may not correspond with or bracket a breakpoint. If the bottoms of banks were not at the same altitudes, a breakpoint on the wetted perimeter and discharge plot that corresponds with the altitudes of the bottoms of banks was used to determine the streamflow requirement. If no breakpoint corresponded to the altitudes of the bottoms of banks, a breakpoint near or between the altitudes of the bottoms of banks that corresponds with the channel width was used to determine the streamflow requirement. If the bottoms of banks were not at the same altitude, and there were no distinct breakpoints between the bottoms of banks, a streamflow requirement was not determined for that cross section.

Range of Variability Approach

The RVA method identifies the range of target streamflows as the interquartile ranges for each of 33 statistical indicators of IHA parameters. The method is a diagnostic technique used to guide management effort to restore or maintain natural variability in hydrologic systems (Instream Flow Council, 2002). The IHA Analysis (Richter and others, 1996) was developed by the Nature Conservancy to assess the range of variation of discharge for a river through a statistical characterization of ecologically related hydrologic parameters. The technique uses daily streamflow records to determine the variation in the 33 parameters. Half of the statistics measure the central tendency of the magnitude or the rate of change of water conditions, and half focus on the magnitude, duration, timing, and frequency of extreme events. This information may be used to formulate target ranges for streamflows for river management. The technique is best applied to gaged, unregulated streams to document the natural variability that can occur in streamflows.

Tennant Method

The Tennant method (Tennant, 1976) is a standard-setting technique that bases its streamflow requirements on the observation that aquatic-habitat conditions are similar in streams carrying the same proportion of the mean annual flow (Q_{MA}). To account for seasonal streamflow variability, the Tennant Method established different streamflow requirements for the summer and winter seasons on the basis of different percentages of the Q_{MA}. In the mountainous western United States, where the Tennant method was developed, precipitation patterns and snowmelt runoff typically result in low streamflows in fall and early winter and high streamflows in the summer. Therefore, the Tennant streamflow recommendations are higher in the summer than in the winter. In southern New England, streamflow generally is lowest in mid summer and early fall and highest in spring. Thus, the summer streamflow criteria recommended by Tennant may be high. Because low summer streamflows in southern New England may also be linked to additional stresses, such as high stream temperatures and low dissolved oxygen concentrations, both the Tennant summer and winter criteria are evaluated in this report for use during summer. The Tennant method is best applied to gaged, unregulated streams.

Streamflow Requirements for Aquatic Habitat Protection

The R2Cross and Wetted-Perimeter standard-setting methods were used to evaluate streamflow requirements for habitat protection for sites on the Assabet River and Charles River for the summer period. Ten riffle reaches were identified for determination of streamflow requirements. One of these sites was in the headwaters of the Assabet River, five were on tributaries to the Assabet River, two were on the main stem of the Charles River, one was in the headwaters of the Charles River, and one was on a tributary to the Charles River. With the exception of two tributary sites in the Assabet River Basin, all sites might have had altered flow conditions due to wellfield withdrawals or direct diversion of flow upstream of the study sites.

Assabet River near Westborough

The study reach on the Assabet River riffle is about 100 ft downstream of the Fisher Street Bridge near Westborough, MA (fig. 5). Five cross sections of trapezoidal shape were surveyed on July 25, 2002, along a 100-ft reach and included in the hydraulic, water-surface-profile model. The channel is bounded by an open field along its left bank with a narrow border of shrubs. Scattered trees and shrubs in front of hardwood forest bound the right bank. The bed material is primarily silt and sand with a few cobbles. The bank material is composed of organic silt and sand. The stream has a moderate slope; the water surface drops from about 0.5 to 0.1 ft along the study reach at measured flows ranging from 0.05 to 27.3 ft^3/s.

The HEC-RAS model was calibrated as a subcritial flow regime by using the standard upstream-step energy method as documented in Appendix 1. The calibration accuracy was calculated as the root mean square of the differences between the observed and modeled water-surface altitudes for all cross

Figure 5. Assabet River near Westborough, Massachusetts, upstream view.

sections with measured discharges in the modeled reach. The calibration accuracy was 0.015 ft over the entire reach for all measured discharges. The HEC-RAS software occasionally indicated the need for more cross sections to reduce velocity head drops between sections. Interpolated cross sections were added to the model between surveyed cross sections to reduce the velocity head drops between sections and improve the model calibration to observed water-surface altitudes.

The R2Cross analysis to determine the required streamflow for habitat protection was based upon the HEC-RAS simulation results for the cross sections 116.71, 127.83, and 136.38 (tables 3 and 4). The cross sections at river stations 116.71, 127.83, and 136.38 were identified as the critical sections in the riffle reach because they are upstream of the point where the riffle is influenced by any backwater. The limiting R2Cross criterion was the average velocity for 3-of-3 criteria and average depth for 2-of-3 criteria for all three study sections.

Relations between wetted perimeter and discharge and between altitude of water surface and wetted perimeter were determined for cross sections at river stations 116.71, 127.83, and 136.38 on the basis of the HEC-RAS simulations for a range of discharges up to bankfull flow. The discharges identified by the Wetted-Perimeter method as required for habitat protection during the summer period are summarized in table 5. The hydraulic parameters associated with these discharges as well as the hydraulic characteristics of the discharges that met the R2Cross 3-of-3 and 2-of-3 criteria requirements are summarized in table 6.

Cold Harbor Brook near Northborough

The riffle study reach on Cold Harbor Brook (fig. 6) is about 250 ft downstream of the bridge on Cherry Street in Northborough, MA. Six cross sections of trapezoidal shape were surveyed on July 26, 2002, along a 60-ft reach and included in the water-surface-profile model. The channel gently meandered along the length of the study reach. There are scattered trees and shrubs with open fields along the right bank and a narrow border of shrubs on the left bank of the channel. The bed material is primarily silt and sand with a few cobbles. The bank material is composed of organic soil, silt, and sand. The stream has a moderate slope; the water surface drops about 0.6 to 0.2 ft along the study reach at measured flows ranging from 0.1 to 11.9 ft^3/s.

The HEC-RAS model was calibrated as a subcritial flow regime by using the standard upstream-step energy method as documented in Appendix 1. The model calibration accuracy was 0.006 ft over the entire reach for all measured discharges. The HEC-RAS software occasionally indicated the need for more cross sections to reduce velocity-head drops between sections. Interpolated cross sections were added to the model between surveyed cross sections to reduce the velocity-head drops between sections and improve the model calibration to observed water-surface altitudes.

Table 3. Streamflows required for habitat protection determined by means of the R2Cross 3-of-3-criteria method.

[ft^3/s, cubic foot per second; $ft^3/s/mi^2$, cubic foot per second per square mile; mi^2, square mile]

River and reach	Drainage area (mi^2)	River station	Discharge (ft^3/s)	Discharge ($ft^3/s/mi^2$)	Limiting R2Cross criteria
Assabet River Basin					
Assabet River near Westborough	6.79	116.71	5.8	0.854	Velocity.
		127.83	6.8	1.001	Velocity.
		136.38	8	1.178	Velocity.
Cold Harbor Brook near Northborough	5.06	137.4	3.5	.692	Velocity.
Danforth Brook at Hudson	5.12	25.9	14.4	2.813	Velocity.
		51.9	10.10	1.973	Velocity.
		60.8	8.10	1.582	Velocity.
		68.7	10.4	2.031	Velocity.
		81.6	11.5	2.246	Velocity.
Fort Meadow Brook near Hudson	4.85	133.7	7.3	1.505	Velocity.
Elizabeth Brook near Stow	18.7	202.05	10	.535	Depth.
		213.57	9	.481	Velocity.
		229.45	10.5	.561	Depth.
		241.46	12	.642	Depth.
Nashoba Brook at West Concord	48.01	120.3	7.1	.148	Depth.
		142.5	6.8	.141	Velocity.
		164.5	5.8	.12	Velocity.
Charles River Basin					
Charles River near Hopkinton	1.58	101.39	2.2	1.392	Velocity.
		157.84	2	1.266	Velocity.
		166.01	2.7	1.709	Velocity.
Mine Brook near Franklin	10.1	112.91	9	.891	Velocity.
		123.60	7	.693	Velocity.
		143.62	6.2	.614	Velocity.
		164.85	4.2	.416	Velocity.
		173.65	2.5	.248	Velocity.
		187.25	8.2	.812	Velocity.
Charles River near Medway upstream	65.7	1,481.8	45.4	.691	Depth.
		1,498.9	52.8	.804	Depth.
Charles River near Medway downstream	65.7	691.6	57	.868	Depth.

Table 4. Streamflows required for habitat protection determined by means of the R2Cross 2-of-3-criteria method.

[ft^3/s, cubic foot per second; $ft^3/s/mi^2$, cubic foot per second per square mile; mi^2, square mile]

River and reach	Drainage area (mi^2)	River station	Discharge (ft^3/s)	Discharge ($ft^3/s/mi^2$)	Limiting R2Cross criteria
Assabet River Basin					
Assabet River near Westborough	6.79	116.71	0.6	0.088	Depth.
		127.83	.4	.059	Depth.
		136.38	.45	.066	Depth.
Cold Harbor Brook near Northborough	5.06	137.4	.2	.53	Depth.
Danforth Brook at Hudson	5.12	25.9	.18	.035	Depth.
		51.9	.40	.078	Depth.
		60.8	1.20	.234	Depth.
		68.7	.90	.176	Depth.
		81.6	2	.391	Depth.
Fort Meadow Brook near Hudson	4.85	133.7	2.2	.454	Depth.
Elizabeth Brook near Stow	18.7	202.05	5	.267	Velocity.
		213.57	6.5	.348	Depth.
		229.45	3.6	.193	Velocity.
		241.46	10.2	.548	Velocity.
Nashoba Brook at West Concord	48.01	120.3	5.2	.108	Velocity.
		142.5	5.5	.115	Depth.
		164.5	4.2	.089	Depth.
Charles River Basin					
Charles River near Hopkinton	1.58	101.39	0.21	0.133	Wetted perimeter.
		157.84	2.0	1.266	Depth.
		166.01	.22	.139	Wetted perimeter.
Mine Brook near Franklin	10.1	112.91	2.3	.228	Depth.
		123.6	.8	.079	Depth.
		143.62	1.1	.109	Depth.
		164.85	1.1	.107	Wetted perimeter.
		173.65	1.9	.188	Depth.
		187.25	3.8	.376	Depth.
Charles River near Medway upstream	65.7	1,481.8	8	.122	Velocity.
		1,498.9	11.6	.177	Velocity.
Charles River near Medway downstream	65.7	691.6	21.6	.329	Velocity.

Table 5. Streamflows required for habitat protection determined by means of the Wetted-Perimeter method.

[ft^3/s, cubic foot per second; $ft^3/s/mi^2$, cubic foot per second per square mile; mi^2, square mile]

River and reach	Drainage area (mi^2)	River station	Discharge (ft^3/s)	Discharge ($ft^3/s/mi^2$)
Assabet River Basin				
Assabet River near Westborough	6.79	116.71	0.6	0.088
		127.83	.2	.029
		136.38	.2	.029
Cold Harbor Brook near Northborough	5.06	137.4	1.3	.257
Danforth Brook at Hudson	5.12	25.9	.5	.195
		81.6	2	.82
Fort Meadow Brook near Hudson	4.85	133.7	1.7	.351
Elizabeth Brook near Stow	18.7	202.05	3.5	.187
		213.57	1.8	.096
		229.45	5.5	.294
		241.46	3	.16
Nashoba Brook at West Concord	48.01	120.3	7.0	.146
		142.5	5	.104
		164.5	4	.083
Charles River Basin				
Charles River near Hopkinton	1.58	101.39	0.2	0.127
		166.01	.45	.285
Mine Brook near Franklin	10.1	112.91	5.8	.574
		123.6	5.2	.515
		143.62	6.2	.614
		164.85	6.5	.644
		173.65	5.6	.337
		187.25	2.2	.218
Charles River near Medway upstream	65.7	1,481.8	16.5	.251
		1,498.9	7.7	.117
Charles River near Medway downstream	65.7	691.6	8.7	.132

Table 6. Hydraulic characteristics at critical cross sections meeting R2Cross and Wetted-Perimeter method criteria for habitat protection at the Assabet River near Westborough, Massachusetts.

[ft, foot; ft^3/s, cubic foot per second; ft/s, foot per second; --, not applicable]

River station	Discharge (ft^3/s)	Top width (ft)	Wetted perimeter (ft)	Average depth (ft)	Average velocity (ft/s)	Notes
116.71	13	14.12	14.95	--	--	Bankfull discharge.
	5.75	--	14.06	0.42	1	Meets 3-of-3 criteria.
	.6	--	13.56	.20	.22	Meets 2-of-3 criteria.
	.6	--	13.56	.20	.22	Meets wetted-perimeter criteria.
127.83	13	15.47	15.53	--	--	Bankfull discharge.
	6.75	--	14.16	.48	1	Meets 3-of-3 criteria.
	.4	--	12.39	.20	.16	Meets 2-of-3 criteria.
	.2	--	11.87	.12	.14	Meets wetted-perimeter criteria.
136.38	13	21.22	21.92	--	--	Bankfull discharge.
	8	--	19.97	.42	1	Meets 3-of-3 criteria.
	.45	--	11.16	.20	.21	Meets 2-of-3 criteria.
	.2	--	10.45	.15	.13	Meets wetted-perimeter criteria.

Figure 6. Cold Harbor Brook near Northborough, Massachusetts, upstream view.

The R2Cross analysis to determine the required streamflow for habitat protection was based upon the HEC-RAS model results for the cross section at river station 137.4 (tables 3 and 4). The hydraulic characteristics that met the R2Cross 3-of-3 and 2-of-3 criteria requirements from the calibrated model for each cross section are summarized in table 7. The cross section at river station 137.4 was identified as being the critical section in the riffle reach because it is upstream of the point where the riffle is influenced by backwater. The limiting R2Cross criterion was the average velocity for 3-of-3 criteria and the average depth for 2-of-3 criteria.

Wetted perimeter-discharge and stage-wetted perimeter relations were determined for cross sections at river station 137.4 on the basis of the HEC-RAS simulations for a range of discharges up to bankfull flow. The discharge identified by the Wetted-Perimeter method as required for habitat protection during the summer period are summarized in table 5. The hydraulic parameters associated this discharge are summarized in table 7.

Table 7. Hydraulic characteristics at critical cross sections meeting R2Cross and Wetted-Perimeter method criteria for habitat protection at Cold Harbor Brook near Northborough, Massachusetts.

[ft, foot; ft^3/s, cubic foot per second; ft/s, foot per second; --, not applicable]

River station	Discharge (ft^3/s)	Top width (ft)	Wetted perimeter (ft)	Average depth (ft)	Average velocity (ft/s)	Notes
137.4	7.2	14.22	14.49	--	--	Bankfull discharge.
	3.5	--	10.12	0.3	1	Meets 3-of-3 criteria.
	.26	--	7.84	.2	.17	Meets 2-of-3 criteria.
	1.3	--	8.73	.30	.51	Meets wetted-perimeter criteria.

Danforth Brook at Hudson

The riffle section studied on Danforth Brook (fig. 7) is about 300 ft upstream of the Route 85 culvert in a conservation area owned by the town of Hudson. Seven cross sections were surveyed on September 19, 2001, in this study reach, six of which were included in the water-surface-profile model. The cross sections were along an 80-ft length of pool and riffle habitats and were predominantly trapezoidal in shape. The channel takes a shallow bend to the left along the study reach. There are scattered trees and shrubs along both banks, the bed material is primarily cobbles, and the bank material is composed of rich organic soil, silt, sand, and cobbles. The stream has a moderately steep slope. The water surface drops about 1.8 to 1.6 ft along the study reach for all measured flows ranging from 0.009 ft^3/s to 28.5 ft^3/s.

The HEC-RAS model was calibrated as a subcritial flow regime by using the standard upstream-step energy method as documented in Appendix 1. The model calibration accuracy was 0.004 ft over the entire reach for all measured discharges. The HEC-RAS software occasionally indicated the need for more cross sections to reduce velocity head drops between sections. Interpolated cross sections were added to the model between surveyed cross sections to reduce the velocity head drops between sections and improve the model calibration to observed water-surface altitudes.

The R2Cross analysis to determine the required streamflow for habitat protection was based upon the HEC-RAS model results for cross sections at river stations 25.9, 51.9, 60.8, 68.7, and 81.6 (tables 3 and 4). The hydraulic characteristics that met the R2Cross 3-of-3 and 2-of-3 criteria requirements from the calibrated model for each cross section are summarized in table 8. The cross sections at river stations 25.9, 51.9, 60.8, 68.7, and 81.6 were identified as being the critical sections in the riffle reach because they are upstream of the point where the riffle is influenced by backwater. The limiting R2Cross criterion for 3-of-3 criteria was the average velocity and the average depth was the limiting criterion for 2-of-3 criteria at all sections. Parker and Armstrong (2001) reported a preliminary estimate of the required streamflow for habitat protection of 10.5 to 14.3 ft^3/s, which meets 3-of-3 criteria for two cross sections at this site. The estimates in table 3 are the result of a HEC-RAS simulation that is calibrated over a greater range of discharges. The streamflow requirements that meet 3-of-3 criteria range from 8.1 to 14.4 ft^3/s for five cross sections (table 3).

Relations between wetted perimeter and discharge and between altitude of the water surface and wetted perimeter were determined for cross sections at river stations 25.9 and 81.6 on the basis of the HEC-RAS simulations for a range of discharges up to bankfull flow. The discharges identified by the Wetted-Perimeter method as required for habitat protection during the summer period as range from 0.5 to 2.0 ft^3/s (table 5). The hydraulic parameters associated with these discharges are summarized in table 8. The range of discharges in table 5 for Danforth Brook are considerably greater than the preliminary estimates reported by Parker and Armstrong (2001). The estimates in table 5 are the result of a HEC-RAS simulation that was calibrated over a greater range of discharges than the range that was used in the preliminary analysis.

Figure 7. Danforth Brook at Hudson, Massachusetts, upstream view.

Table 8. Hydraulic characteristics at critical cross sections meeting R2Cross and Wetted-Perimeter method criteria for habitat protection at Danforth Brook at Hudson, Massachusetts.

[ft, foot; ft^3/s, cubic foot per second; ft/s, foot per second; --, not applicable]

River station	Discharge (ft^3/s)	Top width (ft)	Wetted perimeter (ft)	Average depth (ft)	Average velocity (ft/s)	Notes
25.9	44	20	20.77	--	--	Bankfull discharge.
	14.4	--	19.64	0.75	1	Meets 3-of-3 criteria.
	.18	--	16.25	.2	.06	Meets 2-of-3 criteria.
	.5	--	17.38	.27	.11	Meets wetted-perimeter criteria.
51.9	44	21.45	21.74	--	--	Bankfull discharge.
	10.1	--	18.67	.55	1	Meets 3-of-3 criteria.
	.4	--	12.45	.22	.15	Meets 2-of-3 criteria.
60.8	44	21.18	21.48	--	--	Bankfull discharge.
	8.1	--	19.43	.42	1	Meets 3-of-3 criteria.
	1.2	--	17.27	.21	.34	Meets 2-of-3 criteria.
68.7	44	23.09	23.3	--	--	Bankfull discharge.
	10.4	--	21.3	.49	1	Meets 3-of-3 criteria.
	.9	--	18.1	.23	.22	Meets 2-of-3 criteria.
81.6	44	25.05	25.62	--	--	Bankfull discharge.
	11.5	--	23.59	.5	1	Meets 3-of-3 criteria.
	2	--	20.74	.25	.39	Meets 2-of-3 criteria.
	2	--	20.74	.25	.39	Meets wetted-perimeter criteria.

Fort Meadow Brook near Hudson

The study site on Fort Meadow Brook (fig. 8) is 1,350 ft upstream of the Shay Street culvert in Hudson, MA. Five cross sections were surveyed on July 29, 2002, along a 90-ft reach. The streambed is primarily cobble with some overlying gravel. The cross sections are roughly trapezoidal in shape. The stream banks along the channel have rich organic bank material with large pine trees along both sides. The left bank is primarily lawn under the pine trees with patches of shrub vegetation along the right bank. The stream has a moderate slope. The water surface drops about 0.6 ft along the study reach for all measured flows between 0.84 ft^3/s and 6.8 ft^3/s. A HEC-RAS model was calibrated to simulate a subcritial flow regime by using the standard upstream-step energy method as documented in Appendix 1. The model calibration accuracy was 0.01 ft over the entire modeled reach for all the measured discharges.

The R2Cross analysis to determine the required streamflow for habitat protection was based upon the HEC-RAS simulation results for the cross section at river station 133.7 (tables 3 and 4). The hydraulic characteristics that met the R2Cross 3-of-3 and 2-of-3 criteria requirements from the calibrated model are summarized in table 9. The cross section at river station 133.7 was identified as being the critical section in the riffle reach. The limiting R2Cross criterion for 3-of-3 criteria was the average velocity and the limiting criterion for 2-of-3 criteria was average depth.

Relations between wetted perimeter and discharge and between altitude of the water surface and wetted perimeter were determined for cross sections at river station 133.7 on the basis of the HEC-RAS simulations for a range of discharges up to bankfull flow. The discharge identified by the Wetted-Perimeter method as required for habitat protection during the summer period is presented in table 5. The hydraulic parameters associated with this discharge are summarized in table 9.

Figure 8. Fort Meadow Brook near Hudson, Massachusetts, upstream view.

Table 9. Hydraulic characteristics at critical cross sections meeting R2Cross and Wetted-Perimeter method criteria for habitat protection at Fort Meadow Brook near Hudson, Massachusetts.

[ft, foot; ft^3/s, cubic foot per second; ft/s, foot per second; --, not applicable]

River station	Discharge (ft^3/s)	Top width (ft)	Wetted perimeter (ft)	Average depth (ft)	Average velocity (ft/s)	Notes
133.7	10	19.17	19.57	--	--	Bankfull discharge.
	7.3	--	19.18	0.38	1	Meets 3-of-3 criteria.
	2.2	--	17.54	.20	.63	Meets 2-of-3 criteria.
	1.7	--	16.57	.17	.60	Meets wetted-perimeter criteria.

Elizabeth Brook near Stow

The riffle reach studied on Elizabeth Brook (fig. 9) is just downstream of a ford about 0.2 mi south of White Pond Road on an unnamed road in Stow. Six cross sections were surveyed on September 27, 2001, in this study reach; all were included in the water-surface-profile model. The cross sections were along a 70-ft length of riffle. The channel bends slightly to the right and is predominantly trapezoidal in shape. There are shrubs along both banks and larger deciduous trees further from the channel banks. The bed material is primarily gravel and cobbles. Bank material is a mixture of rich organic soil and cobbles. The reach has a moderate slope and the water surface dropped 0.7 ft to 1.1 ft along the study reach at the measured discharges, which ranged from 1.8 ft^3/s to 50.1 ft^3/s. The model was run as a subcritical flow regime by using the standard upstream-step energy method as documented in Appendix 1. The calibration accuracy was 0.02 ft over the entire modeled reach for all the measured discharges.

The R2Cross analysis was based upon the HEC-RAS simulation results for cross sections at river stations 202.05, 213.57, 229.45, and 241.46 (tables 3 and 4). The hydraulic characteristics that met the R2Cross 3-of-3 and 2-of-3 criteria requirements from the calibrated model are summarized in table 10. The cross section at river stations 202.05, 213.57, 229.45, and 241.46 were identified as being critical because they are upstream of the point where the riffle is influenced by backwater. The limiting R2Cross criteria for 3-of-3 criteria were the average depth at sections 202.05, 229.45, and 241.46 and average velocity at section 213.57. Average velocity was the limiting criterion for 2-of-3 criteria at sections 202.05, 229.45, and 241.46 and average depth was limiting at section 213.57.

The 3-of-3 R2Cross results (table 3) range from ranged from 9 to 12 ft^3/s for four cross sections modeled. This range in discharges is smaller than the 3-of-3 R2Cross results reported by Parker and Armstrong (2001) for the same cross sections (7.4 to 15.0 ft^3/s). The HEC-RAS model used for this report was calibrated from a larger number of measurements made over a greater range of discharges.

Relations between wetted perimeter and discharge and between altitude of the water surface and wetted perimeter were determined for cross sections at stations 202.05, 213.57, 229.45, and 241.46 on the basis of the HEC-RAS simulations for a range of discharges up to bankfull flow. The discharges identified by the Wetted-Perimeter method as required for habitat protection during the summer period are summarized in table 5. The hydraulic parameters associated with these discharges are summarized in table 10. The range of discharges in table 5 for Elizabeth Brook is about the same as reported in the preliminary estimates reported by Parker and Armstrong (2001).

Figure 9. Elizabeth Brook near Stow, Massachusetts, downstream view.

Table 10. Hydraulic characteristics at critical cross sections meeting R2Cross and Wetted-Perimeter method criteria for habitat protection at Elizabeth Brook near Stow, Massachusetts.

[ft, foot; ft^3/s, cubic foot per second; ft/s, foot per second; --, not applicable]

River station	Discharge (ft^3/s)	Top width (ft)	Wetted perimeter (ft)	Average depth (ft)	Average velocity (ft/s)	Notes
202.50	40.4	31.67	32.04	--	--	Bankfull discharge.
	10	--	22.24	0.32	1.4	Meets 3-of-3 criteria.
	5	--	20.79	.24	1	Meets 2-of-3 criteria.
	3.5	--	20.27	.20	.86	Meets wetted-perimeter criteria.
213.57	40.4	27.54	28.15	--	--	Bankfull discharge.
	9	--	1	.35	1	Meets 3-of-3 criteria.
	6	--	26.05	.28	.82	Meets 2-of-3 criteria.
	1.8	--	24.93	.17	.43	Meets wetted-perimeter criteria.
229.45	40.4	26.78	27.01	--	--	Bankfull discharge.
	10.5	--	23.17	.27	1.67	Meets 3-of-3 criteria.
	3.6	28.81	19.84	.18	1	Meets 2-of-3 criteria.
	5.5	--	22.13	.20	1.27	Meets wetted-perimeter criteria.
241.46	40.4	23.09	29.21	--	--	Bankfull discharge.
	12	--	26.13	.29	1.07	Meets 3-of-3 criteria.
	10.2	--	25.92	.28	1	Meets 2-of-3 criteria.
	3.0	--	24.51	.20	.611	Meets wetted-perimeter criteria.

Nashoba Brook at West Concord

The riffle section studied on Nashoba Brook (fig. 10) is about 110 ft downstream of the bridge under Commonwealth Avenue in West Concord. Four cross sections were surveyed on August 5, 2002, in this study reach, all of which were included in the water-surface-profile model. The cross sections were along a 130-ft length of riffle habitat and were predominantly trapezoidal in shape. The channel takes a shallow bend to the left along the study reach. There are scattered trees and shrubs along the left bank with a vertical stone-and-concrete wall along the right bank. The bed material is primarily cobbles, and the left bank material is composed of rich organic soil, silt, sand, and cobbles. The stream has a moderate slope. The water surface drops about 0.7 to 0.3 ft along the study reach for all measured flows ranging from 1.0 ft^3/s and 74.9 ft^3/s. A HEC-RAS model was calibrated to simulate a subcritial flow regime by using the standard upstream-step energy method as documented in Appendix 1. The calibration accuracy was 0.01 ft over the entire modeled reach for all the measured discharges.

The R2Cross analysis to determine the required streamflow for habitat protection was based upon the HEC-RAS model results for the cross sections at river stations 120.3, 142.5, and 164.5 (tables 3 and 4). The hydraulic characteristics that met the R2Cross 3-of-3 and 2-of-3 criteria requirements from the calibrated model are summarized in table 11. The cross sections at river stations 120.3, 142.5, and 164.5 were identified as being the critical sections in the riffle reach. The limiting R2Cross criteria for 3-of-3 criteria were the average depth at section 120.3 and average velocity at sections 142.5 and 164.5. Average velocity was the limiting criterion for 2-of-3 criteria at section 120.3 and average depth was limiting at sections 142.5 and 164.5.

Relations between wetted perimeter and discharge and between altitude of the water surface and wetted perimeter were determined for cross sections at stations 120.3, 142.5, and 164.5 on the basis of the HEC-RAS simulations for a range of discharges up to bankfull flow. The discharges identified by the Wetted-Perimeter method as required for habitat protection during the summer period are summarized in table 5. The hydraulic parameters associated with these discharges are summarized in table 11.

Resulting normalized discharges estimated by The R2Cross and Wetted-Perimeter methods as needed to protect habitat are significantly less than the results from the other study sites (tables 3, 4, and 6). The wall on the right bank, which is on the outside of the channel bend, restricted the natural movement of the channel in that direction. The results for this site were not included in any subsequent analyses.

Figure 10. Nashoba Brook at West Concord, Massachusetts, downstream view.

Table 11. Hydraulic characteristics at critical cross sections meeting R2Cross and Wetted-Perimeter method criteria for habitat protection at Nashoba Brook at West Concord, Massachusetts.

[ft, foot; ft^3/s, cubic foot per second; ft/s, foot per second; --, not applicable]

River station	Discharge (ft^3/s)	Top width (ft)	Wetted perimeter (ft)	Average depth (ft)	Average velocity (ft/s)	Notes
120.3	150	27.36	29.58	--	--	Bankfull discharge.
	7.1	--	22.32	0.27	1.19	Meets 3-of-3 criteria.
	5.2	--	22.23	.24	1	Meets 2-of-3 criteria.
	7.0	--	22.25	.25	1.26	Meets wetted-perimeter criteria.
142.5	150	26.53	28.59	--	--	Bankfull discharge.
	6.8	--	23.38	.29	1	Meets 3-of-3 criteria.
	5.5	--	23.29	.27	.89	Meets 2-of-3 criteria.
	5	--	23.25	.26	.85	Meets wetted-perimeter criteria.
164.5	150	25.73	28.02	--	--	Bankfull discharge.
	5.8	--	19.17	.30	1	Meets 3-of-3 criteria.
	4.2	--	18.72	.26	.88	Meets 2-of-3 criteria.
	4	--	18.64	.25	.86	Meets wetted-perimeter criteria.

Charles River near Hopkinton

The riffle section studied on the Charles River in Hopkinton (fig. 11) is about 300 ft downstream of the Echo Lake Dam, which regulates the flow through the study section, and 3,450 ft upstream of State Route 85 culvert in Milford. Seven cross sections were surveyed on August 2, 2001, all of which were included in the water-surface-profile model. The cross sections were along a 90-ft length of pool and riffle habitats and were predominantly trapezoidal in shape. The channel takes a shallow meander starting with a bend to the right along the study reach. There are scattered trees and shrubs along both banks, the bed material is primarily cobbles, and the bank material is composed of organic soil, silt, sand, and cobbles. The stream has a moderately steep slope. The channel in this river section was frequently dry during the period of this study. The water surface drops about 1.6 ft to 1.1 ft along the study reach for all measured flows ranging from 0.03 ft^3/s and 8.4 ft^3/s. A HEC-RAS model was calibrated to simulate a subcritial flow regime by using the standard upstream-step energy method as documented in Appendix 1. The calibration accuracy was 0.01 ft over the entire modeled reach for all the measured discharges.

The R2Cross analysis to determine the required streamflow for habitat protection was based upon the HEC-RAS model results for the cross section at river stations 101.39, 157.84, and 166.01 (tables 3 and 4). The hydraulic characteristics from the calibrated model used to meet the R2Cross 3-of-3 and 2-of-3 criteria requirements are summarized in table 12. The cross sections at river stations 101.39, 157.84, and 166.01 were identified as being critical. The limiting R2Cross criterion for 3-of-3 criteria was the average velocity and wetted perimeter was the limiting criterion for 2-of-3 criteria.

Relations between wetted perimeter and discharge and between altitude of the water surface and wetted perimeter were determined for cross sections at stations 101.39 and 166.01 on the basis of the HEC-RAS simulations for a range of discharges up to bankfull flow. The discharges identified by the Wetted-Perimeter method as required for habitat protection during the summer period are summarized in table 5. The hydraulic parameters associated with these discharges are summarized in table 12.

Figure 11. Charles River near Hopkinton, Massachusetts, upstream view.

Table 12. Hydraulic characteristics at critical cross sections meeting R2Cross and Wetted-Perimeter method criteria for habitat protection at Charles River near Hopkinton, Massachusetts.

[ft, foot; ft^3/s, cubic foot per second; ft/s, foot per second; --, not applicable]

River station	Discharge (ft^3/s)	Top width (ft)	Wetted perimeter (ft)	Average depth (ft)	Average velocity (ft/s)	Notes
101.39	8.4	11.69	12.04	--	--	Bankful discharge.
	2.2	--	7.16	0.33	1	Meets 3-of-3 criteria.
	.21	--	6.02	.22	.17	Meets 2-of-3 criteria.
	.2	--	5.98	.22	.16	Meets wetted-perimeter criteria.
157.84	8.4	10.79	11.49	--	--	Bankful discharge.
	2.0	--	6.04	.35	1	Meets 3-of-3 criteria.
	.38	--	5.74	.34	.21	Meets 2-of-3 criteria.
166.01	8.4	14.74	15.04	--	--	Bankful discharge.
	2.7	--	10.96	.28	1	Meets 3-of-3 criteria.
	.22	--	7.52	.26	.12	Meets 2-of-3 criteria.
	.45	--	10.18	.23	.21	Meets wetted-perimeter criteria.

Mine Brook near Franklin

The riffle section on Mine Brook (fig. 12) is about 680 ft upstream of a culvert under Route 140 in the town of Franklin. Seven cross sections were surveyed on August 8, 2001, along an 87-ft length of riffle habitat and all were included in the water-surface-profile model. The predominantly trapezoidal cross sections are in a straight reach of riffle channel. The reach flows through a forest of large deciduous trees and a few scattered shrubs line both banks. The bed material is primarily cobbles and the bank material is a mixture of organic soil and cobbles. The water surface dropped 0.7 to 1.10 ft along the study reach at measured discharges ranging from 2.03 ft^3/s to 70 ft^3/s. A HEC-RAS model was calibrated to simulate a subcritial flow regime by using the standard upstream-step energy method as documented in Appendix 1. The calibration accuracy was 0.01 ft over the entire reach for measured discharges.

The R2Cross analysis was applied on the basis of the HEC-RAS model results for the cross sections at river stations 112.91, 123.60, 143.62, 164.85, 173.65, and 187.25 (tables 3 and 4). The hydraulic characteristics from the calibrated model used to meet the R2Cross 3-of-3 and 2-of-3 criteria requirements are summarized in table 13. The cross sections at all six river stations were identified as being critical. The limiting R2Cross criterion for 3-of-3 criteria was average velocity. Average depth was the limiting 2-of-3 criterion at stations 112.91, 123.60, 143.62, 173.65, and 187.25 and wetted perimeter was limiting at station 164.85.

The 3-of-3 R2Cross results (table 3) ranged from 2.5 to 9 ft^3/s for the six cross sections modeled. This range of discharges is smaller than the 3-of-3 results reported by Parker and Armstrong (2001) for four cross-sections (2.4 to 8.75 ft^3/s). The HEC-RAS model used for this report was calibrated from a larger number of measurements made over a greater range of discharges than the model used by Parker and Armstrong (2001).

Relations between wetted perimeter and discharge and between altitude of the water surface and wetted perimeter were determined for cross sections at stations 112.91, 123.60, 143.62, 164.85, 173.65, and 187.25 on the basis of the HEC-RAS simulations for a range of discharges up to bankfull flow. The discharges identified by the Wetted-Perimeter method as required for habitat protection during the summer period as are summarized in table 5. The hydraulic parameters associated with these discharges are summarized in table 13. The discharges in table 5 for Mine Brook range from 2.1 to 6.5 ft^3/s for six cross sections modeled. These discharges are greater than the discharges reported in the preliminary estimates reported by Parker and Armstrong (2001) for four cross sections (1.0 to 5.2 ft^3/s). The four cross-sections analyzed in the Parker and Armstrong (2001) report are included in the six cross sections analyzed in this report. The current results are more than 0.1 $ft^3/s/mi^2$ higher than the results in the preliminary report.

Figure 12. Mine Brook near Franklin, Massachusetts, downstream view.

Table 13. Hydraulic characteristics at critical cross sections meeting R2Cross and Wetted-Perimeter method criteria for habitat protection at Mine Brook near Franklin, Massachusetts.

[ft, foot; ft^3/s, cubic foot per second; ft/s, foot per second; --, not applicable]

River station	Discharge (ft^3/s)	Top width (ft)	Wetted perimeter (ft)	Average depth (ft)	Average velocity (ft/s)	Notes
112.91	48	24.91	25.34	--	--	Bankful discharge.
	9	--	21.95	0.41	1	Meets 3-of-3 criteria.
	2.3	--	18.00	.25	.52	Meets 2-of-3 criteria.
	5.8	--	20.99	.33	.84	Meets wetted-perimeter criteria.
123.60	48	18.90	19.95	--	--	Bankful discharge.
	7	--	16.54	.43	1	Meets 3-of-3 criteria.
	.8	--	10.46	.20	.39	Meets 2-of-3 criteria.
	5.2	--	15.52	.37	.92	Meets wetted-perimeter criteria.
143.62	48	17.49	18.26	--	--	Bankful discharge.
	6.2	--	15.11	.41	1	Meets 3-of-3 criteria.
	1.1	--	12.23	.20	.45	Meets 2-of-3 criteria.
	6.2	--	15.08	.41	1	Meets wetted-perimeter criteria.
164.85	48	14.94	16.42	--	--	Bankful discharge.
	4.2	--	12.98	.33	1	Meets 3-of-3 criteria.
	1.1	--	8.21	.27	.51	Meets 2-of-3 criteria.
	6.5	--	14.46	.40	1.17	Meets wetted-perimeter criteria.
173.65	48	16.38	17.96	--	--	Bankful discharge.
	2.5	--	11.64	.22	1	Meets 3-of-3 criteria.
	1.9	--	10.25	.20	.93	Meets 2-of-3 criteria.
	5.6	--	11.97	.22	1.32	Meets wetted-perimeter criteria.
187.25	48	20.79	21.66	--	--	Bankful discharge.
	8.2	--	19.40	.44	1	Meets 3-of-3 criteria.
	3.8	--	18.88	.21	.67	Meets 2-of-3 criteria.
	2.2	--	18.78	.28	.43	Meets wetted-perimeter criteria.

Charles River at Medway

Two riffle sections were studied along a 1,500 ft reach upstream of the streamflow-gaging station at Charles River at Medway (01103200). The first riffle is at the upstream end of the reach and the downstream riffle is about 600 ft upstream of the Walker Street Bridge (fig. 13). The survey of 11 cross-sections in this study reach was completed between July and September, 2001. Nine cross-sections were included in a single water-surface-profile model spanning the river length from Walker Street Bridge to the upstream riffle; the cross sections at river stations 641.1 and 691.6 were at the downstream riffle and those at river stations 1466.3, 1481.8, and 1498.9 were at the upstream riffle. The riffle cross sections are predominantly trapezoidal in shape. The channel takes several shallow bends along the course of the study reach. The vegetation along the southern banks of the reach includes large hemlocks, with deciduous trees, small shrubs, and lawn along the northern side. The bed material is primarily gravel; the bank material is a mixture of organic soil, silt, sand, and cobbles. The surveyed water surface dropped 2.49 ft along the study reach at 8.2 ft^3/s and 2.14 ft at 76.2 ft^3/s. A HEC-RAS model was calibrated to simulate a subcritial flow regime by using the standard upstream-step energy method as documented in Appendix 1 at the end of this report. The calibration accuracy was 0.10 ft over the entire reach for measured discharges.

The R2Cross analysis to determine streamflow requirements for habitat protection was based upon the HEC-RAS simulation results for the cross sections at river station 691.6 in the downstream study riffle and at river stations 1481.8 and 1498.9 in the upstream riffle (tables 3 and 4). The hydraulic characteristics from the calibrated model that met the R2Cross 3-of-3 and 2-of-3 criteria requirements for both the upstream and downstream riffle reaches are summarized in table 14. For the downstream riffle, the cross section at river station 691.6 was identified as being the critical because it is upstream of the point where the riffle is influenced by backwater. The upstream cross sections at river stations 1481.8 and 1498.9 are upstream of the influence of backwater. The limiting R2Cross criterion for 3-of-3 criteria was the average depth at the study sections for both riffle reaches. Average velocity was limiting for 2-of-3 criteria at the study sections for both riffle reaches. The results have not changed from the results presented in the preliminary report (Parker and Armstrong, 2001).

Relations between wetted perimeter and discharge and between altitude of the water surface and wetted perimeter were determined for the cross section at river station 691.6 in the downstream study riffle and at river stations 1481.8 and 1498.9 in the upstream riffle. The relations were developed on the basis of the HEC-RAS simulations for a range of discharges up to bankfull flow. The HEC-RAS model used in the Wetted-Perimeter method analysis was not changed from the model presented by Parker and Armstrong (2001). However, the output for the model was analyzed by using the Wetted-Perimeter methods presented in this report. The discharges identified by the Wetted-Perimeter method as required for habitat protection during the summer period for both riffle reaches are summarized in table 5. These discharges are different from those presented by Parker and Armstrong (2001). The hydraulic parameters associated with these discharges are summarized in table 14.

Table 14. Hydraulic characteristics at critical cross sections meeting R2Cross and Wetted-Perimeter method criteria for habitat protection at Charles River at Medway, Massachusetts.

[ft, foot; ft^3/s, cubic foot per second; ft/s, foot per second; --, not applicable]

River station	Discharge (ft^3/s)	Top width (ft)	Wetted perimeter (ft)	Average depth (ft)	Average velocity (ft/s)	Notes
691.6	172	61.39	62.51	--	--	Bankful discharge.
	57	--	58.7	0.61	1.59	Meets 3-of-3 criteria.
	21.6	--	56.52	.39	1	Meets 2-of-3 criteria.
	8.7	--	54.98	.24	.67	Meets wetted-perimeter criteria.
1,481.8	172	53.41	53.73	--	--	Bankful discharge.
	45.4	--	41.00	.53	2.08	Meets 3-of-3 criteria.
	8	--	30.40	.26	1	Meets 2-of-3 criteria.
	16.5	--	34.27	.33	1.45	Meets wetted-perimeter criteria.
1,498.9	172	58.02	59.40	--	--	Bankful discharge.
	52.8	--	45.91	.58	2.03	Meets 3-of-3 criteria.
	11.6	--	35.50	.33	1	Meets 2-of-3 criteria.
	7.7	--	34.66	.31	.73	Meets wetted-perimeter criteria.

A.

B.

Figure 13. Charles River at Medway, Massachusetts, downstream views of the study reaches: *A*, the upstream riffle; and *B*, the downstream riffle.

Fish-Community Sampling and Assessment

Fish-community assessments involve the sampling and description of fish species to indicate the ecological condition of a river. Fish-community data used in this report were collected in the Assabet and Charles River Basins between August 1999 and September 2002 by the Massachusetts Division of Fisheries and Wildlife (MDFW) as part of the MDFW Statewide Fisheries Assessment Program. Fish-community data were also collected in the Charles River Basin during August of 2002 by the Massachusetts Department of Environmental Protection (MADEP), Division of Watershed Management, as part of the MADEP Charles River Watershed Monitoring Program. Fish were sampled during summer periods of low to moderate streamflow because fish assemblages during summer are relatively stable and contain the full range of resident species (Gibson and others, 1996). Biological monitoring in this study targeted fish because they are long-lived and are sensitive to a wide range of stresses. In comparison to macroinvertebrates, fish are easy to identify, and the relations between fish and stream health are better understood and valued by the public. In addition, streamflows adequate to maintain fisheries are usually sufficient to maintain macroinvertebrates and other aquatic life. A disadvantage of using fish to indicate flow degradation is that fish integrate the effects of many stresses; thus, it is difficult to determine the effect of each stress.

The fish-community assessment was designed to characterize the diversity and relative abundance of fish species, and the length-frequency distribution of fish in the Charles and Assabet Basins. Sampling reaches were distributed over the length of the main stem and tributaries of the Charles and Assabet Basins. Sampling reaches included at least 300 ft of stream length, where possible. Fish were sampled by electrofishing with pulsed direct current (DC) backpack units and barges (Massachusetts Division of Fisheries and Wildlife, written commun., 2003) (fig. 14). Backpack electrofishing units are best used in small or shallow streams and were appropriate for sampling most tributary and headwater reaches of the Assabet and Charles Rivers. Barge electrofishing units are best used in wadeable reaches where a stronger power supply and more labor for electrofishing are required. Barge units were appropriate for sampling many of the free-flowing reaches of the main stems of the Assabet and Charles Rivers.

Fish sampled in this study were classified on the basis of their habitat use. Fish communities were compared to a target fish community developed for the Quinebaug River (Bain and Meixler, 2000). The Quinebaug target fish community (fig. 15) can be used to represent a healthy fish community for larger streams and smaller rivers in the region. Habitat-use categories developed for the Quinebaug River have been used to assess fish communities in other river basins in Massachusetts and Rhode Island (table 15) (Armstrong and others, 2001; Armstrong and Parker, 2003).

Fish were classified into three macrohabitat classes on the basis of their habitat use: macrohabitat generalists, fluvial dependents, and fluvial specialists (Bain and Knight, 1996, Bain and Meixler, 2000). Macrohabitat generalists, such as pumpkinseed and redfin pickerel, are fish species that use a broad range of habitat. They include species commonly found in lakes, reservoirs, and streams, and can complete their life cycle in any one of these systems. Fluvial dependents, such as white sucker, require access to streams or flowing-water habitats for a specific life stage, but otherwise are commonly found in lakes, reservoirs, and streams. Fluvial specialists, such as blacknose dace and creek chubsucker, are almost always reported in streams or rivers and require flowing-water habitats throughout their life cycle (Bain and Travnichek, 1996).

Fish can live in different habitat conditions in different geographic areas. For example, in Massachusetts, fish that require cold or well-oxygenated water are found primarily in flowing streams. Therefore, for the purposes of this study, the Quinebaug target fish community was modified from Bain and Melch (2000) to accommodate for regional differences in habitat requirements. The Creek chub were reclassified from a macrohabitat generalists to a fluvial specialist based on their habitat used in Massachusetts streams. The American eel, a catadromous fish that requires access to stream habitats for a portion of its life cycle, was reclassified from a fluvial dependent to a macrohabitat generalist because it occupies a wide range of habitats during the portion of its life cycle in freshwater streams. Stocked rainbow trout, brown trout, and brook trout (as opposed to the wild trout found in the samples), were not included in the fish-community analysis. Trout captured in waters not stocked with trout were considered wild. Trout captured in cold water streams were categorized as wild or stocked based on fish size (trout less than 0.5 ft are not stocked) and species.

Figure 14. Massachusetts Division of Fisheries and Wildlife personnel barge electrofishing for the fish-community assessment.

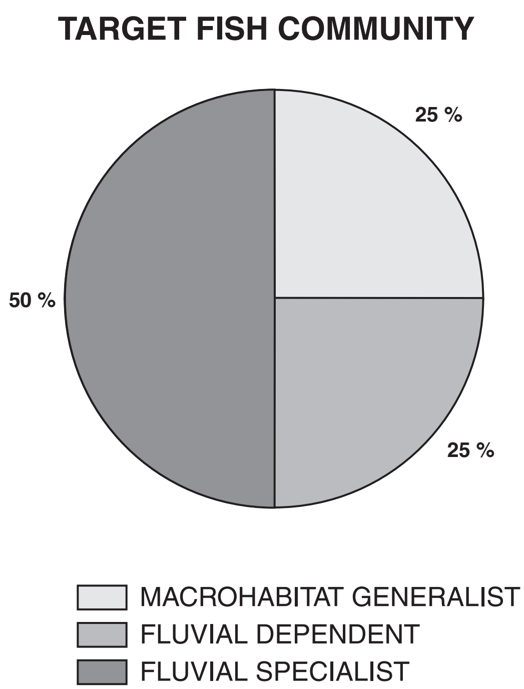

Figure 15. Target fish community for the Quinebaug River, Massachusetts (modified from Bain and Meixler, 2000).

Table 15. Percentages of fish in each habitat-use classification sampled in flowing reaches of several river basins in Massachusetts.

[--, target percentage has not been developed]

Habitat-use classification	Watershed								
	Quinebaug	Westfield	Shawsheen	Blackstone	Nashua	Assabet	Charles	Housatonic	Ipswich
Main-Stem Site[1]									
Macrohabitat generalist species	36.4	22.1	92.1	36.1	30.2	50.4	98.1	70.1	97.0
Fluvial-dependent species	36.2	28	1.2	58.8	32	23.7	1.7	12.9	1.5
Fluvial-specialist species	27.4	49.9	6.7	5.1	37.8	25.9	.2	17	1.5
Taget for Main-Stem Reaches[2]									
Macrohabitat generalist species	25	--	--	--	--	--	--	--	--
Fluvial-dependent species	25	--	--	--	--	--	--	--	--
Fluvial-specialist species	50	--	--	--	--	--	--	--	--
Tributary Site[3]									
Macrohabitat generalist species	8.4	4.6	70.4	24.4	8.1	49.4	87.6	13.6	75.9
Fluvial-dependent species	21.3	5.4	7.7	35.0	21.2	17.3	8.5	12.3	2.6
Fluvial-specialist species	70.3	90	21.9	40.6	70.7	33.3	3.9	74.1	21.5

[1]A location along the named watershed with a drainage area greater than 30 square miles.

[2]Modified from Bain and Meixler (2000).

[3]Tributary site, a location in the watershed with a drainage area less than 30 square miles.

Fish-sampling information and community assessments were categorized by basin size and free-flowing status. Reaches with drainage areas of greater than 30 mi^2 were classified as main-stem reaches (M. Anderson and A. Olivero, The Nature Conservancy, written commun., 2003). Reaches with drainage areas less than 30 mi^2 were classified as tributary or headwater reaches. Only the fish-community data from the main-stem reaches were directly compared to the Quinebaug River target fish communities. The Quinebaug River target fish-community was developed for the main stem between the outlet of the East Brimfield Reservoir and the Massachusetts–Connecticut State boundary. Data gathered from tributaries were also used to illustrate their degree of degradation in comparison to target fish communities. Although fish information gathered on tributaries has not often been published in terms of target fish communities, several characteristics of tributary fish communities makes the comparison valid, with certain limitations. For example, tributary sites are expected to have a higher proportion of fluvial-fish species than main-stem reaches (M.B. Bain, Cornell University, oral commun., 2003); in particular, the riffle reaches included in this study should be composed nearly exclusively of fluvial fish under restored conditions. Most of the habitat in these riffle reaches is unsuitable for macrohabitat generalists.

Analysis conducted by using recent fish collections in the Quinebaug, Blackstone, Westfield, Nashua, Housatonic, and Shawsheen Rivers (table 15) strongly indicates that tributaries should have a higher percent of fluvial fish than their corresponding main-stem reaches. In all cases, main-stem samples consisted of considerably higher percentages of macrohabitat generalists than their tributaries. Even the most impaired rivers, such as the Ipswich, exhibited this trend. Under restored conditions (as represented by the target fish community proportions developed for the Quinebaug River Basin), the tributaries should exhibit a higher proportion of fluvial fish than the main stem. Conservatively, for the purpose of this report, tributary fish communities will be considered degraded if the proportion of macrohabitat generalists is greater than 25 percent.

Sampling Results

Fish communities from a range of habitat types were assessed to characterize fish-species diversity, relative abundance, and length-frequency distribution in the Assabet and Charles River Basins. To assess anthropogenic effects on the fish community, the composition of the fish communities in the Assabet and Charles River systems was compared to a target fish community developed for the Quinebaug River (Bain and Meixler, 2000) as well as to the fish communities in other river basins in Massachusetts.

Assabet River Basin Sampling

From 1999 to 2001, 1,980 fish of 22 different species were collected at 33 free-flowing sites in the Assabet River Basin (fig. 16). In the main stem of the Assabet River, from June 2000 to August 2001, 781 fish of 22 different species (table 16) were collected from 6 sites. The electrofishing effort included a total length of more than 2,470 ft of stream, with site lengths ranging from 325 to 570 ft.

In the tributaries and headwaters, 1,199 fish of 17 different species were collected from 27 sites between August 1999 and August 2000. The electrofishing effort included a length of more than 8,800 ft of stream, with site lengths ranging from 170 to 650 ft. The 27 sites included 3 from the Assabet River headwaters (these sites have contributing areas of 30 mi^2 or less), and 14 from tributaries, including Assabet Brook, Cold Harbor Brook, Elizabeth Brook, Fort Meadow Brook, Great Brook, Guggins Brook, Hog Brook, Hop Brook, Mill Brook, Nashoba Brook, North Brook, Spencer Brook, and 2 unnamed tributaries.

Charles River Basin Sampling

Between 2000 and 2002, 1,025 fish of 19 different species were collected at 11 free-flowing sites in the Charles River Basin (fig. 16). In the main stem of the Charles River, 639 fish of 16 different species were collected from 4 sites (table 16). From September 2001 to August 2002, four fish collections were made. The electrofishing effort included a total length of more than 2,350 ft of stream, with site lengths ranging from 260 to 1,190 ft.

In 9 tributaries and in the headwaters, 386 fish of 16 different species were collected from 16 sites. From August 2000 to September 2002, 16 fish collections were made. The electrofishing effort included a total length of more than 2,620 ft of stream, with site lengths ranging from 325 to 552 ft. In addition to the Charles River headwaters, tributaries sampled include Beaver Brook, Cherry Brook, Chicken Brook, Fuller Brook, Hopping Brook, Mine Brook, Stony Brook, Stop River, and Trout Brook.

Fish-Community Assessment

In accordance with habitat-use classifications used in this report, fish species sampled in the Assabet and Charles River main stems were divided into one of three macrohabitat classes: macrohabitat generalists, fluvial dependents, and fluvial specialists. Stocked fish previously described were removed from the count at this stage of the analysis. Fish in the free-flowing reaches of the Assabet River main stem consisted of 52.9 percent macrohabitat generalists, 22.3 percent fluvial dependents, and 24.8 percent fluvial specialists (fig. 17). White sucker and American eel dominated the fish communities in the main stem, composing by number 24 and 10 percent of the main-stem samples, respectively. The remaining 20 species each made up less than 10 percent of the total number of fish collected. Fish in the free-flowing reaches of the Charles River main stem consisted of 98.3 percent macrohabitat generalists and 1.7 percent fluvial dependents. No fluvial specialists were sampled in this reach. American eel (40 percent), redbreast sunfish (29 percent), and bluegill (19 percent) dominated the fish communities in the main stem. The remaining 10 species each made up less than 10 percent of the total number of fish collected. In general, the Charles River is dominated by macrohabitat generalist species; fluvial species are rare or absent.

Habitat-use classifications for the main-stem Charles and Assabet River fish communities were compared to habitat-use classifications for target fish communities developed for the Quinebaug River, Massachusetts. Fish in the Quinebaug River target fish community with the classifications used in this report had a population consisting of 25 percent macrohabitat generalists, 25 percent fluvial dependents, and 50 percent fluvial specialists (fig. 15). The percentages of fluvial fish species in the Charles River were considerably less than those in the Quinebaug target fish community (fig. 15 and fig. 17). The fish community of the Assabet River main stem is less dominated by macrohabitat generalists and is less degraded than the fish community found in the Charles River (fig. 17).

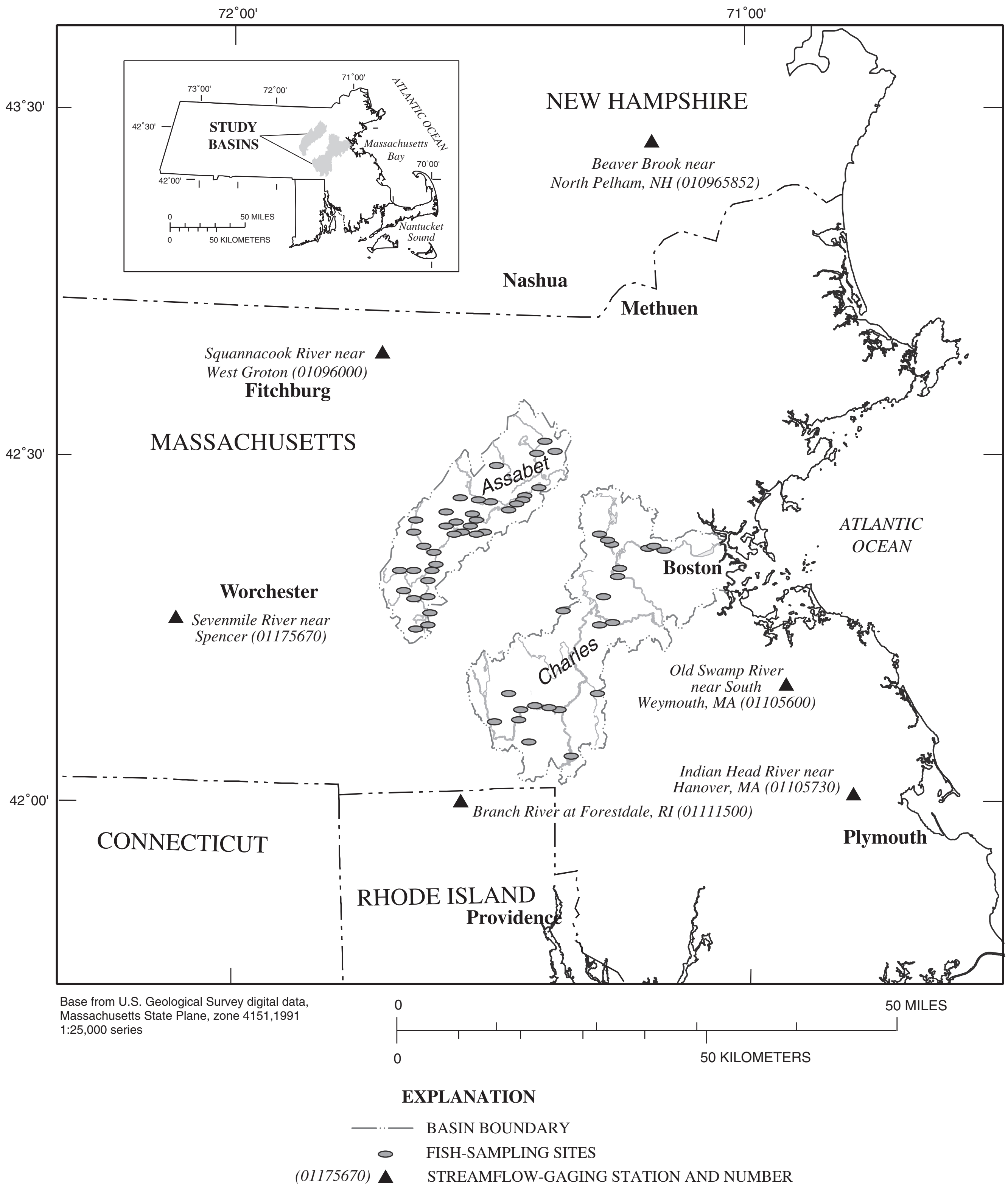

Figure 16. Location of fish-sampling sites and habitat study sites in the Charles and Assabet River Basins, Massachusetts.

Table 16. Number of each species and percent of total number of fish collected in the main stem, tributaries, and headwaters of the Assabet and Charles River Basins, Massachusetts, by the Massachusetts Division of Fisheries and Wildlife from 1999 through 2001.

[Species: FD, Fluvial dependent species; FS, Fluvial specialist species; MG, Macrohabitat generalist species. <, actual value is less than value shown]

Habitat-use classification	Number collected	Percent
Assabet River Basin		
Mainstem		
White sucker (FD)	185	24
American eel (MG)	75	10
Blacknose dace (FS)	74	9
Fallfish (FS)	74	9
Bluegill (MG)	72	9
Largemouth bass (MG)	58	7
Redbreast sunfish (MG)	56	7
Yellow bullhead (MG)	39	5
Redfin pickerel (MG)	25	3
Brown trout (FS)	20	3
Pumpkinseed (MG)	19	2
Golden shiner (MG)	17	2
Rainbow trout (FS)	16	2
Creek chubsucker (FS)	15	2
Spottail shiner (MG)	11	1
Yellow perch (MG)	8	1
Black crappie (MG)	6	< 1
Chain pickerel (MG)	4	< 1
Brown bullhead (MG)	2	< 1
Banded sunfish (MG)	2	< 1
Tiger trout (FS)	1	< 1
All species	780	100
Assabet River Basin—Continued		
Tributaries and headwaters		
White sucker (FD)	208	17
Blacknose dace (FS)	188	16
Brook trout (FS)	175	15
Pumpkinseed (MG)	133	11
Redfin pickerel (MG)	118	10
Golden shiner (MG)	75	6
Yellow bullhead (MG)	72	6
Chain pickerel (MG)	47	4
American eel (MG)	40	3
Largemouth bass (MG)	37	3
Bluegill (MG)	34	3
Brown bullhead (MG)	27	2
Fallfish (FS)	19	2
Brown trout (FS)	10	< 1
Creek cubsucker (FS)	7	< 1
Yellow perch (MG)	6	< 1
Banded sunfish (MG)	3	< 1
All species	1,199	100

Table 16. Number of each species and percent of total number of fish collected in the main stem, tributaries, and headwaters of the Assabet and Charles River Basins, Massachusetts, by the Massachusetts Division of Fisheries and Wildlife from 1999 through 2001.—Continued

[Species: FD, Fluvial dependent species; FS, Fluvial specialist species; MG, Macrohabitat generalist species. <, actual value is less than value shown]

Species	Number collected	Percent
Charles River Basin		
Mainstem		
American eel (MG)	254	40
Redbreast sunfish (MG)	184	29
Bluegill (MG)	124	19
Pumpkinseed (MG)	27	4
Largemouth bass (MG)	14	2
White sucker (FD)	11	2
Smallmouth bass (MG)	4	< 1
White catfish (MG)	4	< 1
Yellow perch (MG)	4	< 1
Black crappie (MG)	3	< 1
Yellow bullhead (MG)	3	< 1
Chain pickerel (MG)	2	< 1
White perch (MG)	2	< 1
Brown bullhead (MG)	1	< 1
Brown trout (FS)	1	< 1
Golden shiner (MG)	1	< 1
All species	639	100
Charles River Basin—Continued		
Tributaries and headwaters		
Redfin pickerel (MG)	96	25
Yellow bullhead (MG)	91	24
Bluegill (MG)	65	17
White sucker (FD)	33	9
Largemouth bass (MG)	25	6
Redbreast sunfish (MG)	14	4
Brown bullhead (MG)	13	3
Pumpkinseed (MG)	12	3
Brook trout (FS)	10	3
Chain pickerel (MG)	8	2
Brown trout (FS)	5	1
Yellow perch (MG)	5	1
American eel (MG)	4	1
Golden shiner (MG)	2	< 1
Black crappie (MG)	1	< 1
Redfin/Chain pickerel hybrid (MG)	1	< 1
Swamp darter (MG)	1	< 1
All species	386	100

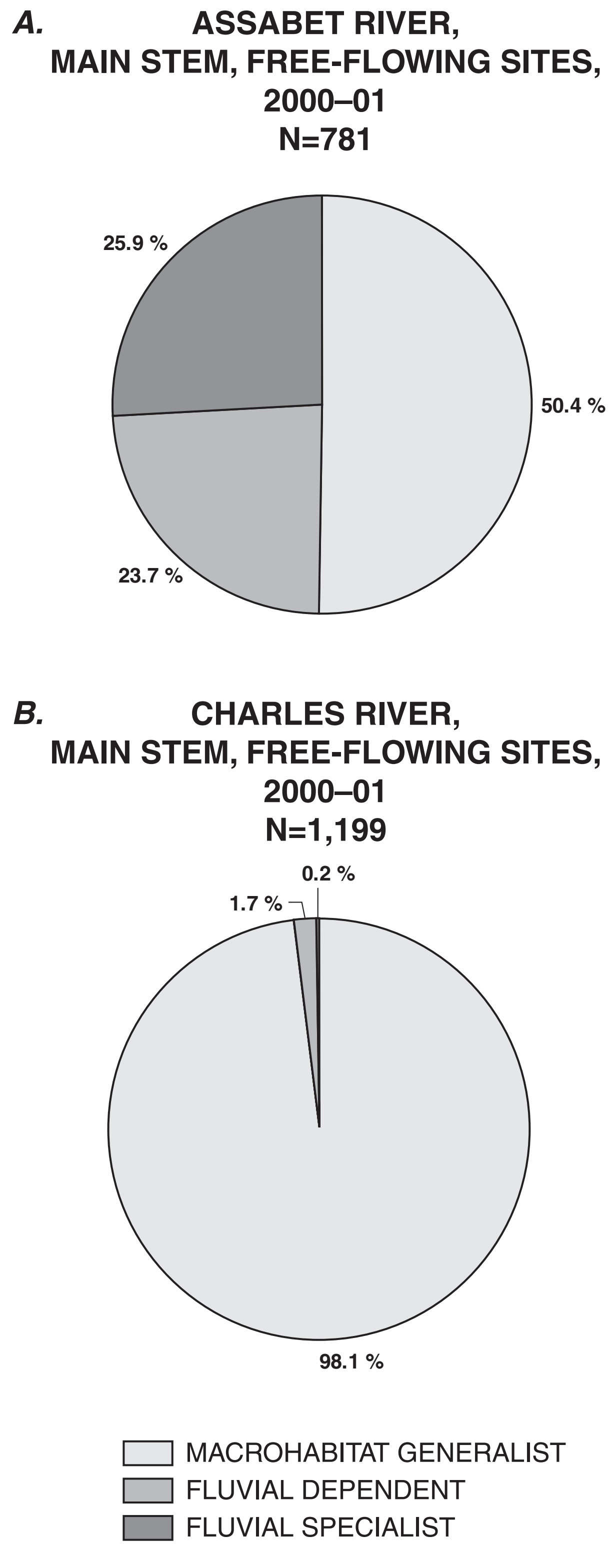

Figure 17. Fish species habitat-use classifications: *A*, main-stem free-flowing sites on the Assabet River, 2000–01; and *B*, main-stem free-flowing sites on the Charles River, 2000–01.

Fish communities were sampled in two adjacent reaches on the Charles River main stem in Medway. High-gradient riffles and runs, good canopy cover and stable substrates dominated the upstream reach. Lower gradient, runs and pools, open canopy and sandy substrate dominated the downstream reach. The fish community in the upstream reach would be expected to be dominated by fluvial species that prefer high water velocities. The downstream reach had habitat suitable for generalist species, but would be expected to have the same fluvial species as in the upstream reach but in fewer numbers. The fish community in the downstream reach should more closely resemble the Quinebaug River target fish community. Both the upstream and downstream reaches, however, yielded fish populations heavily dominated by generalists (both greater than 95 percent macrohabitat generalists). The higher proportion of generalists indicates that the fish community is degraded. The specific nature of this degradation could be caused by changes in physical habitat, impoundments, or a degradation of water quantity or quality.

Target fish communities have not been designed for tributaries and headwater reaches. The percentage of fluvial species in tributaries and headwaters is expected to be much higher than in the main-stem reaches of the corresponding river systems. The fish species compositions of the Assabet and Charles River tributaries and headwaters are considerably different. Fish in the free-flowing reaches of the Assabet River tributaries and headwaters consisted of 50.8-percent macrohabitat generalists, 17.9-percent fluvial dependents, and 31.3-percent fluvial specialists. White sucker (17 percent), blacknose dace (16 percent), brook trout (15 percent), pumpkinseed (11 percent), and redfin pickerel (10 percent) dominated the fish communities in the Assabet River tributaries and headwaters. The remaining 12 species each composed less than 10 percent of the total number of fish collected. Fish in the free-flowing reaches of the Charles River tributaries and headwaters consisted of 88.9-percent macrohabitat generalists, 8.7-percent fluvial dependents, and 2.4-percent fluvial specialists. Redfin pickerel (25 percent), yellow bullhead (24 percent), and bluegill (17 percent) dominated the fish communities in the Charles River tributaries and headwaters. The remaining 13 species each composed less than 10 percent of the total number of fish collected. These results indicate that the macrohabitat generalists compose a larger proportion of the fish community in the tributaries and main stem of the Charles River than would be expected in either basin.

Despite the apparent degraded state of the fish communities in the tributaries and headwaters of both river systems, the results do support the theory that tributary fish communities consist of a greater percentage of fluvial fish than the main-stem fish communities. In both basins, the tributaries have a higher percentage of fluvial species than the corresponding main-stem reaches.

Fish communities were also sampled in two headwater and tributary riffle sites in the Assabet River Basin. The two sites are the Assabet River near Westborough and Danforth Brook at Hudson, MA. The composite fish-community data for those two sites had almost the same percentage of generalist fish species than the percentage found in the composite of data for all the Assabet River tributary (54 percent versus 50.8 percent) sampling sites. These two sites are dominated by riffles and would have been expected to be composed of nearly all fluvial species if the river was ecologically unaltered.

The fish communities in the main stem and tributaries in both the Assabet and Charles River Basins for all habitat types indicate degraded aquatic ecosystems. However, the degree of degradation differs between the two basins. In the Assabet River Basin tributaries, only 30 percent (8 of 27) of the samples were devoid of fluvial fish species. Also, 38 percent (10 of 27) of the fish-community samples were composed of 75 percent or more fluvial fish species. In the Charles River tributaries, 56 percent (9 of 16) of the samples were devoid of fluvial fish. Only 13 percent (2 of 16) of the tributary fish community samples were composed of 75 percent more fluvial fish species. Many of the generalist species are tolerant to degraded water quality. The extreme predominance of tolerant generalist species in the 16 samples from the Charles River demonstrates the cumulative effects of degraded flow, habitat, and water quality on the fish communities, combined with the effects of nearby impoundments and changing land use.

Comparison of Streamflow Requirement Methods

A review of the streamflow requirements (tables 3, 4, and 5) determined at selected cross sections, excluding the Nashoba Brook riffle site, by using the R2Cross and Wetted-Perimeter methods (fig. 18) illustrates the variability that can be found within and between these two standard-setting methods of analysis. For the nine riffle sites, the 25th and 75th percentiles interquartile range of the streamflow requirements, normalized for drainage area, for the R2Cross 3-of-3 criteria method are 0.65 $ft^3/s/mi^2$ and 1.48 $ft^3/s/mi^2$. The streamflow requirements derived from the R2Cross 2-of-3 criteria and Wetted-Perimeter methods have a narrower interquartile range of 0.09 $ft^3/s/mi^2$ to 0.26 $ft^3/s/mi^2$ and 0.12 $ft^3/s/mi^2$ to 0.38 $ft^3/s/mi^2$, respectively, than the interquartile range for the R2Cross 3-of-3 criteria requirements. The interquartile ranges from the R2Cross 2-of-3 criteria and Wetted-Perimeter methods (fig. 17) agree closely with each other but do not overlap with the R2Cross 3-of-3 criteria results. The lack of overlap indicates that the methods identify different streamflow requirements.

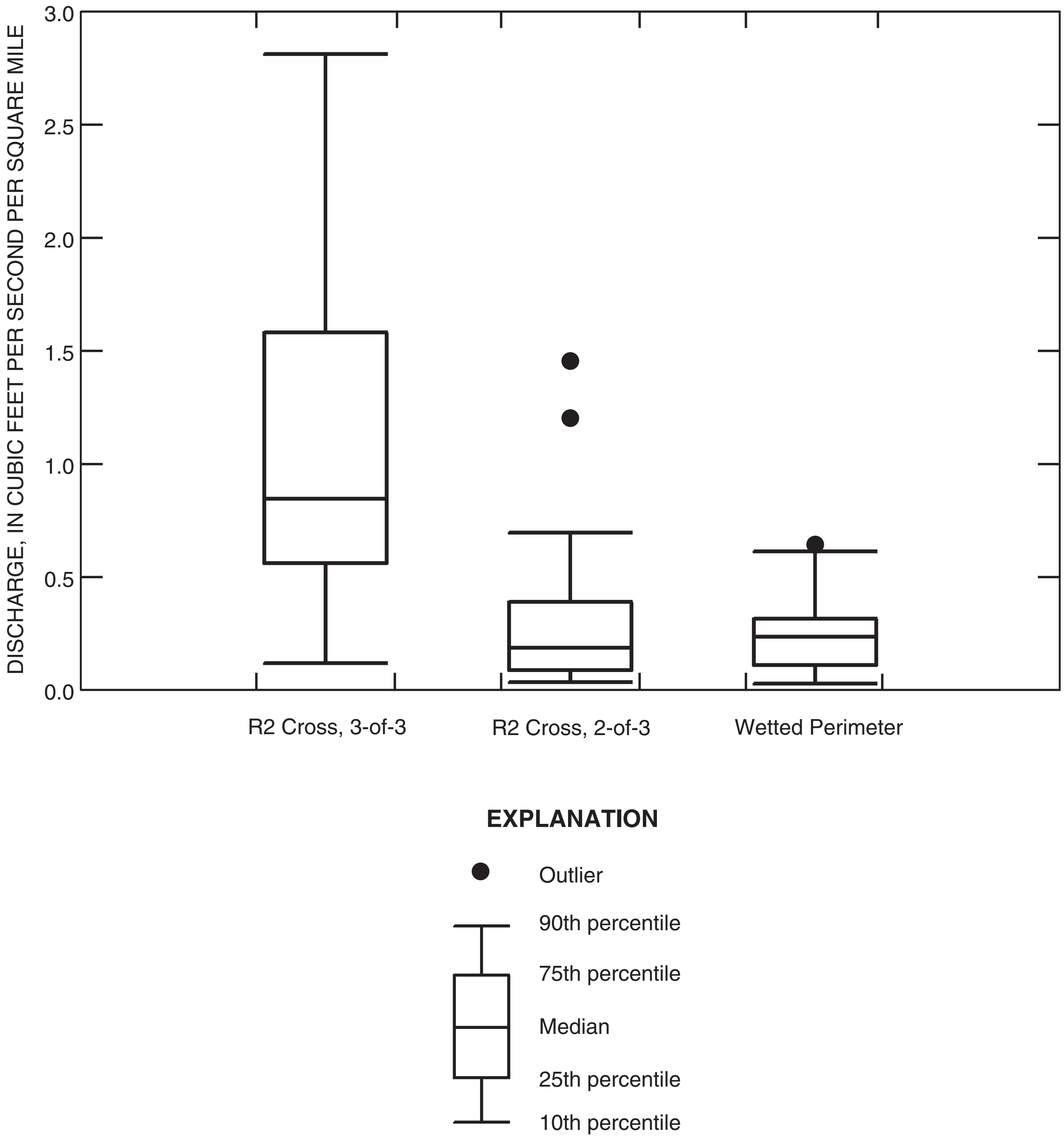

Figure 18. Streamflow requirements determined by the R2Cross 3-of-3 criteria, R2Cross 2-of-3 criteria, and Wetted-Perimeter methods for all cross sections analyzed.

Table 17 shows the average of the cross-section flow requirements within each of the nine riffle reaches. The median and mean streamflow requirements determined by the R2Cross 3-of-3 criteria were 0.86 $ft^3/s/mi^2$ and 1.10 $ft^3/s/mi^2$, respectively. The higher mean streamflow values reflect the influence of high flow events on the computation. The median and mean R2Cross 2-of-3 criteria streamflow requirements for habitat protection were 0.18 $ft^3/s/mi^2$ and 0.22 $ft^3/s/mi^2$, respectively. The median and mean Wetted-Perimeter streamflow requirements were 0.23 $ft^3/s/mi^2$ and 0.27 $ft^3/s/mi^2$, respectively.

A comparison of the R2Cross and Wetted-Perimeter streamflow requirements from the 9 Assabet River and Charles River sites to results determined from 10 index streamflow-gaging stations in southern New England reported by Armstong and others (2004) (fig. 19) shows that the streamflow requirements for the Assabet and Charles River sites are lower. The 10 index streamflow-gaging stations were the Squannacook River near West Groton, MA (01096000), Beaver Brook near North Pelham, NH (010965852), Old Swamp River near South Weymouth, MA (01105600), Wood River near Arcadia, RI (01117800), Mount Hope River near Warrenville, CT (01121000), Little River near Hanover, CT (01123000), South River near Conway, MA (01169900), Green River near Colrain, MA (01170100), Sevenmile River near Spencer, MA (01175670), and Green River at Williamstown, MA (01333000). These 10 index stations were on rivers with nearly unaltered streamflows and a variety of land uses. Most of the riffle sites in the Assabet and Charles River sites were on stream reaches with altered streamflows and areas of suburban land use. The size of the contributing areas of the Assabet River and Charles River study sites were generally less than those of the 10 index streamflow-gaging stations in southern New England (fig. 20). The median drainage area of the 9 Assabet and Charles River sites is 5.9 mi^2; the median drainage areas for the 10 southern New England stations were 32.6 mi^2. The R2Cross 3-of-3 streamflow requirements from both data sets have similar median values, however, the streamflow requirements for the Assabet and Charles River sites show a wider interquartile range than that for the southern New England stations. This is especially evident for the R2Cross 2-of-3 and Wetted-Perimeter results that were close to half of the flows determined at the 10 southern New England stations.

Differences in the streamflow requirements from these two standard-setting methods for the different riffle sites may be due to differences in stream-channel geometry between sites.

Table 17. Summary of R2Cross and Wetted-Perimeter streamflow requirements for nine riffle sites included in analysis, Assabet and Charles River Basins, Massachusetts.

[$ft^3/s/mi^2$, cubic foot per second per square mile]

River and reach	Discharge ($ft^3/s/mi^2$)		
	R2Cross		Wetted perimeter
	3 of 3 criteria	2 of 3 criteria	
Assabet River near Westborough	1.01	0.07	0.05
Cold Harbor Brook near Northborough	.69	.05	.26
Danforth Brook at Hudson	2.13	.18	.24
Fort Meadow Brook near Hudson	1.5	.45	.35
Elizabeth Brook near Stow	.56	.33	.18
Charles River near Hopkinton	1.44	.38	.21
Mine Brook near Franklin	.61	.18	.47
Charles River at Medway upstream	.75	.15	.18
Charles River at Medway downstream	.87	.33	.13
Median	0.87	0.18	0.21
Mean	1.06	.24	.23

Stream-channel morphology differs between stream systems, between tributaries of a single system, within a single reach, and even within the same channel type (Wood-Smith and Buffington, 1996; Trainor and Church, 2003). Channel cross sections and bed topography also vary over time. This variability may be small in stable, straight channels or large in rapidly changing channels.

The R2Cross and Wetted-Perimeter methods are applied to riffle habitats, which usually are stable stream features. Stream systems are not static, however. Alluvial channels adjust to produce an approximate equilibrium between the channel and the water and sediment it must transport (Leopold and Maddock, 1953). This quasi-equilibrium is achieved through changes in channel type, cross section (width, depth), slope, and bed topography (hydraulic roughness). The shape of the cross section of a natural channel primarily depends on stream discharge, although other factors, such as bedrock, a tributary delivering quantities of sediment, varying bank materials, riparian vegetation, or changes in flow resistance from woody debris can cause local differences.

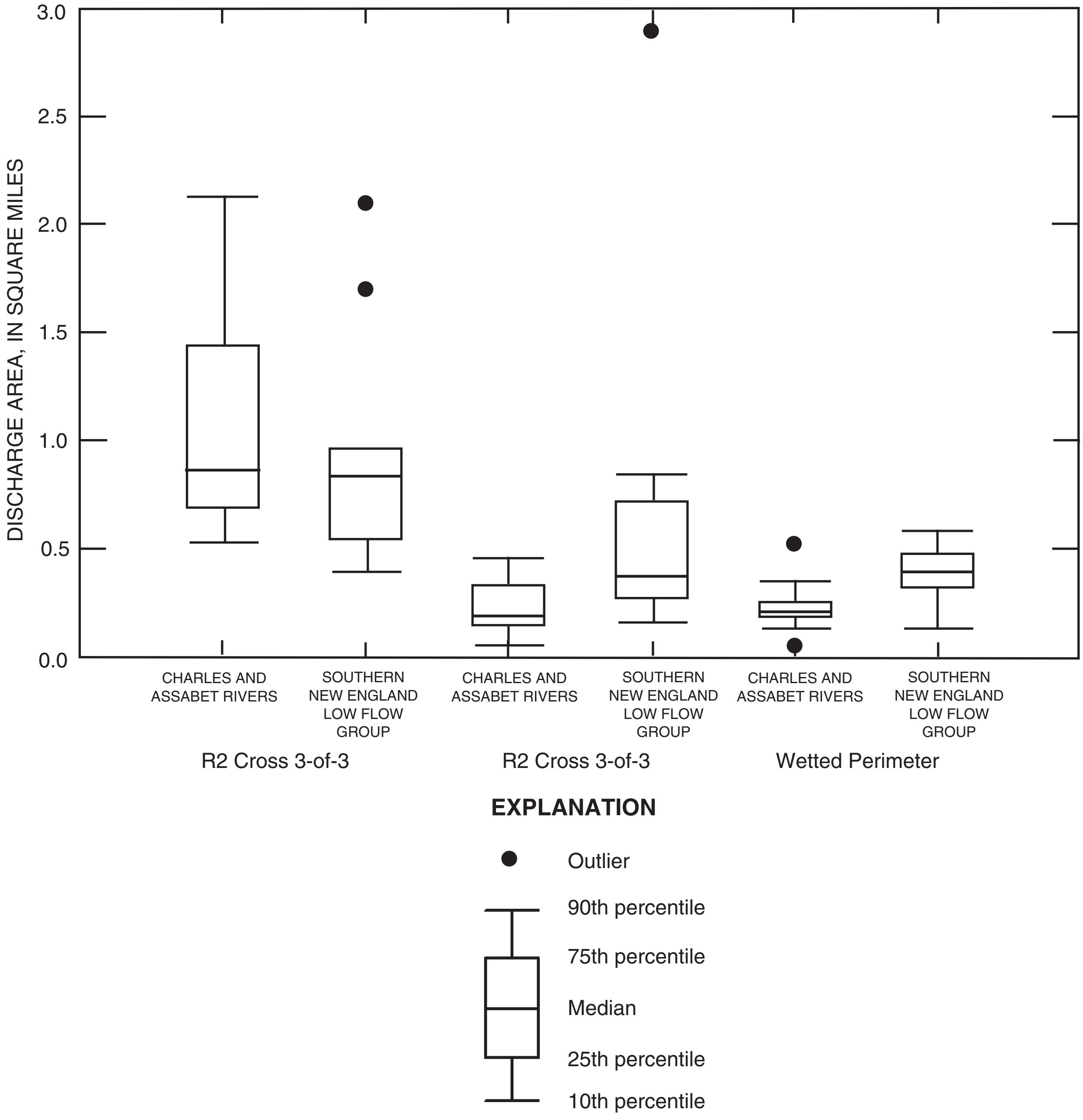

Figure 19. R2Cross, 3-of-3 criteria, R2Cross, 2-of-3 criteria, and Wetted-Perimeter method streamflow requirements determined at 9 riffle sites in the Assabet and Charles River Basins, Massachusetts, and at 10 streamflow-gaging stations in southern New England reported in Armstrong and others (2004).

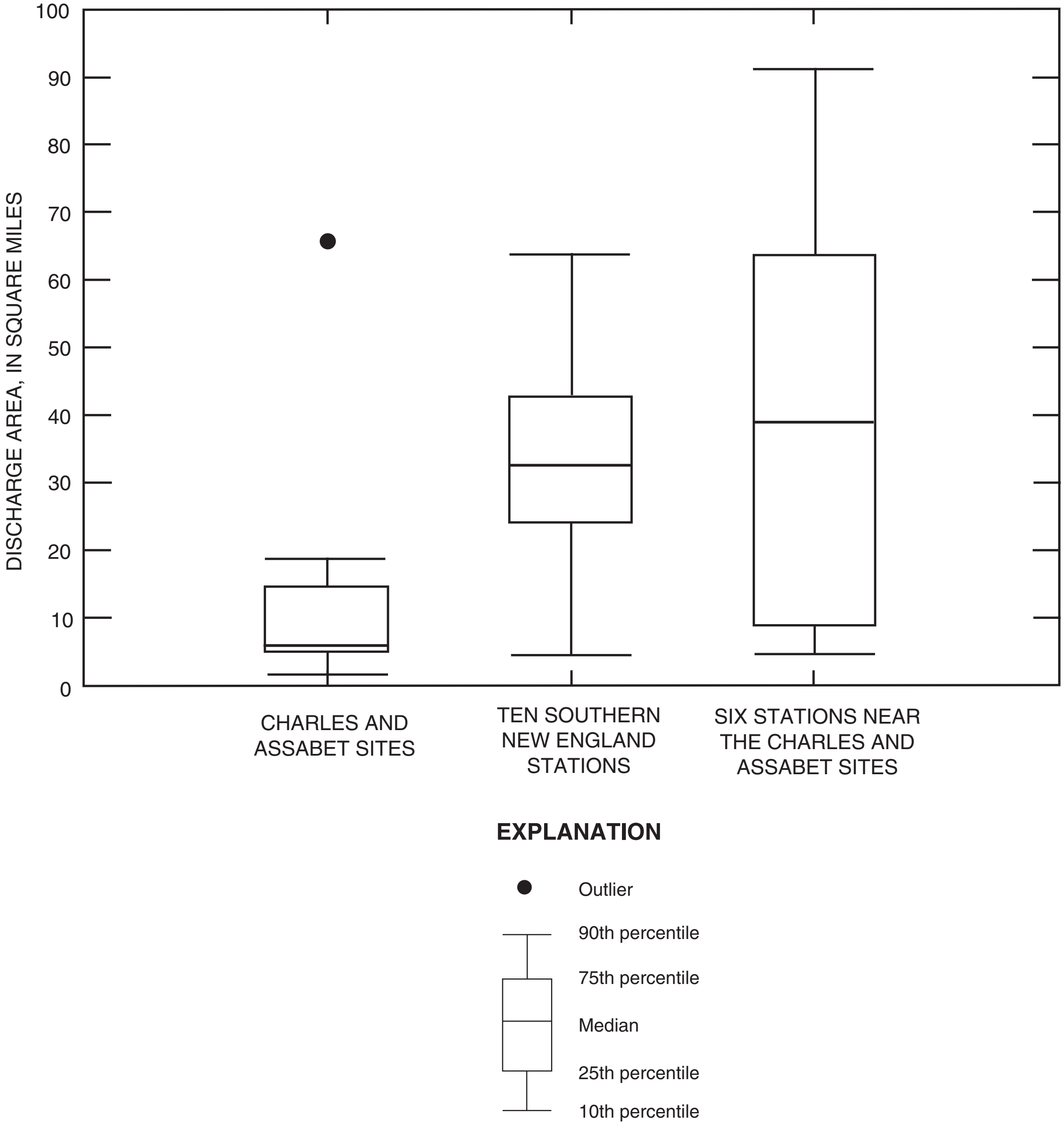

Figure 20. Drainage area at 9 riffle sites in the Assabet and Charles River Basins, Massachusetts, at 10 streamflow-gaging stations in southern New England reported in Armstrong and others (2004), and six streamflow-gaging stations near the Assabet and Charles River Basins.

Over time, channels will respond to altered flow conditions. For example, changes in land use, such as urbanization, can increase runoff and result in increased channel width. Impoundments may cause upstream aggradation and downstream degradation of sediment. Reduced discharges are thought to result in reduced channel widths and depths, decreases in channel cross-sectional area, width-to-depth ratio changes, and emplacement of large woody debris; the extent of these changes depends on the particle sizes of bed load, bed, and banks. Vegetation established on bars during prolonged low-flow periods also may affect channel capacity and processes. Channel adjustments are not instantaneous; channels can exist in non-equilibrium states for substantial periods of time (Jacobson and others, 2001). The degree to which stream channels adjust to altered flows and the effects of these channel adjustments on Wetted-Perimeter and R2Cross streamflow requirements is not well understood.

A diagnostic method (RVA) [Richter and others, 1997] and a standard-setting method (Tennant, 1976; Instream Flow Council, 2002) were applied to streamflow records from 1976 to 2000 for the summer low-flow period from six streamflow-gaging stations in MA, NH, and RI near the Assabet and Charles River Basins with relatively unaltered flow. The six streamflow-gaging stations chosen for this analysis were the Squannacook River near West Groton, MA (01096000), Beaver Brook near North Pelham, NH (010965852), Old Swamp River near South Weymouth, MA (01105600), Indian Head River near Hanover, MA (01105730), Branch River at Forestdale, RI (01111500), and Sevenmile River near Spencer, MA (01175670) (fig. 2).

The RVA method defines the range of target streamflows as the interquartile ranges for each of 33 statistical IHA parameters (Richter and others, 1996). Half of the statistics measure the central tendency of the magnitude or rate of change of flow, and half focus on the magnitude, duration, timing, and frequency of extreme events. The results the IHA analyses for all six streamflow-gaging stations are presented in table 19 at the end of this report.

The variability of monthly discharges among the six streamflow-gaging stations is mostly due to the differences in the contributing drainage areas for the stations. A linear regression plot between drainage area and the medians of the monthly flow durations showed that R2 ranged from 0.90 to 0.99 for the lower-quartile flows and from 0.88 to 0.99 for the upper-quartile flows. These values indicate that at least 90 percent of the variability in streamflows is due to the differences in the drainage areas for each of the streamflow-gaging stations. Consequently, regional streamflow statistics were determined by combining the monthly flows, normalized by drainage area, from each of the streamflow-gaging stations.

The interquartile ranges of the mean monthly discharges for the six streamflow-gaging stations (fig. 21), normalized for drainage area, are mostly bracketed by the R2Cross 3-of-3 criteria on the upper end and the R2Cross 2-of-3 criteria and Wetted-Perimeter median streamflow requirements on the lower end for the summer low-flow period of July through September. The drainage areas for the six nearby streamflow-gaging stations are significantly larger than the drainage areas for the nine Assabet and Charles River Basin riffle sites (fig. 20). The median R2Cross 2-of-3 and Wetted-Perimeter requirements are less than the 25th-percentile monthly flow for the summer months. Use of a monthly flow statistic can indicate only variability between years. Monthly flow statistics do not give an indication of daily variation. An analysis of the duration of daily flows during each month of the year, which was beyond the scope of this report, would give a better understanding of how often the streamflow requirements are met within any month of the year.

The Tennant method (Tennant, 1976) bases its streamflow requirements on the observation that aquatic habitat conditions are similar in streams carrying the same proportion of the mean annual flow (Q_{MA}). The Tennant method has different criteria for the winter (October–March) and summer (April–September) flow periods. During summer low-flow periods, specified percentages of the mean annual discharge (Q_{MA}) are defined as providing good, fair, and poor habitat conditions, respectively, according to Tennant (1976). The medians for the six streamflow-gaging stations are presented in table 18. The median R2Cross 3-of-3 criteria streamflow requirement for the nine riffles (0.87 $ft^3/s/mi^2$; table 17) is close to the Tennant 0.4 Q_{MA}, which is defined as providing good-habitat conditions (0.74 $ft^3/s/mi^2$). The median Wetted-Perimeter and R2Cross 2-of-3 criteria streamflow requirements (0.21 $ft^3/s/mi^2$ and 0.18 $ft^3/s/mi^2$; table 15) are close to the Tennant 0.1 Q_{MA}, which is defined as providing poor habitat conditions (0.19 $ft^3/s/mi^2$).

Application of R2Cross and Wetted-Perimeter methods to sites with altered streamflows or at sites that are only riffles at low to moderate flows can result in a greater variability of streamflow requirements than would result if the methods were applied to riffles on natural channels with unaltered streamflows. The R2Cross 2-of-3 and the Wetted-Perimeter streamflow requirements for the Assabet and Charles River sites show narrower interquartile ranges and lower median steamflow requirements than for 10 index streamflow-gaging stations in southern New England stations (Armstrong and others, 2004). The R2Cross 2-of-3 and Wetted-Perimeter results were also less than the 25th-percentile of monthly mean flows during the summer months as determined for six nearby streamflow-gaging stations. These streamflow requirements are in the poor habitat range as indicated by a Tennant analysis of the same six stations. These comparisons indicate that the R2Cross and Wetted-Perimeter methods under-estimate streamflow requirements when applied to sites in smaller drainage areas and channels that are runs at higher flows.

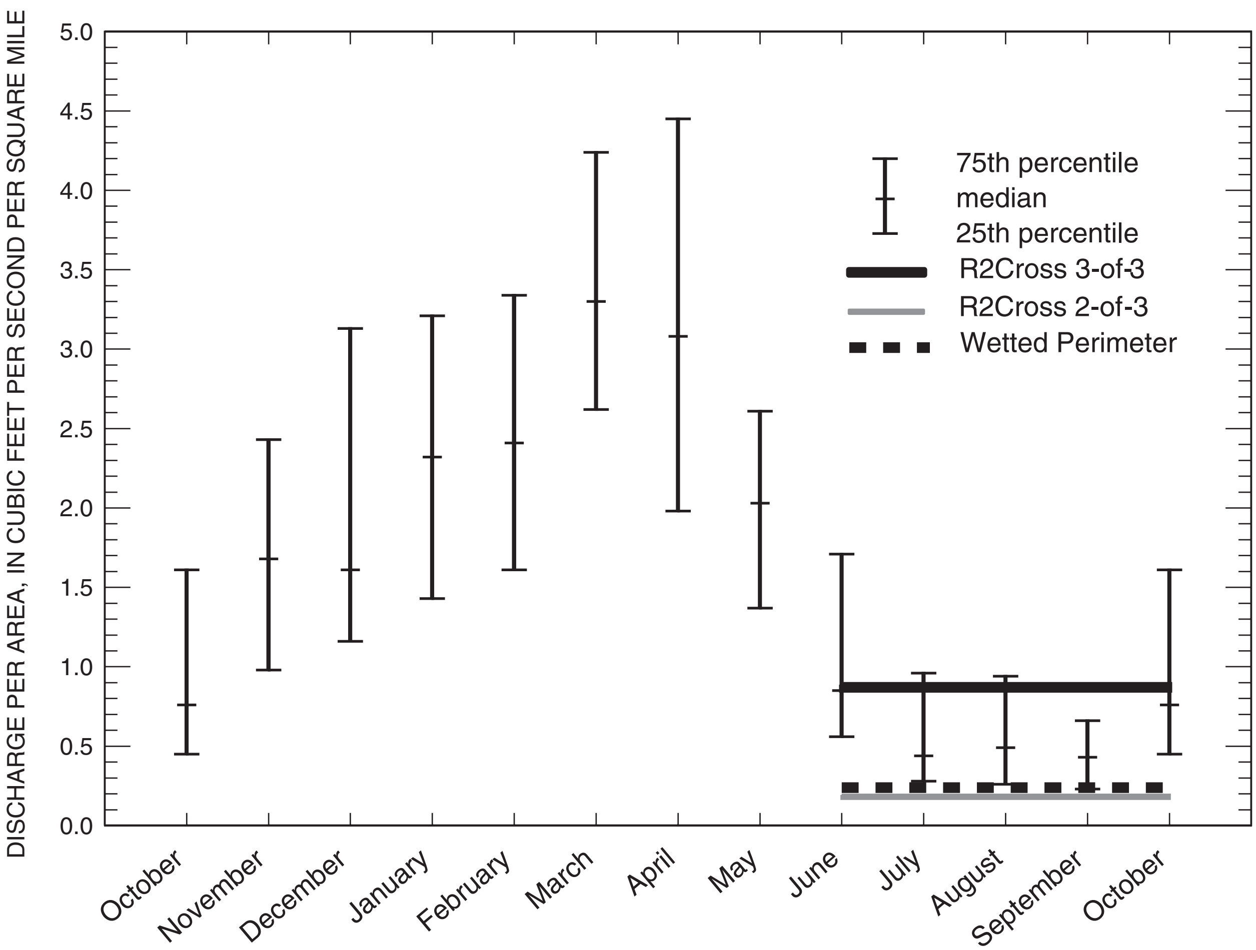

Figure 21. Quartiles of mean monthly discharges for the period 1976–2000 for six streamflow-gaging stations compared with median streamflow requirements estimated by the R2Cross 3-of-3 criteria, R2Cross 2-of-3 criteria, and Wetted-Perimeter methods for nine riffles in the Assabet and Charles River Basins, Massachusetts.

Table 18. Streamflow requirements estimated by the Tennant method from the combined records of six streamflow-gaging stations near the Assabet and Charles River Basins, Massachusetts.

[$ft^3/s/mi^2$, cubic foot per second per square mile]

Percentage of mean annual flow	Tennant classification	Median streamflow requirement ($ft^3/s/mi^2$)
0.5	Excellent habitat, April–September	0.93
.4	Good habitat, April–September Outstanding habitat, October–March	0.74
.3	Fair habitat, April–September Excellent habitat, October–March	.56
.2	Good habitat, October–March	.37
.1	Poor habitat, April–September Fair/Poor habitat, October–March	.19

Conclusions

The U.S. Geological Survey (USGS), in cooperation with the Massachusetts Executive Office of Environmental Affairs Watershed Initiative Program and Massachusetts Department of Conservation and Recreation, began a habitat assessment in 2001 to determine the streamflow requirements in the Assabet and Charles River Basins. In addition, the USGS coordinated its work with fish-assessment studies conducted by the Massachusetts Division of Fisheries and Wildlife to evaluate the current (2000–02) fish population in the Assabet and Charles River Basins. In 2002, a project was started by the USGS in cooperation with the Town of Hudson, MA, and in collaboration with the Organization of the Assabet River, to study additional riffle reaches in the Assabet River Basin. This report presents comparisons of R2Cross and Wetted-Perimeter methods of determining streamflow requirements with the Range of Variability Approach and Tennant method. The variability of the R2Cross and Wetted-Perimeter methods were also determined by comparison of results from the Assabet River and Charles River sites to results from riffles near 10 index streamflow-gaging stations in Southern New England. The study area includes two main-stem riffle reaches and a main-stem headwater reach of the Charles River, a main-stem headwater reach of the Assabet River and six reaches on tributaries to the Assabet and Charles Rivers in Massachusetts. The Assabet River tributary reaches were on Cold Harbor Brook, Danforth Brook, Fort Meadow Brook, Elizabeth Brook, and Nashoba Brook. The main-stem headwater reach of the Assabet River was near Westborough. The Charles River Basin reaches were on Mine Brook and on the main stem of the Charles River at Medway and the main-stem headwater reach of the Charles River was near Hopkinton.

Fish-community assessments were used to indicate the ecological condition of the Assabet and Charles Rivers. Biological monitoring in this study targeted fish because they are long-lived, and are sensitive to a wide range of stresses. Fish-community data used in this report were collected in the Assabet and Charles River Basins between August 1999 and September 2002, as part of the Massachusetts Division of Fisheries and Wildlife Statewide Fisheries Assessment Program. Additional fish-community data used in this report were collected in the Charles River Basin during August of 2002, as part of the Massachusetts Department of Environmental Protection, Charles River Watershed Monitoring Program. Sampling reaches were distributed over the length of the main stem and tributaries of the Charles and Assabet River Basins.

The observed fish communities in the main stems of the Charles and Assabet Rivers were compared to the expected target-fish community developed for the Quinebaug River, as well as to the fish communities in other river basins in Massachusetts. Fish were classified into three macrohabitat classes on the basis of their habitat use: macrohabitat generalists, fluvial dependents, and fluvial specialists (Bain and Knight, 1996, Bain and Meixler, 2000). Stocked fish, including rainbow trout, brown trout, and stocked brook trout were not included in the fish-community analysis.

Fish-sampling information and community assessments were categorized by basin size and free-flowing status. Reaches with drainage areas of greater than 30 mi^2 were classified as main-stem reaches (Anderson and Olivero, The Nature Conservancy, written commun., 2003). Reaches with drainage areas less than 30 mi^2 were classified as tributary or headwater reaches. Only the fish-community data from the main-stem reaches were compared to target fish communities developed for the Quinebaug River because target fish communities have only been developed for main-stem reaches. Tributary sites are expected to have larger proportions of fluvial fish species than main-stem reaches (M.B. Bain, Cornell University, oral commun., 2003). Analysis of recent fish collections in the Quinebaug, Blackstone, Westfield, Nashua, Housatonic, and Shawsheen River Basins strongly indicates that tributaries normally have a higher percent of fluvial fish than their corresponding main-stem reaches.

Fish in the free-flowing reaches with drainage areas greater than 30 mi^2 in the Assabet River main stem consisted of 52.9 percent macrohabitat generalists, 22.3 percent fluvial dependents, and 24.8 percent fluvial specialists. Fish in free-flowing reaches with drainage areas greater than 30 mi^2 in the Charles River main stem consisted of 98.3 percent macrohabitat generalists, 1.7 percent fluvial dependents, and no fluvial specialists. In general, the Charles River is dominated by macrohabitat generalist species; fluvial species are rare or absent. The percentages of fluvial fish species in the Charles River were considerably less than those in the Quinebaug River target fish community. These higher percentages of generalists indicate that the Charles River fish community is degraded. The species composition of the Assabet River main stem also indicates a degraded fish community, although the fish-community of the Assabet River Basin is less degraded than that of the Charles River Basin.

The fish species compositions of the Assabet and Charles River tributaries and headwaters are considerably different. Fish in free-flowing reaches with drainage areas less than 30 mi^2 in the Assabet River tributaries and headwaters consisted of 50.8-percent macrohabitat generalists, 17.9-percent fluvial dependents, and 31.3-percent fluvial specialists. Fish in free-flowing reaches in the Charles River tributaries and headwaters consisted of 88.9-percent macrohabitat generalists, 8.7-percent fluvial dependents, and 2.4-percent fluvial specialists. These results indicate that the macrohabitat generalists compose a larger proportion of the fish community in the tributaries and main stem of the Charles River than would be expected. The composite data for all the Assabet River tributaries strongly indicates that the fish community is also degraded.

The fish communities in the main stem and tributary reaches of both the Assabet and Charles River Basins for all habitat types indicate degraded aquatic ecosystems. However, the degree of degradation of the Charles River fish community is greater than that of the Assabet River fish community. The extreme predominance of tolerant generalist species in the Charles River fish community demonstrates the effects of degraded flow, habitat, and water quality combined with the effects of nearby impoundments and changing land use.

The R2Cross and Wetted-Perimeter methods require collection of site-specific physical and hydraulic data, such as channel geometry, average velocity, and average depth at riffle sites. An advantage of the R2Cross and Wetted-Perimeter methods is that they are based upon results from a calibrated hydraulic model and do not require streamflow records; thus, the flow values obtained by these methods can be applied in hydrologically disturbed drainage basins and at carefully selected gaged or ungaged sites. Consequently, streamflow requirements determined for natural riffle sites may not be sufficient to protect habitat at sites in a widened channel and may be excessive at sites in an artificially restricted channel. Conversely, flow requirements estimated at sites with a narrowed channel may not provide sufficient flows for habitat protection in undisturbed stream reaches. Because one site (Nashoba Brook in the Assabet River Basin) had a concrete wall along its right bank, the estimated streamflow requirement for this site was not included in comparisons with results obtained by other methods.

The median streamflow requirements defined by the R2Cross 3-of-3 criteria, R2Cross 2-of-3 criteria, and Wetted-Perimeter methods for the nine natural riffle reaches were 0.86 $ft^3/s/mi^2$, 0.18 $ft^3/s/mi^2$, and 0.23 $ft^3/s/mi^2$, respectively. For the R2Cross 3-of-3 criteria method for the nine riffle sites, the 25th and 75th percentiles interquartile range of the streamflow requirements, normalized for drainage area are 0.65 $ft^3/s/mi^2$ and 1.48 $ft^3/s/mi^2$, respectively. The streamflow requirements derived from the R2Cross 2-of-3 criteria and Wetted-Perimeter methods have a narrower interquartile range of 0.09 $ft^3/s/mi^2$ to 0.26 $ft^3/s/mi^2$ and 0.12 $ft^3/s/mi^2$ to 0.38 $ft^3/s/mi^2$, respectively, than the interquartile range for the R2Cross 3-of-3 criteria requirements. The discharge required for each riffle site was calculated by averaging the streamflow requirements for the critical cross sections within each riffle reach.

A comparison of the R2Cross and Wetted-Perimeter streamflow requirements from the 9 Assabet River and Charles River sites to results determined from 10 index streamflow-gaging stations in southern New England reported by Armstrong and others (2004) shows that the streamflow requirements for the Assabet River and Charles River sites are lower. Most of the riffle sites in the Assabet and Charles River sites were on stream reaches with altered streamflows and areas of suburban land use. The R2Cross 3-of-3 streamflow requirements from both data sets have similar median values; however, the streamflow requirements for the Assabet and Charles River sites show a wider interquartile range than that for the southern New England stations. This is especially evident for the R2Cross 2-of-3 and Wetted-Perimeter results that were close to half of the flows determined at the 10 southern New England stations. Differences in the streamflow requirements from these two standard-setting methods for the different riffle sites may be due to differences in stream-channel geometry between sites. The degree to which stream channels adjust to altered flows and the effects of these channel adjustments on Wetted-Perimeter and R2Cross streamflow requirements is not well understood.

The RVA diagnostic method was applied to records for the common period of 1976 to 2000 from six streamflow-gaging stations with relatively unaltered flow in or around the Assabet River and Charles River Basins, so that regional and seasonal comparisons with the R2Cross and Wetted-Perimeter results for the nine ungaged riffle reaches could be made. The median R2Cross and Wetted-Perimeter streamflow requirements for July through September mostly bracket the interquartile ranges of the mean monthly discharges normalized for drainage area from all six streamflow-gaging stations. The R2Cross 2-of-3 and Wetted-Perimeter median flow requirements are less than the 25th-percentile flow for all 5 months of June through October.

The Tennant standard-setting method was applied to the records for the same six regional streamflow-gaging stations used in the RVA analysis. The Tennant method commonly defines minimum streamflows for small streams during summer flow periods as 40, 30, and 10 percent of the mean annual discharge (Q_{MA}); these values represent good, fair, and poor habitat conditions, respectively. The median R2Cross 3-of-3 criteria streamflow requirement for the nine riffles compares closely to the median Tennant 0.4 Q_{MA} definition for good habitat. The median Wetted-Perimeter and R2Cross 2-of-3 criteria streamflow requirement compares closely to the median Tennant 0.1 Q_{MA} definition for poor habitat. These results correspond well with the R2Cross and Wetted-Perimeter streamflow requirements, which, in turn, bracket the RVA monthly interquartile ranges for the summer-period.

Application of R2Cross and Wetted-Perimeter methods to sites with altered streamflows or at sites that are riffles only at low to moderate flows can result in a greater variability of streamflow requirements than would result if the methods were applied to riffles on natural channels with unaltered streamflows. The R2Cross 2-of-3 and the Wetted-Perimeter streamflow requirements for the Assabet and Charles River sites show narrower interquartile ranges and lower median steamflow requirements than for 10 index streamflow-gaging stations in southern New England (Armstrong and others, 2004). The R2Cross 2-of-3 and Wetted-Perimeter results were also less than the 25th-percentile of monthly mean flows during the summer months as determined for six nearby streamflow-gaging stations. These streamflow requirements are in the poor habitat range as indicated by a Tennant Method analysis of the same six stations. These comparisons indicate that the R2Cross and Wetted-Perimeter methods underestimate streamflow requirements when applied to sites in drainage areas smaller than 30 mi^2 and channels that are runs at higher flows.

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Table 19. Flow statistics determined for Indicators of Hydrologic Alteration approach for six streamflow-gaging stations near the Assabet and Charles River Basins, Massachusetts.

Table 19. Flow statistics determined for Indicators of Hydrologic Alteration approach for six streamflow-gaging stations near the Assabet and Charles River Basins, Massachusetts.

Period or condition	Percentile					
	10th	25th	50th	75th	90th	(75-25)/50
SQUANNACOOK RIVER NEAR WEST GROTON, MA (01096000) Pre-impact period: 1976–2000 (25 years)						
Magnitude of monthly mean discharge (cubic feet per second)						
October	19.57	25.66	40.06	99.52	156.46	1.84
November	30.35	52.4	108.7	150.08	225.33	.9
December	39.61	65.11	85.65	183.39	252.38	1.38
January	37.42	68.97	132.1	180.85	244.18	.85
February	59.76	86.91	123.86	199.73	248.41	.91
March	131.88	188.37	227.61	275.11	417.17	.38
April	96.9	146.63	246.37	334.48	410.51	.76
May	59.91	95.5	145.26	180.35	239.59	.58
June	26.78	38.72	61.13	134.87	258.27	1.57
July	14.76	24.74	30.9	60.1	76.35	1.14
August	12.93	18.15	26.94	49.56	79.45	1.17
September	12.55	15.13	26.47	37.97	53.02	.86
Magnitude and duration of annual discharge conditions (cubic feet per second)						
1-day minimum	6.8	9.25	12	14.5	17.8	.44
3-day minimum	7.08	9.37	13	14.83	18	.42
7-day minimum	7.59	10.07	13.71	15.79	18.34	.42
30-day minimum	9.71	12.64	16.67	19.58	29	.42
90-day minimum	13.65	17.22	25.76	35.6	48.32	.71
1-day maximum	655.6	820.5	1,200	2,035	2,368	1.01
3-day maximum	459.07	631.83	804	1,311.17	1,520.93	.84
7-day maximum	348.37	421.57	586.43	857.57	957.94	.74
30-day maximum	233.13	262.37	335.43	424.38	556.03	.48
90- day maximum	166.68	195.43	242.04	281.67	333.64	.36
Zero discharge days	0	0	0	0	0	0
7-day minimum/mean annual discharge	.06	.08	.11	.15	.2	.68
Timing of annual discharge extremes (Julian day)						
Date of minimum 1-day discharge	226.6	237	256	272	283.8	.1
Date of maximum 1-day discharge	314.8	28.5	74	102.5	121.6	.2
Frequency and duration of high and low pulses						
Times that daily discharge is less than the 25th percentile of daily discharge (count)	3.6	4.5	6	8.5	12.6	.67
Days that daily discharge is less than the 25th percentile	5.94	7.92	11.22	17.5	30.84	.85
Times that daily discharge is greater than the 75th percentile of daily discharge (count)	5.6	8.5	11	14	17	.5
Days that daily discharge is greater than the 75th percentile	3.99	5.71	7.75	11.08	12.86	.69

Table 19. Flow statistics determined for Indicators of Hydrologic Alteration approach for six streamflow-gaging stations near the Assabet and Charles River Basins, Massachusetts.—Continued

Period or condition	Percentile					
	10th	25th	50th	75th	90th	(75-25)/50
SQUANNACOOK RIVER NEAR WEST GROTON, MA (01096000), Pre-impact period: 1976–2000 (25 years)—Continued						
Rate and frequency of hydrograph changes						
Mean of all positive differences between consecutive daily discharges (rise rate)	31.09	40.18	51.26	73.37	90.46	0.65
Mean of all negative differences between consecutive daily discharges (fall rate)	-40.44	-31.61	-24.49	-19.4	-15.03	-.5
Number of reversals	85.6	93	95	104	108	.12
BEAVER BROOK AT NORTH PELHAM, MA (010965852), Pre-impact period: 1976–2000 (25 years)						
Magnitude of monthly mean discharge (cubic feet per second)						
October	11.15	14.24	25.03	69.74	107.29	2.22
November	17.66	30.3	74.9	102.47	142.71	.96
December	27.06	32.35	59.97	122.37	175.35	1.5
January	25.77	48.53	79.77	116.68	170.25	.85
February	37.79	55.89	85.79	121.96	180.61	.77
March	90.21	126.48	147.13	188.29	282.45	.42
April	62.37	87.18	147.23	213.72	281.69	.86
May	42.15	63.05	92.55	121.81	132.93	.63
June	16.07	21.48	42.63	72.07	183.06	1.19
July	6.1	10.01	20.51	41.45	52.29	1.53
August	3.51	5.8	15.14	31.63	60.96	1.71
September	4.07	6.35	16	23.89	35.97	1.1
Magnitude and duration of annual discharge conditions (cubic feet per second)						
1-day minimum	1.2	1.95	4.6	5.65	8.7	.8
3-day minimum	1.27	2.07	4.87	5.88	9.07	.78
7-day minimum	1.37	2.29	5.24	7.37	9.64	.97
30-day minimum	1.95	3.66	7.48	11.23	16.66	1.01
90-day minimum	3.43	7.73	15.33	21.54	31.22	.9
1-day maximum	393.6	519	753	1,270	1,464	1
3-day maximum	311.47	402	601	975.33	1,147.33	.95
7-day maximum	225.8	294.93	452.86	622.21	780.03	.72
30-day maximum	140.41	172.72	226.27	289.72	399.72	.52
90- day maximum	117.08	127.9	161.47	190.33	222.39	.39
Zero discharge days	0	0	0	0	0	0
7-day minimum/mean annual discharge	.02	.02	.07	.09	.15	1.07
Timing of annual discharge extremes (Julian day)						
Date of minimum 1-day discharge	220.2	242	254	270	283.6	.08
Date of maximum 1-day discharge	320	28	74	97	162.2	.19

Table 19. Flow statistics determined for Indicators of Hydrologic Alteration approach for six streamflow-gaging stations near the Assabet and Charles River Basins, Massachusetts.—Continued

Period or condition	Percentile					
	10th	25th	50th	75th	90th	(75-25)/50
BEAVER BROOK AT NORTH PELHAM, MA (010965852), Pre-impact period: 1976–2000 (25 years)—Continued						
Frequency and duration of high and low pulses						
Times that daily discharge is less than the 25th percentile of daily discharge (count)	3	5	7	9	13.4	0.57
Days that daily discharge is less than the 25th percentile	6.28	7.24	11.14	17.37	27.35	.91
Times that daily discharge is greater than the 75th percentile of daily discharge (count)	5.6	7.5	11	13	17	.5
Days that daily discharge is greater than the 75th percentile	4.47	6.5	9	11.17	13.01	.52
Rate and frequency of hydrograph changes						
Mean of all positive differences between consecutive daily discharges (rise rate)	16.45	24	34.9	40.65	57.02	.48
Mean of all negative differences between consecutive daily discharges (fall rate)	-22.2	-17.14	-14.63	-10.61	-7.29	-.45
Number of reversals	80.4	88	93	100	111.6	.13
OLD SWAMP RIVER NEAR SOUTH WEYMOUTH, MA (01105600), Pre-impact period: 1976–2000 (25years)						
Magnitude of monthly mean discharge (cubic feet per second)						
October	1.69	2.51	3.41	8.1	10.64	1.64
November	3.28	4.71	8.97	11.99	18.43	.81
December	3.62	5.54	8.95	15.4	21.35	1.1
January	3.56	8.2	11.64	16.84	27.25	.74
February	6.14	6.92	11.93	16.59	24.8	.81
March	7	10.01	13.72	20.07	29.96	.73
April	5.02	7.33	12.01	17.57	26.69	.85
May	4.38	5.6	8.14	10.91	16.42	.65
June	1.54	2.48	3.17	9.57	23.25	2.24
July	.7	.92	1.82	5.36	6.7	2.44
August	.81	1.24	3.11	4.37	7.5	1.01
September	.71	1.4	2.17	3.47	7.69	.96

Table 19. Flow statistics determined for Indicators of Hydrologic Alteration approach for six streamflow-gaging stations near the Assabet and Charles River Basins, Massachusetts.—Continued

Period or condition	Percentile					
	10th	25th	50th	75th	90th	(75-25)/50
OLD SWAMP RIVER NEAR SOUTH WEYMOUTH, MA (01105600), Pre-impact period: 1976–2000 (25 years)—Continued						
Magnitude and duration of annual discharge conditions (cubic feet per second)						
1-day minimum	0.15	0.19	0.33	0.51	0.62	0.98
3-day minimum	.16	.23	.36	.56	.71	.9
7-day minimum	.19	.31	.51	.68	.84	.73
30-day minimum	.34	.58	.93	1.18	1.72	.65
90-day minimum	.82	1.48	1.91	2.92	3.76	.75
1-day maximum	59.2	100	122	193.5	278	.77
3-day maximum	44.13	59.17	83.33	122	198.33	.75
7-day maximum	29.25	37.86	54.14	74.5	110.94	.68
30-day maximum	16.93	19.16	26.58	34.23	43.89	.57
90- day maximum	11.41	15.16	19.16	20.74	25.94	.29
Zero discharge days	0	0	0	0	0	0
7-day minimum/mean annual discharge	.03	.04	.05	.08	.1	.84
Timing of annual discharge extremes (Julian day)						
Date of minimum 1-day discharge	201.4	212	237	273	276.4	.17
Date of maximum 1-day discharge	331.2	25.5	71	107.5	141	.22
Frequency and duration of high and low pulses						
Times that daily discharge is less than the 25th percentile of daily discharge (count)	6	8.5	11	12	15.4	.32
Days that daily discharge is less than the 25th percentile	4.51	6.21	8	9.38	16.53	.4
Times that daily discharge is greater than the 75th percentile of daily discharge (count)	9.8	16	20	23.5	26.8	.38
Days that daily discharge is greater than the 75th percentile	2.63	3.36	5	5.69	7.12	.47
Rate and frequency of hydrograph changes						
Mean of all positive differences between consecutive daily discharges (rise rate)	3.74	6.13	7.35	9.5	11.79	.46
Mean of all negative differences between consecutive daily discharges (fall rate)	-4.87	-3.76	-2.8	-2.38	-1.43	-.49
Number of reversals	88.6	100	106	112	117	.11

Table 19. Flow statistics determined for Indicators of Hydrologic Alteration approach for six streamflow-gaging stations near the Assabet and Charles River Basins, Massachusetts.—Continued

Period or condition	Percentile					
	10th	25th	50th	75th	90th	(75-25)/50
SEVENMILE RIVER NEAR SPENCER, MA (01175670), Pre-impact period: 1976–2000 (25 years)						
Magnitude of monthly mean discharge (cubic feet per second)						
October	3.17	5.66	18.07	28.68	2.63	3.17
November	6.83	12	22	26.55	1.26	6.83
December	8.05	14.56	25.48	36.9	1.2	8.05
January	10.24	19.52	28.92	41.33	.96	10.24
February	12.14	18.57	26.54	36.7	.78	12.14
March	23.11	28.77	37.63	46.87	.5	23.11
April	19.07	29	41.4	48.43	.77	19.07
May	13.92	17.86	21.96	31.39	.45	13.92
June	5.08	6.35	17.41	32.33	1.94	5.08
July	2.18	4.38	7.37	9.39	1.18	2.18
August	1.71	3.72	7.75	13.68	1.62	1.71
September	1.09	1.88	5.96	10.9	2.59	1.09
Magnitude and duration of annual discharge conditions (cubic feet per second)						
1-day minimum	.11	.17	.29	.62	.89	1.55
3-day minimum	.15	.22	.3	.82	.97	1.99
7-day minimum	.19	.31	.4	1.02	1.44	1.76
30-day minimum	.35	.45	1.12	1.83	2.9	1.23
90-day minimum	.81	1.65	2.24	4.09	6.91	1.09
1-day maximum	75.2	99.5	161	194.5	235.6	.59
3-day maximum	55.47	80.33	117.33	149.5	182.73	.59
7-day maximum	41.34	59.5	83.57	102.14	141.14	.51
30-day maximum	27.85	37.43	47.1	56.22	68.3	.4
90- day maximum	22.3	27.55	32.46	37.32	39.8	.3
Zero discharge days	0	0	0	0	0	0
7-day minimum/mean annual discharge	.01	.02	.03	.06	.1	1.79
Timing of annual discharge extremes (Julian day)						
Date of minimum 1-day discharge	209	240	257	273	279.6	.09
Date of maximum 1-day discharge	295	20.5	70	102.5	154.4	.22
Frequency and duration of high and low pulses						
Times that daily discharge is less than the 25th percentile of daily discharge (count)	4	5.5	8	9.5	12.8	.5
Days that daily discharge is less than the 25th percentile	4.56	7.4	11.57	15.61	21.58	.71
Times that daily discharge is greater than the 75th percentile of daily discharge (count)	7.6	9.5	12	15	19.4	.46
Days that daily discharge is greater than the 75th percentile	3.86	5.61	6.83	8.66	10.15	.45

Table 19. Flow statistics determined for Indicators of Hydrologic Alteration approach for six streamflow-gaging stations near the Assabet and Charles River Basins, Massachusetts.—Continued

Period or condition	Percentile					
	10th	25th	50th	75th	90th	(75-25)/50
SEVENMILE RIVER NEAR SPENCER, MA (01175670), Pre-impact period: 1976–2000 (25 years)—Continued						
Rate and frequency of hydrograph changes						
Mean of all positive differences between consecutive daily discharges (rise rate)	4.04	4.95	7.02	8.38	9.34	0.49
Mean of all negative differences between consecutive daily discharges (fall rate)	-4.3	-3.63	-3.01	-2.38	-1.88	-.41
Number of reversals	95	98	106	111.5	124.8	.13
INDIAN HEAD RIVER AT HANOVER, MA (01105730), Pre-impact period: 1976–2000 (25 years)						
Magnitude of monthly mean discharge (cubic feet per second)						
October	9.98	14.21	26.03	62.55	81.87	1.86
November	24.31	34	65.8	81.38	116.56	.72
December	29.08	39.08	59.77	118.98	155.27	1.34
January	25.11	55.29	79.03	114.15	176.25	.74
February	44.77	58.04	93.57	115.85	152.88	.62
March	68.22	79.02	98.9	149.11	190.03	.71
April	41.09	53.4	83.3	122.6	197.5	.83
May	30.02	41.11	63.16	82.5	104.92	.66
June	12.39	16.78	24.33	55.02	154.55	1.57
July	6.42	7.88	12.47	37.73	49.38	2.39
August	4.85	8.09	20.48	37.66	53.92	1.44
September	4.97	8.86	15.51	24.03	49.98	.98
Magnitude and duration of annual discharge conditions (cubic feet per second)						
1-day minimum	.72	2.1	3.5	4.25	5.58	.61
3-day minimum	1.1	2.42	3.77	4.87	6.56	.65
7-day minimum	2.03	2.89	4.44	7.35	8.22	1
30-day minimum	3.06	5.01	6.54	10.2	14.03	.79
90-day minimum	5.93	8.64	13.78	23.48	29.31	1.08
1-day maximum	334.4	422.5	600	759.5	946.2	.56
3-day maximum	256.8	341.17	469	578.83	748.07	.51
7-day maximum	168.8	231.5	287.86	404.21	489	.6
30-day maximum	114.87	133.75	184.87	218.75	240.76	.46
90- day maximum	78.22	97.5	125.72	148.43	169.21	.41
Zero discharge days	0	0	0	0	0	0
7-day minimum/mean annual discharge	.04	.05	.08	.11	.15	.83
Timing of annual discharge extremes (Julian day)						
Date of minimum 1-day discharge	200.2	212.5	257	275	277.4	.17
Date of maximum 1-day discharge	331.6	26.5	63	107.5	155.4	.22

Table 19. Flow statistics determined for Indicators of Hydrologic Alteration approach for six streamflow-gaging stations near the Assabet and Charles River Basins, Massachusetts.—Continued

Period or condition	Percentile					
	10th	25th	50th	75th	90th	(75-25)/50
INDIAN HEAD RIVER AT HANOVER, MA (01105730), Pre-impact period: 1976–2000 (25 years)—Continued						
Frequency and duration of high and low pulses						
Times that daily discharge is less than the 25th percentile of daily discharge (count)	3.6	5	7	9	13.4	0.57
Days that daily discharge is less than the 25th percentile	4.75	7.03	10.17	16.2	26.24	.9
Times that daily discharge is greater than the 75th percentile of daily discharge (count)	7.6	12	15	18	19.4	.4
Days that daily discharge is greater than the 75th percentile	3.33	4	6.83	7.9	11.58	.57
Rate and frequency of hydrograph changes						
Mean of all positive differences between consecutive daily discharges (rise rate)	15.23	25.01	30.3	36.28	40.45	.37
Mean of all negative differences between consecutive daily discharges (fall rate)	-16.99	-16.12	-12.27	-9.98	-6.95	-.5
Number of reversals	90	95	102	111	119.2	.16
BRANCH RIVER AT FORESTDALE, RI (01111500), Pre-impact period: 1976–2000 (25 years)						
Magnitude of monthly mean discharge (cubic feet per second)						
October	58.48	69.11	85.87	132.27	333.57	.74
November	77.36	109.83	156.17	226.18	323.52	.75
December	79.76	109.42	162.61	324.03	460.44	1.32
January	96.07	129.06	252.77	323.18	491.65	.77
February	139.18	174.43	242	337.61	380.22	.67
March	179.57	233.9	307.68	400.42	580.01	.54
April	128.04	186.42	305.23	398.53	643.49	.69
May	121.68	126.34	184.39	271.84	320.77	.79
June	47.71	52.88	84.47	180.72	375.49	1.51
July	25.55	33.47	46.1	85.97	127.54	1.14
August	22.39	26.45	52.13	94.34	157.08	1.3
September	21.47	33.38	45.87	72.59	116.05	.85

Table 19. Flow statistics determined for Indicators of Hydrologic Alteration approach for six streamflow-gaging stations near the Assabet and Charles River Basins, Massachusetts.—Continued

Period or condition	Percentile					
	10th	25th	50th	75th	90th	(75-25)/50
BRANCH RIVER AT FORESTDALE, RI (01111500), Pre-impact period: 1976–2000 (25 years)—Continued						
Magnitude and duration of annual discharge conditions (cubic feet per second)						
1-day minimum	11	14.5	18	22.5	27.2	0.44
3-day minimum	11.2	14.67	19.33	24.33	28.53	.5
7-day minimum	11.94	15.5	21.29	26.57	32.2	.52
30-day minimum	14.96	21.78	25.87	37.7	46.61	.62
90-day minimum	24.01	34.97	47.19	59.26	89.4	.51
1-day maximum	788.6	1,180	1,730	2,170	3,350	.57
3-day maximum	623.67	988	1,155	1,581.17	2,634.67	.51
7-day maximum	441.06	662.71	862.57	1,153.64	1,859.91	.57
30-day maximum	305.24	371.35	546.1	655.08	763.09	.52
90- day maximum	238.48	278.5	368.53	413.01	493.6	.36
Zero discharge days	0	0	0	0	0	0
7-day minimum/mean annual discharge	.06	.08	.12	.15	.18	.51
Timing of annual discharge extremes (Julian day)						
Date of minimum 1-day discharge	203	220.5	248	265.5	275.4	.12
Date of maximum 1-day discharge	308.2	26	71	96.5	143	.19
Frequency and duration of high and low pulses						
Times that daily discharge is less than the 25th percentile of daily discharge (count)	4.6	5	7	8.5	11.4	.5
Days that daily discharge is less than the 25th percentile	5.36	8.38	14	18.4	23.78	.72
Times that daily discharge is greater than the 75th percentile of daily discharge (count)	7.6	9	11	16	17	.64
Days that daily discharge is greater than the 75th percentile	3.42	5.06	7.29	9.99	11.95	.68
Rate and frequency of hydrograph changes						
Mean of all positive differences between consecutive daily discharges (rise rate)	35.06	55.39	68.31	99.31	116.72	.64
Mean of all negative differences between consecutive daily discharges (fall rate)	-48.82	-43.72	-32.63	-25.31	-17.85	-.56
Number of reversals	93	98.5	105	108	113	.09

Appendix 1: Water-Surface-Profile Model Documentation

Contents

Tables

Assabet River near Westborough, Massachusetts

Six measurements of water surfaces were taken at five surveyed cross sections for the purpose of model calibration. The calibration discharges were modeled at normal (subcritical) depth for the most downstream section and a slope of 0.0008 ft/ft was set as a downstream boundary condition. This slope was calculated from water-surface altitudes at surveyed reference points at the most downstream end of the reach. Bankfull discharge was estimated by comparison with the altitudes of observed bankfull indicators surveyed at the study site.

Initial roughness coefficients for each cross section were estimated by solution of Manning's equation on the basis of the measured discharges and surveyed cross-sectional areas and slopes. The authors, as required, varied the roughness coefficients for each cross section, until calculated water-surface altitudes matched measured water-surface altitudes with reasonable accuracy. The variability in the roughness coefficients between river stations (table 1-1) is due to the variability of the actual flow length as opposed to the straight-line lengths between river stations. The longer path the water takes in flowing around the bed material at different discharges changes the energy slope in the analysis and is compensated for by increasing the roughness coefficient to obtain acceptable model calibration. The calibration accuracy was 0.015 ft over the entire reach for both measured discharges.

For all study sites, the HEC-RAS software occasionally indicated the need for more cross sections to reduce velocity head drops between sections. Addition of interpolated cross sections would reduce the number of these messages, but would not significantly affect the water-surface profile.

Cold Harbor Brook near Northborough, Massachusetts

Seven measurements of water surfaces were taken at each of five surveyed cross sections for the purpose of model calibration. The calibration discharges were modeled at normal (subcritical) depth for the most downstream section and a slope of 0.0008 ft/ft was set as a downstream boundary condition. This slope was calculated from water-surface altitudes at surveyed reference points at the most downstream end of the reach. Bankfull discharge was estimated by comparison with the altitudes of observed bankfull indicators surveyed at the study site.

Initial roughness coefficients for each cross section were estimated by solution of Manning's equation on the basis of the measured discharges and surveyed cross-sectional areas and slopes. The roughness coefficients for each cross section were varied as required until calculated water-surface altitudes matched measured water-surface altitudes with reasonable accuracy. The variability in the roughness coefficients between river stations (table 1-2) is due to the variability of the actual flow length as opposed to the straight-line lengths between river stations. The longer path the water takes in flowing around the bed material at different discharges changes the energy slope in the analysis and is compensated for by increasing the roughness coefficient to obtain acceptable model calibration. The calibration accuracy was 0.006 ft over the entire reach for both measured discharges.

Danforth Brook near Hudson, Massachusetts

Nine measurements of water surfaces were taken at each of six surveyed cross sections for the purpose of model calibration. The calibration discharges were modeled at normal (subcritical) depth for the most downstream section and a slope of 0.01 ft/ft was set as a downstream boundary condition. This slope was calculated from water-surface altitudes at surveyed reference points at the most downstream end of the reach. Bankfull discharge was estimated by comparison with the altitudes of observed bankfull indicators surveyed at the study site.

Initial roughness coefficients for each cross section were estimated by solution of Manning's equation on the basis of the measured discharges and surveyed cross-sectional areas and slopes. The roughness coefficients for each cross section were varied as required until calculated water-surface altitudes matched measured water-surface altitudes with reasonable accuracy. The variability in the roughness coefficients between river stations (table 1-3) is due to the variability of the actual flow length as opposed to the straight-line lengths between river stations. The longer path the water takes in flowing around the bed material at different discharges changes the energy slope in the analysis and is compensated for by increasing the roughness coefficient to obtain acceptable model calibration. The calibration accuracy was 0.037 ft over the entire reach for both measured discharges.

Table 1-1. HEC-RAS model calibration to measured streamflows and water-surface altitudes at Assabet River near Westborough, Massachusetts.

[ft, foot; ft/ft, foot per foot; ft^2, square foot; ft^3/s, cubic foot per second; --, not applicable]

River station	Discharge (ft^3/s)	Manning's coefficient	Flow area (ft^2)	Hydraulic radius (ft)	Slope (ft/ft)	Froude number	Observed water altitude (ft)	Calculated water-surface altitude (ft)
100	0.052	2	4.35	0.43	0.0008	0.00	497.64	497.62
100	.104	1.081	4.59	.45	.0008	.01	497.64	497.64
100	.185	.838	5.73	.52	.0008	.01	497.75	497.75
100	5.22	.079	11.03	.84	.0008	.09	--	498.2
100	6.84	.062	11.26	.85	.0008	.11	498.22	498.22
100	27.3	.05	24.8	1.37	.0008	.16	--	499.16
109.99	.052	.035	3.21	.24	.0000	.01	497.64	497.62
109.99	.104	.035	3.52	.26	.0000	.01	497.64	497.64
109.99	.185	.033	5.01	.36	.0000	.01	497.72	497.75
109.99	5.22	.033	11.43	.75	.0002	.09	--	498.2
109.99	6.84	.033	11.71	.77	.0002	.11	498.21	498.22
109.99	27.3	.035	26.05	1.48	.0003	.14	499.16	499.16
116.71	.052	.183	.29	.04	.0365	.16	497.78	497.78
116.71	.104	.209	.53	.06	.0359	.15	497.81	497.81
116.71	.185	.284	.83	.08	.054	.14	497.85	497.84
116.71	5.22	.05	5.64	.4	.0033	.25	--	498.21
116.71	6.84	.05	5.91	.42	.0048	.31	498.23	498.23
116.71	27.3	.035	19.2	1.17	.0008	.22	499.14	499.16
127.83	.052	.2	.35	.05	.0195	.11	498.03	497.99
127.83	.104	.202	.5	.06	.0352	.15	498.01	498.01
127.83	.185	.376	1.31	.11	.0234	.07	498.09	498.09
127.83	5.22	.074	5.57	.41	.0072	.26	498.43	498.43
127.83	6.84	.085	6.86	.48	.0085	.25	498.52	498.52
127.83	27.3	.12	17.15	.94	.0154	.29	499.18	499.18
136.38	.052	.13	.34	.05	.0086	.12	498.13	498.09
136.38	.104	.13	.61	.07	.0074	.11	498.13	498.13
136.38	.185	.298	1.44	.14	.0092	.06	498.21	498.21
136.38	5.22	.172	5.76	.33	.0459	.27	498.56	498.56
136.38	6.84	.12	7.08	.37	.0214	.27	498.63	498.63
136.38	27.3	.07	2.5	.82	.0046	.25	499.25	499.25

Table 1-2. HEC-RAS model calibration to measured streamflows and water-surface altitudes at Cold Harbor Brook near Northborough, Massachusetts.

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

River station	Discharge (ft^3/s)	Manning's coefficient	Flow area (ft^2)	Hydraulic radius (ft)	Slope (ft/ft)	Froude number	Observed water altitude (ft)	Calculated water-surface altitude (ft)
100	0.1	0.09	0.79	0.14	0.0008	0.06	498.47	498.47
100	.96	.045	2.25	.31	.0008	.13	498.71	498.71
100	1.9	.024	2.66	.27	.0008	.24	498.76	498.76
100	4.6	.037	6.38	.5	.0008	.18	499.09	499.09
100	5.1	.04	7.27	.55	.0008	.16	499.16	499.16
100	7.3	.045	9.88	.7	.0008	.15	499.36	499.36
100	11.9	.061	16.11	1.05	.0008	.12	499.82	499.82
125.7	.1	.9	1.31	.23	.0152	.03	498.8	498.8
125.7	.96	.193	2.42	.38	.0096	.11	498.99	498.99
125.7	1.9	.065	2.98	.38	.0028	.18	499.07	499.07
125.7	4.6	.049	5.47	.37	.0025	.24	499.32	499.32
125.7	5.1	.046	6.04	.38	.0021	.24	499.36	499.36
125.7	7.3	.095	9.12	.51	.0056	.19	499.55	499.55
125.7	11.9	.1	14.93	.79	.0036	.15	499.88	499.88
131.7	.1	.391	.83	.1	.0202	.06	498.9	498.9
131.7	.96	.09	2	.22	.0064	.18	499.04	499.04
131.7	1.9	.099	2.58	.26	.0147	.25	499.11	499.11
131.7	4.6	.031	5.22	.39	.0012	.25	499.33	499.33
131.7	5.1	.042	5.81	.4	.002	.24	499.37	499.38
131.7	7.3	.274	9.41	.6	.0387	.17	499.65	499.62
131.7	11.9	.152	14.21	.76	.0091	.17	499.92	499.92
137.4	.1	.299	.89	.12	.0082	.06	498.97	498.97
137.4	.96	.592	2.21	.26	.1764	.15	499.15	499.15
137.4	1.9	.168	2.87	.31	.0265	.21	499.22	499.22
137.4	4.6	.036	4.01	.37	.0029	.33	499.34	499.34
137.4	5.1	.034	4.5	.4	.0023	.31	499.37	499.38
137.4	7.3	.085	8.35	.57	.0052	.2	499.68	499.68
137.4	11.9	.041	14.94	.64	.0008	.17	499.93	499.93
147.7	.1	.39	.8	.12	.0177	.06	499.05	499.05
147.7	.96	.026	2.57	.22	.0003	.14	499.23	499.24
147.7	1.9	.039	3.81	.28	.0009	.16	499.34	499.34
147.7	4.6	.285	7.14	.49	.04	.16	499.59	499.59
147.7	5.1	.255	7.45	.5	.0345	.17	499.61	499.61
147.7	7.3	.1	10.16	.61	.0045	.16	499.78	499.78
147.7	11.9	.075	13.48	.79	.0027	.17	499.98	499.99

Table 1-3. HEC-RAS model calibration to measured streamflows and water-surface altitudes at Danforth Brook near Hudson, Massachusetts.

[ft, foot; ft/ft, foot per foot; ft^2, square foot; ft^3/s, cubic foot per second; --, not applicable]

River station	Discharge (ft^3/s)	Manning's coefficient	Flow area (ft^2)	Hydraulic radius (ft)	Slope (ft/ft)	Froude number	Observed water altitude (ft)	Calculated water-surface altitude (ft)
18.2	0.009	0.7	0.22	0.08	0.01	0.02	496.55	496.54
18.2	.11	.22	.76	.1	.01	.08	496.63	496.63
18.2	.15	.397	1.5	.14	.01	.05	496.71	496.71
18.2	1.5	.122	3.21	.24	.01	.16	496.86	496.86
18.2	3.1	.108	4.98	.3	.01	.19	496.98	496.98
18.2	4.4	.098	5.9	.35	.01	.22	497.03	497.04
18.2	5.5	.095	6.7	.38	.01	.23	497.09	497.09
18.2	12	.085	10.48	.53	.01	.27	497.3	497.3
18.2	28.5	.053	13.58	.65	.01	.45	497.46	497.46
25.9	.009	1.2	.59	.07	.0049	.01	496.64	496.62
25.9	.11	.521	1.67	.12	.0094	.03	496.72	496.71
25.9	.15	1.144	3.01	.19	.0138	.02	496.81	496.8
25.9	1.5	.222	5.82	.33	.0065	.08	496.97	496.97
25.9	3.1	.2	7.76	.43	.009	.11	497.08	497.08
25.9	4.4	.218	9.52	.51	.0112	.11	497.18	497.18
25.9	5.5	.179	10.38	.55	.009	.12	497.22	497.22
25.9	12	.149	13.88	.71	.0118	.18	497.41	497.41
25.9	28.5	.052	16.11	.81	.005	.34	497.53	497.53
51.9	.009	.05	.11	.03	.0006	.08	496.65	496.65
51.9	.11	.123	.99	.1	.0018	.06	496.8	496.8
51.9	.15	.18	1.8	.16	.0012	.04	496.88	496.88
51.9	1.5	.067	3.91	.28	.0016	.13	497.05	497.05
51.9	3.1	.06	5.8	.35	.0019	.16	497.17	497.17
51.9	4.4	.06	7.48	.43	.0018	.16	497.27	497.27
51.9	5.5	.06	8.36	.47	.002	.17	497.32	497.32
51.9	12	.02	10.6	.56	.0005	.27	497.44	497.44
51.9	28.5	.035	14.17	.7	.0036	.42	497.63	497.63
60.8	.009	.389	.12	.05	.0157	.05	497.1	497.1
60.8	.11	.303	.89	.08	.02	.08	497.22	497.22
60.8	.15	.5	1.54	.1	.0219	.05	497.27	497.27
60.8	1.5	.2	3.82	.22	.0212	.15	497.41	497.41
60.8	3.1	.101	4.37	.24	.0155	.25	--	497.44
60.8	4.4	.093	5.35	.29	.0137	.27	497.5	497.5
60.8	5.5	.12	6.95	.37	.0156	.23	497.58	497.58
60.8	12	.089	9.3	.47	.0164	.33	497.7	497.7
60.8	28.5	.044	11.93	.58	.0103	.55	497.83	497.83
68.7	.009	1.2	.37	.06	.0145	.02	497.26	497.26
68.7	.11	.624	1.83	.12	.0113	.03	497.39	497.39
68.7	.15	1.374	2.81	.17	.0267	.02	497.45	497.45
68.7	1.5	.244	4.17	.23	.0248	.13	497.53	497.53
68.7	3.1	.084	5.46	.29	.0054	.19	497.6	497.6

Table 1-3. HEC-RAS model calibration to measured streamflows and water-surface altitudes at Danforth Brook near Hudson, Massachusetts.—Continued

[ft, foot; ft/ft, foot per foot; ft^2, square foot; ft^3/s, cubic foot per second; --, not applicable]

River station	Discharge (ft^3/s)	Manning's coefficient	Flow area (ft^2)	Hydraulic radius (ft)	Slope (ft/ft)	Froude number	Observed water altitude (ft)	Calculated water-surface altitude (ft)
68.7	4.4	0.132	6.98	0.35	0.0127	0.19	497.68	497.68
68.7	5.5	.173	9.05	.43	.0153	.16	497.78	497.78
68.7	12	.104	10.61	.5	.0158	.28	497.85	497.85
68.7	28.5	.055	13.56	.61	.0117	.47	497.99	497.99
81.6	.009	1.8	.77	.08	.0053	.01	497.36	497.36
81.6	.11	.301	1.87	.13	.0021	.03	497.45	497.45
81.6	.15	.345	2.78	.17	.0017	.02	497.51	497.51
81.6	1.5	.08	4.39	.22	.0025	.13	497.6	497.6
81.6	3.1	.095	5.89	.28	.0063	.18	497.68	497.68
81.6	4.4	.093	8.01	.35	.0048	.16	497.77	497.77
81.6	5.5	.079	9.8	.42	.0028	.15	497.85	497.85
81.6	12	.05	11.68	.49	.003	.26	497.93	497.93
81.6	28.5	.042	15.6	.64	.0048	.4	498.1	498.1

Fort Meadow Brook near Hudson, Massachusetts

Five measurements of water surfaces were taken at each of five surveyed cross sections for the purpose of model calibration. The calibration discharges were modeled at normal (subcritical) depth for the most downstream section and a slope of 0.007 ft/ft was set as a downstream boundary condition. This slope was calculated from water-surface altitudes at surveyed reference points at the most downstream end of the reach. Bankfull discharge was estimated by comparison with the altitudes of observed bankfull indicators surveyed at the study site.

Initial roughness coefficients for each cross section were estimated by solution of Manning's equation on the basis of the measured discharges and surveyed cross-sectional areas and slopes. The roughness coefficients for each cross section were varied as required until calculated water-surface altitudes matched measured water-surface altitudes with reasonable accuracy. The variability in the roughness coefficients between river stations (table 1-4) is due to the variability of the actual flow length as opposed to the straight-line lengths between river stations. The longer path the water takes in flowing around the bed material at different discharges changes the energy slope in the analysis and is compensated for by increasing the roughness coefficient to obtain acceptable model calibration. The calibration accuracy was 0.010 ft over the entire reach for both measured discharges.

Elizabeth Brook near Stow, Massachusetts

Seven measurements of water surfaces were taken at each of six surveyed cross sections for the purpose of model calibration. The calibration discharges were modeled at normal (subcritical) depth for the most downstream section and a slope of 0.0197 ft/ft was set as a downstream boundary condition. This slope was calculated from water-surface altitudes at surveyed reference points at the most downstream end of the reach. Bankfull discharge was estimated by comparison with the altitudes of observed bankfull indicators surveyed at the study site.

Initial roughness coefficients for each cross section were estimated by solution of Manning's equation on the basis of the measured discharges and surveyed cross-sectional areas and slopes. The roughness coefficients for each cross section were varied as required until calculated water-surface altitudes matched measured water-surface altitudes with reasonable accuracy. The variability in the roughness coefficients between river stations (table 1-5) is due to the variability of the actual flow length as opposed to the straight-line lengths between river stations. The longer path the water takes in flowing around the bed material at different discharges changes the energy slope in the analysis and is compensated for by increasing the roughness coefficient to obtain acceptable model calibration. The calibration accuracy was 0.019 ft over the entire reach for both measured discharges.

Table 1-4. HEC-RAS model calibration to measured streamflows and water-surface altitudes at Fort Meadow Brook near Hudson, Massachusetts.

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

River station	Discharge (ft^3/s)	Manning's coefficient	Flow area (ft^2)	Hydraulic radius (ft)	Slope (ft/ft)	Froude number	Observed water altitude (ft)	Calculated water-surface altitude (ft)
100	1.167	0.092	2.82	0.17	0.0071	0.18	497.87	497.87
100	1.485	.079	2.98	.18	.007	.21	497.88	497.88
100	1.665	.124	4.19	.25	.007	.14	497.95	497.95
100	3.531	.105	5.99	.35	.007	.17	498.06	498.06
100	6.773	.1	8.65	.49	.007	.19	498.22	498.22
114.9	1.167	.194	3.7	.27	.0099	.11	497.98	497.98
114.9	1.485	.125	3.85	.28	.0059	.13	497.99	497.99
114.9	1.665	.142	4.51	.31	.0059	.12	498.06	498.03
114.9	3.531	.14	7.09	.44	.0065	.13	498.21	498.21
114.9	6.773	.13	10.48	.63	.0059	.14	498.42	498.42
124.4	1.167	.18	2.15	.18	.0426	.23	498.08	498.07
124.4	1.485	.152	2.44	.18	.0376	.25	498.09	498.09
124.4	1.665	.15	2.82	.18	.0351	.25	498.12	498.12
124.4	3.531	.069	4.85	.28	.0063	.24	498.24	498.24
124.4	6.773	.012	8.11	.45	.0001	.22	498.41	498.42
133.7	1.167	.181	2.36	.16	.0402	.21	498.39	498.39
133.7	1.485	.131	2.52	.17	.0294	.25	498.4	498.4
133.7	1.665	.118	2.72	.17	.0261	.26	498.41	498.41
133.7	3.531	.074	4.48	.24	.0103	.28	498.51	498.51
133.7	6.773	.05	6.88	.36	.0043	.29	498.64	498.64
150.9	1.167	.174	3.54	.21	.0122	.13	498.52	498.51
150.9	1.485	.18	3.85	.22	.0166	.14	498.54	498.53
150.9	1.665	.18	4.56	.24	.0128	.13	498.58	498.57
150.9	3.531	.17	7.47	.31	.0138	.15	498.71	498.71
150.9	6.773	.09	10.42	.41	.005	.17	498.83	498.83

Table 1-5. HEC-RAS model calibration to measured streamflows and water-surface altitudes at Elizabeth Brook near Stow, Massachusetts.

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

River station	Discharge (ft^3/s)	Manning's coefficient	Flow area (ft^2)	Hydraulic radius (ft)	Slope (ft/ft)	Froude number	Observed water altitude (ft)	Calculated water-surface altitude (ft)
174.35	1.8	0.196	4.76	0.21	0.0197	0.14	497.03	497.03
174.35	4.1	.127	6.15	.26	.0197	.23	497.09	497.09
174.35	9	.092	8.19	.34	.0197	.33	497.18	497.18
174.35	15.3	.07	9.55	.39	.0197	.45	497.24	497.24
174.35	31	.06	13.51	.54	.0197	.55	497.4	497.4
174.35	40.4	.083	19.46	.73	.0197	.43	497.63	497.63
174.35	50.1	.088	25.29	.69	.0197	.42	497.82	497.78
185.68	1.8	.074	3.66	.19	.0056	.2	497.2	497.14
185.68	4.1	.074	5.53	.26	.0082	.25	497.23	497.23
185.68	9	.085	8.48	.37	.0141	.31	497.38	497.37
185.68	15.3	.084	11.73	.4	.0183	.36	497.47	497.47
185.68	31	.048	15.27	.49	.0111	.51	497.58	497.58
185.68	40.4	.055	21.54	.67	.0081	.4	497.79	497.78
185.68	50.1	.038	24.13	.74	.0041	.42	497.85	497.86
202.05	1.8	.07	2.64	.15	.0131	.31	497.34	497.33
202.05	4.1	.067	4.55	.22	.0123	.34	497.42	497.43
202.05	9	.044	6.63	.3	.008	.43	497.53	497.53
202.05	15.3	.053	9.12	.39	.0126	.47	497.67	497.64
202.05	31	.028	12	.4	.0082	.72	497.71	497.72
202.05	40.4	.039	20.48	.64	.0049	.43	498.05	497.99
202.05	50.1	.04	22.3	.69	.0059	.47	498.01	498.05
213.57	1.8	.1	4.16	.17	.0092	.19	497.51	497.47
213.57	4.1	.088	5.9	.23	.012	.25	497.55	497.54
213.57	9	.059	9.03	.34	.0066	.3	497.65	497.66
213.57	15.3	.073	12.51	.47	.0098	.31	497.8	497.8

Table 1-5. HEC-RAS model calibration to measured streamflows and water-surface altitudes at Elizabeth Brook near Stow, Massachusetts.—Continued

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

River station	Discharge (ft^3/s)	Manning's coefficient	Flow area (ft^2)	Hydraulic radius (ft)	Slope (ft/ft)	Froude number	Observed water altitude (ft)	Calculated water-surface altitude (ft)
213.57	31	0.1	17.51	0.64	0.0258	0.39	497.98	497.98
213.57	40.4	.088	23.28	.83	.0134	.33	498.23	498.2
213.57	50.1	.06	24.62	.87	.008	.38	498.21	498.24
229.45	1.8	.07	2.18	.16	.0172	.36	497.67	497.66
229.45	4.1	.057	3.84	.19	.0156	.44	497.75	497.75
229.45	9	.052	5.37	.23	.0239	.61	497.82	497.82
229.45	15.3	.058	9	.37	.0163	.49	497.98	497.98
229.45	31	.048	14.71	.57	.0098	.49	498.21	498.21
229.45	40.4	.055	18.74	.69	.0103	.45	498.36	498.36
229.45	50.1	.055	19.25	.71	.0146	.54	498.38	498.38
241.46	1.8	.057	2.61	.13	.0108	.34	497.69	497.83
241.46	4.1	.135	6.63	.26	.0186	.21	498	498
241.46	9	.13	9.62	.37	.025	.27	498.13	498.12
241.46	15.3	.095	12.98	.49	.0147	.3	498.25	498.25
241.46	31	.062	17.6	.64	.0099	.39	498.42	498.42
241.46	40.4	.081	22.94	.79	.0123	.35	498.62	498.62
241.46	50.1	.09	24.59	.83	.0191	.39	498.67	498.67

Nashoba Brook at West Concord, Massachusetts

Nine measurements of water surfaces were taken at each of four surveyed cross sections for the purpose of model calibration. The calibration discharges were modeled at normal (subcritical) depth for the most downstream section and a slope of 0.0143 ft/ft was set as a downstream boundary condition. This slope was calculated from water-surface altitudes at surveyed reference points at the most downstream end of the reach. Bankfull discharge was estimated by comparison with the altitudes of observed bankfull indicators surveyed at the study site.

Initial roughness coefficients for each cross section were estimated by solution of Manning's equation on the basis of the measured discharges and surveyed cross-sectional areas and slopes. The roughness coefficients for each cross section were varied as required until calculated water-surface altitudes matched measured water-surface altitudes with reasonable accuracy. The variability in the roughness coefficients between river stations (table 1-6) is due to the variability of the actual flow length as opposed to the straight-line lengths between river stations. The longer path the water takes in flowing around the bed material at different discharges changes the energy slope in the analysis and is compensated for by increasing the roughness coefficient to obtain acceptable model calibration. The calibration accuracy was 0.008 ft over the entire reach for both measured discharges.

Table 1-6. HEC-RAS model calibration to measured streamflows and water-surface altitudes at Nashoba Brook at West Concord, Massachusetts.

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

River station	Discharge (ft^3/s)	Manning's coefficient	Flow area (ft^2)	Hydraulic radius (ft)	Slope (ft/ft)	Froude number	Observed water altitude (ft)	Calculated water-surface altitude (ft)
100	1	0.26	8.65	0.39	0.0014	0.03	496.57	496.57
100	2.5	.172	11.95	.51	.0014	.05	496.72	496.72
100	6.7	.101	16.22	.64	.0014	.09	496.9	496.9
100	7.3	.1	16.98	.67	.0014	.09	496.93	496.93
100	13.9	.083	22.71	.86	.0014	.11	497.15	497.15
100	20.6	.073	26.9	1	.0014	.13	497.32	497.32
100	27.3	.064	29.54	1.08	.0014	.15	497.42	497.42
100	30	.067	32.21	1.13	.0014	.15	497.52	497.52
100	74.9	.049	47.43	1.54	.0014	.22	498.07	498.07
120.3	1	.16	2.32	.16	.025	.19	497	497
120.3	2.5	.15	4.25	.2	.0313	.23	497.1	497.1
120.3	6.7	.058	5.49	.25	.0145	.43	497.16	497.16
120.3	7.3	.084	6.72	.3	.019	.35	497.21	497.21
120.3	13.9	.045	8.72	.38	.0084	.45	497.3	497.3
120.3	20.6	.037	11.26	.49	.0053	.46	497.42	497.42
120.3	27.3	.033	13.38	.57	.0043	.47	497.51	497.51
120.3	30	.023	14.49	.62	.002	.46	497.56	497.56
120.3	74.9	.032	27.98	1.05	.0031	.45	498.13	498.13
142.5	1	.17	3.28	.17	.0129	.13	497.27	497.27
142.5	2.5	.05	4.27	.2	.0033	.23	497.32	497.32
142.5	6.7	.04	6.78	.29	.0037	.32	497.43	497.43
142.5	7.3	.04	7.61	.32	.003	.3	497.44	497.46
142.5	13.9	.04	9.85	.41	.0047	.38	497.57	497.56
142.5	20.6	.05	12.61	.52	.0072	.4	497.67	497.68
142.5	27.3	.05	14.57	.59	.008	.42	497.76	497.76
142.5	30	.045	14.73	.6	.0074	.46	497.76	497.77
142.5	74.9	.02	25.65	.97	.0016	.51	498.18	498.2
164.5	1	.045	2.57	.14	.0018	.18	497.35	497.35
164.5	2.5	.056	3.69	.2	.0056	.26	497.43	497.41
164.5	6.7	.065	6.29	.32	.0097	.32	497.55	497.55
164.5	7.3	.065	6.66	.34	.0097	.33	497.58	497.57
164.5	13.9	.055	9.2	.44	.0093	.39	497.7	497.7
164.5	20.6	.045	11.75	.54	.0064	.41	497.82	497.82
164.5	27.3	.04	13.49	.6	.006	.45	497.91	497.9
164.5	30	.04	13.61	.6	.0069	.49	497.92	497.91
164.5	74.9	.141	22.68	.86	.1176	.61	498.32	498.29

Charles River near Hopkinton, Massachusetts

Three measurements of water surfaces were taken at each of seven surveyed cross sections for the purpose of model calibration. The calibration discharges were modeled at normal (subcritical) depth for the most downstream section and a slope of 0.002 ft/ft was set as a downstream boundary condition. This slope was calculated from water-surface altitudes at surveyed reference points at the most downstream end of the reach. Bankfull discharge was estimated by comparison with the altitudes of observed bankfull indicators surveyed at the study site.

Initial roughness coefficients for each cross section were estimated by solution of Manning's equation on the basis of the measured discharges and surveyed cross-sectional areas and slopes. The roughness coefficients for each cross section were varied as required until calculated water-surface altitudes matched measured water-surface altitudes with reasonable accuracy. The variability in the roughness coefficients between river stations (table 1-7) is due to the variability of the actual flow length as opposed to the straight-line lengths between river stations. The longer path the water takes in flowing around the bed material at different discharges changes the energy slope in the analysis and is compensated for by increasing the roughness coefficient to obtain acceptable model calibration. The calibration accuracy was 0.006 ft over the entire reach for both measured discharges.

Mine Brook near Franklin, Massachusetts

Five measurements of water surfaces were taken at each of seven surveyed cross sections for the purpose of model calibration. The calibration discharges were modeled at normal (subcritical) depth for the most downstream section and a slope of 0.019 ft/ft was set as a downstream boundary condition. This slope was calculated from water-surface altitudes at surveyed reference points at the most downstream end of the reach. Bankfull discharge was estimated by comparison with the altitudes of observed bankfull indicators surveyed at the study site.

Initial roughness coefficients for each cross section were estimated by solution of Manning's equation on the basis of the measured discharges and surveyed cross-sectional areas and slopes. The roughness coefficients for each cross section were varied as required until calculated water-surface altitudes matched measured water-surface altitudes with reasonable accuracy. The variability in the roughness coefficients between river stations (table 1-8) is due to the variability of the actual flow length as opposed to the straight-line lengths between river stations. The longer path the water takes in flowing around the bed material at different discharges changes the energy slope in the analysis and is compensated for by increasing the roughness coefficient to obtain acceptable model calibration. The calibration accuracy was 0.014 ft over the entire reach for both measured discharges.

Charles River at Medway, Massachusetts

Nine measurements of water surfaces were taken at each of nine surveyed cross sections the study reach for the purpose of model calibration. The calibration discharges were modeled at normal (subcritical) depth for the most downstream section. The downstream boundary was set to known elevations determined from the stage discharge relation for streamgaging station at Charles River at Medway (01103200) for the discharges that corresponded to when water surface measurements were made at the riffle sections. Bankfull discharge was estimated by comparison with the altitudes of observed bankfull indicators surveyed at the study site.

Initial roughness coefficients for each cross section were estimated by solution of Manning's equation on the basis of the measured discharges and surveyed cross-sectional areas and slopes. The roughness coefficients for each cross section were varied as required until calculated water-surface altitudes matched measured water-surface altitudes with reasonable accuracy. The variability in the roughness coefficients between river stations (table 1-9) is due to the variability of the actual flow length as opposed to the straight-line lengths between river stations. The longer path the water takes in flowing around the bed material at different discharges changes the energy slope in the analysis and is compensated for by increasing the roughness coefficient to obtain acceptable model calibration. The calibration accuracy was 0.097 ft over the entire reach for both measured discharges.

Table 1-7. HEC-RAS model calibration to measured streamflows and water-surface altitudes at Charles River near Hopkinton, Massachusetts.

[ft, foot; ft/ft, foot per foot; ft^2, square foot; ft^3/s, cubic foot per second; --, not applicable]

River station	Discharge (ft^3/s)	Manning's coefficient	Flow area (ft^2)	Hydraulic radius (ft)	Slope (ft/ft)	Froude number	Observed water altitude (ft)	Calculated water-surface altitude (ft)
93.91	0.028	0.599	0.74	0.2	0.002	0.01	498.1	498.1
93.91	2.551	.03	2.28	.35	.002	.32	498.44	498.44
93.91	8.408	.053	7.31	.74	.002	.22	499.12	499.12
101.39	.028	.8	.35	.11	.0325	.04	--	498.2
101.39	2.551	.07	2.37	.33	.0101	.33	498.58	498.58
101.39	8.408	.035	7.64	.63	.001	.24	499.13	499.13
133.22	.028	.355	.65	.22	.0008	.02	498.27	498.27
133.22	2.551	.015	2.31	.33	.0005	.33	498.62	498.62
133.22	8.408	.032	6.41	.69	.0011	.27	499.16	499.16
144.91	.028	1.2	.55	.12	.0286	.03	--	498.38
144.91	2.551	.035	2.1	.32	.0034	.37	498.66	498.66
144.91	8.408	.035	5.75	.65	.0017	.31	499.17	499.17
157.84	.028	2.478	.87	.17	.0318	.01	498.92	498.92
157.84	2.551	.15	2.01	.33	.0661	.38	499.14	499.14
157.84	8.408	.16	6.17	.54	.0423	.32	499.56	499.56
166.01	.028	3	.85	.17	.0471	.01	499.39	499.37
166.01	2.551	.2	2.86	.26	.0626	.3	499.65	499.65
166.01	8.408	.24	7.75	.52	.0623	.26	500.03	500.04
184.11	.028	3	1.37	.32	.0063	.01	499.62	499.61
184.11	2.551	.169	3.91	.46	.0105	.16	500.04	500.04
184.11	8.408	.062	5.73	.58	.0056	.33	500.26	500.26

Table 1-8. HEC-RAS model calibration to measured streamflows and water-surface altitudes at Mine Brook near Franklin, Massachusetts.

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

River station	Discharge (ft^3/s)	Manning's coefficient	Flow area (ft^2)	Hydraulic radius (ft)	Slope (ft/ft)	Froude number	Observed water altitude (ft)	Calculated water-surface altitude (ft)
100	2.03	0.16	4.14	0.24	0.019	0.17	495.89	495.89
100	2.3	.197	5.16	.28	.019	.15	495.95	495.95
100	4	.175	6.88	.35	.019	.17	496.04	496.04
100	17.2	.123	14.34	.61	.019	.26	496.42	496.4
100	70	.113	33.18	1.13	.019	.34	497.19	497.19
112.91	2.03	.068	3.57	.21	.0053	.22	496	496
112.91	2.3	.078	4.45	.25	.0047	.18	496.05	496.05
112.91	4	.042	5.4	.28	.0024	.25	496.1	496.1
112.91	17.2	.028	12.6	.55	.0015	.32	496.44	496.44
112.91	70	.025	32.17	1.06	.001	.37	497.22	497.22
123.6	2.03	.087	3.75	.26	.0061	.19	496.16	496.17
123.6	2.3	.078	4.05	.28	.005	.19	496.14	496.19
123.6	4	.06	4.73	.31	.0055	.26	496.23	496.23
123.6	17.2	.11	12.67	.7	.0164	.28	496.71	496.71
123.6	70	.055	24.49	1.03	.0087	.48	497.34	497.34
143.62	2.03	.052	3.71	.28	.002	.18	496.23	496.23
143.62	2.3	.079	4.29	.31	.0039	.17	496.28	496.28
143.62	4	.036	4.55	.33	.002	.27	496.29	496.3
143.62	17.2	.032	11.98	.72	.0015	.29	496.78	496.78
143.62	70	.03	23.05	1.2	.0029	.48	497.42	497.42
164.85	2.03	.07	3.29	.28	.0047	.2	496.3	496.3
164.85	2.3	.041	3.64	.3	.0015	.2	496.32	496.33
164.85	4	.055	4.09	.32	.006	.3	496.36	496.36
164.85	17.2	.019	10.08	.66	.0008	.36	496.75	496.79
164.85	70	.09	21.31	1.21	.0289	.5	497.55	497.55
173.65	2.03	.09	2.15	.21	.027	.36	496.45	496.45
173.65	2.3	.103	2.46	.21	.0324	.35	496.48	496.48
173.65	4	.053	3.02	.23	.0163	.49	496.49	496.53
173.65	17.2	.1	10.63	.66	.0207	.34	497.04	497.04
173.65	70	.11	23.6	1.22	.033	.45	497.86	497.85
187.25	2.03	.129	3.59	.21	.0199	.22	496.97	496.96
187.25	2.3	.265	5.23	.28	.0338	.15	497.05	497.05
187.25	4	.142	5.77	.31	.0212	.22	497.08	497.08
187.25	17.2	.101	11.93	.59	.0191	.33	497.41	497.41
187.25	70	.1	21.89	.99	.0455	.55	497.9	497.9

Table 1-9. HEC-RAS model calibration to measured streamflows and water-surface altitudes at Charles River at Medway, Massachusetts.

[ft, foot; ft/ft, foot per foot; ft^2, square foot; ft^3/s, cubic foot per second; --, not applicable]

River station	Discharge (ft^3/s)	Manning's coefficient	Flow area (ft^2)	Hydraulic radius (ft)	Slope (ft/ft)	Froude number	Observed water altitude (ft)	Calculated water-surface altitude (ft)
100	8.2	0.035	14.35	0.32	0.0008	0.18	--	787.99
100	10.5	.035	16.63	.35	.0009	.19	--	788.04
100	12.6	.035	18.92	.35	.001	.2	--	788.09
100	14.2	.035	20.27	.37	.001	.2	--	788.11
100	19.1	.035	23.53	.43	.0011	.22	--	788.17
100	32.6	.035	28.86	.52	.0017	.27	--	788.27
100	44	.035	33.44	.6	.0019	.3	--	788.35
100	49.7	.035	37.43	.67	.0017	.28	--	788.43
100	76.2	.035	43.72	.77	.0024	.35	--	788.54
374.2	8.2	.035	12.73	.47	.0006	.17	--	788.19
374.2	10.5	.035	14.61	.51	.0007	.18	--	788.26
374.2	12.6	.033	16.2	.52	.0007	.19	--	788.31
374.2	14.2	.032	17.09	.53	.0007	.2	--	788.34
374.2	19.1	.028	19.56	.59	.0007	.22	--	788.42
374.2	32.6	.022	23.85	.68	.0007	.29	--	788.54
374.2	44	.021	27.72	.75	.0007	.32	--	788.65
374.2	49.7	.021	30.05	.79	.0008	.33	788.68	788.71
374.2	76.2	.023	38.61	.96	.001	.35	--	788.93
580.9	8.2	.035	27.65	.44	.0001	.08	788.27	788.25
580.9	1.5	.032	31.79	.48	.0001	.08	788.31	788.32
580.9	12.6	.03	35.15	.51	.0001	.09	788.31	788.37
580.9	14.2	.028	37.03	.53	.0001	.09	--	788.4
580.9	19.1	.024	42.51	.58	.0001	.1	788.39	788.47
580.9	32.6	.025	54.2	.67	.0002	.13	788.56	788.63
580.9	44	.036	68.82	.68	.0004	.14	788.71	788.8
580.9	49.7	.042	76.6	.75	.0005	.13	788.76	788.87
580.9	76.2	.063	107.41	1.04	.0009	.12	789.24	789.18
641.1	8.2	.5	5.71	.33	1.0067	.43	788.49	788.27
641.1	10.5	.5	6.74	.37	1.0197	.44	788.47	788.33
641.1	12.6	.5	7.54	.4	1.0773	.46	788.47	788.37
641.1	14.2	.5	7.98	.41	1.195	.49	788.41	788.39
641.1	19.1	.5	9.47	.37	1.7431	.58	788.62	788.46
641.1	32.6	.5	15.01	.36	2.0714	.63	788.77	788.63
641.1	44	.482	27.58	.46	.761	.41	788.93	788.87
641.1	49.7	.39	33.42	.53	.3534	.36	--	788.96
641.1	76.2	.088	54.49	.81	.0091	.27	789.28	789.29
691.6	8.2	.047	12.23	.22	.0033	.25	788.84	788.9
691.6	10.5	.048	14.55	.26	.0032	.25	788.92	788.94
691.6	12.6	.049	16.64	.3	.0031	.24	788.94	788.98
691.6	14.2	.05	18.1	.32	.0031	.24	788.92	789
691.6	19.1	.043	20.48	.36	.0028	.27	789	789.05

Table 1-9. HEC-RAS model calibration to measured streamflows and water-surface altitudes at Charles River at Medway, Massachusetts.—Continued

[ft, foot; ft/ft, foot per foot; ft^2, square foot; ft^3/s, cubic foot per second; --, not applicable]

River station	Discharge (ft^3/s)	Manning's coefficient	Flow area (ft^2)	Hydraulic radius (ft)	Slope (ft/ft)	Froude number	Observed water altitude (ft)	Calculated water-surface altitude (ft)
691.6	32.6	0.032	24.84	0.44	0.0024	0.35	789.12	789.12
691.6	44	.024	27.8	.48	.0017	.4	789.2	789.18
691.6	49.7	.02	29.25	.51	.0013	.42	--	789.2
691.6	76.2	.034	45.14	.76	.0021	.34	789.21	789.47
1284	8.2	.06	22.65	.52	.0005	.09	--	789.52
1284	10.5	.06	25.92	.58	.0005	.09	--	789.59
1284	12.6	.06	28.56	.63	.0006	.1	--	789.65
1284	14.2	.06	30.62	.66	.0006	.1	--	789.7
1284	19.1	.06	35.86	.72	.0007	.11	--	789.81
1284	32.6	.06	45.95	.87	.001	.13	--	790
1284	44	.06	50.48	.94	.0013	.16	--	790.09
1284	49.7	.06	51	.95	.0017	.18	--	790.1
1284	76.2	.06	72.16	1.26	.0013	.17	790.48	790.48
1466.3	8.2	.04	3.81	.17	.0345	.91	790.26	790.11
1466.3	10.5	.04	4.21	.19	.0412	1.01	790.33	790.13
1466.3	12.6	.04	4.77	.21	.0401	1.01	790.4	790.15
1466.3	14.2	.04	5.23	.23	.0384	1	790.35	790.17
1466.3	19.1	.04	6.45	.27	.0367	1.01	--	790.23
1466.3	32.6	.07	14.72	.4	.0367	.61	790.61	790.49
1466.3	44	.07	21.63	.55	.0204	.48	--	790.67
1466.3	49.7	.07	25.27	.62	.0164	.44	--	790.76
1466.3	76.2	.07	35.84	.8	.0136	.42	791.05	791.01
1481.8	8.2	.07	7.83	.26	.0148	.36	790.5	790.5
1481.8	10.5	.064	9.08	.29	.013	.38	790.54	790.54
1481.8	12.6	.06	9.96	.31	.0126	.4	790.7	790.57
1481.8	14.2	.057	10.62	.32	.0121	.42	790.56	790.59
1481.8	19.1	.051	12.23	.35	.0117	.46	--	790.63
1481.8	32.6	.043	17.15	.45	.0091	.5	790.73	790.77
1481.8	44	.044	21.27	.52	.0089	.5	--	790.87
1481.8	49.7	.044	23.83	.57	.0083	.49	--	790.93
1481.8	76.2	.046	33.26	.73	.0076	.47	791.19	791.15
1498.9	8.2	.11	10.81	.31	.0149	.24	790.76	790.76
1498.9	10.5	.09	11.4	.32	.014	.28	790.76	790.78
1498.9	12.6	.075	11.83	.33	.0127	.32	790.84	790.79
1498.9	14.2	.067	12.1	.34	.0118	.35	790.8	790.8
1498.9	19.1	.059	13.8	.37	.0115	.4	--	790.84
1498.9	32.6	.053	17.8	.45	.0126	.48	790.97	790.95
1498.9	44	.055	22.43	.52	.0126	.48	--	791.06
1498.9	49.7	.059	24.7	.55	.014	.47	--	791.11
1498.9	76.2	.065	35.15	.67	.0145	.46	791.38	791.33