Characteristics and Classification of Least Altered Streamflows in Massachusetts

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Abstract

Streamflow records from 85 streamflow-gaging stations at which streamflows were considered to be least altered were used to characterize natural streamflows within southern New England. Period-of-record streamflow data were used to determine annual hydrographs of median monthly flows. The shapes and magnitudes of annual hydrographs of median monthly flows, normalized by drainage area, differed among stations in different geographic areas of southern New England. These differences were gradational across southern New England and were attributed to differences in basin and climate characteristics. Period-of-record streamflow data were also used to analyze the statistical properties of daily streamflows at 61 stations across southern New England by using L-moment ratios. An L-moment ratio diagram of L-skewness and L-kurtosis showed a continuous gradation in these properties between stations and indicated differences between base-flow-dominated and runoff-dominated rivers.

Streamflow records from a concurrent period (1960–2004) for 61 stations were used in a multivariate statistical analysis to develop a hydrologic classification of rivers in southern New England. Missing records from 46 of these stations were extended by using a Maintenance of Variation Extension technique. The concurrent-period streamflows were used in the Indicators of Hydrologic Alteration and Hydrologic Index Tool programs to determine 224 hydrologic indices for the 61 stations. Principal-components analysis (PCA) was used to reduce the number of hydrologic indices to 20 that provided nonredundant information. The PCA also indicated that the major patterns of variability in the dataset are related to differences in flow variability and low-flow magnitude among the stations.

Hierarchical cluster analysis was used to classify stations into groups with similar hydrologic properties. The cluster analysis classified rivers in southern New England into two broad groups: (1) base-flow-dominated rivers, whose statistical properties indicated less flow variability and high magnitudes of low flow, and (2) runoff-dominated rivers, whose statistical properties indicated greater flow variability and lower magnitudes of low flow. A four-cluster classification further classified the runoff-dominated streams into three groups that varied in gradient, elevation, and differences in winter streamflow conditions: high-gradient runoff-dominated rivers, northern runoff-dominated rivers, and southern runoff-dominated rivers. A nine-cluster division indicated that basin size also becomes a distinguishing factor among basins at finer levels of classification. Smaller basins (less than 10 square miles) were classified into different groups than larger basins.

A comparison of station classifications indicated that a classification based on multiple hydrologic indices that represent different aspects of the flow regime did not result in the same classification of stations as a classification based on a single type of statistic such as a monthly median. River basins identified by the cluster analysis as having similar hydrologic properties tended to have similar basin and climate characteristics and to be in close proximity to one another. Stations were not classified in the same cluster on the basis of geographic location alone; as a result, boundaries cannot be drawn between geographic regions with similar streamflow characteristics. Rivers with different basin and climate characteristics were classified in different clusters, even if they were in adjacent basins or upstream and downstream within the same basin.

Introduction

The Massachusetts Department of Conservation and Recreation (MDCR) is interested in identifying flows that maintain the seasonal and annual streamflow variability needed to maintain the physical, chemical, and biological integrity of rivers in Massachusetts. Information about natural streamflow regimes and streamflow variability would allow managers to make more informed decisions regarding activities that alter streamflows in Massachusetts. Streamflow alterations may be the result of direct manipulation of streamflow, such as by water withdrawals, interbasin transfers, wastewater returns, flow regulation by mills and hydropower generation, or the result of flow attenuation or releases from impoundments such as flood-control reservoirs, water-supply reservoirs, or impoundments used for recreation. Flow may also be altered by more indirect causes such as changes in land use and alterations to river networks. For example, increases in impervious surface area and building of storm drains can alter hydrologic processes that generate streamflow such as runoff, base flow, evapotranspiration, and recharge; and channel modifications such as the filling of wetlands or straightening of rivers can modify streamflows by altering channel-storage characteristics and downstream routing of flood peaks. Alterations to the landscape and to stream channels are common throughout southern New England because of the high population density and several centuries of settlement in the region. Consequently, few streamflow-gaging stations exist that have records that can be used to characterize natural streamflows.

The MDCR and the Massachusetts Water Resources Commission are beginning the process of developing a statewide streamflow policy for Massachusetts (L. Hutchins, Massachusetts Department of Conservation and Recreation, written commun., April 2006). A recent analysis of streamflows at 23 active index stations in southern New England (Armstrong and others, 2004) indicated regional differences in median monthly flows; these differences were attributed to climate characteristics during high-flow months (November through May) and basin characteristics during low-flow months (June through October). The MDCR was interested in expanding this analysis by using streamflow information from additional active and discontinued index stations in southern New England to characterize streamflows in Massachusetts and by using selected streamflow statistics (representing the magnitude, frequency, duration, timing, and rate of change of streamflow) to develop a hydrologic classification of rivers in Massachusetts. To facilitate the management of water resources, the MDCR was also interested in determining whether distinct geographic regions with similar streamflow characteristics could be identified.

Recognition of these needs by State agencies and others prompted this study by the U.S. Geological Survey (USGS), carried out from 2005 through 2007, in cooperation with the MDCR, the Massachusetts Department of Fish and Game Riverways Program (Riverways), and the Division of Fisheries and Wildlife (MDFW) to characterize and classify natural streamflows in Massachusetts. As the primary Federal agency responsible for scientific evaluation of the natural resources of the United States, including its water and biological resources, the USGS also has an interest in providing quantifiable, scientifically sound information about both water quantity and environmental water needs of ecosystems (Kempthorne and Myers, 2007). Results of the study will enable water-resource managers to make more informed decisions about managing streamflow and water withdrawals in Massachusetts while factoring ecosystem health and sustainability into the decision-making process. Results of the study will have transfer value to the surrounding states in southern New England and to other areas that have similar climatic and hydrogeologic conditions.

Purpose and Scope

This report uses ecologically relevant indices for least-altered gaged rivers to characterize and classify streamflow regimes in Massachusetts. Although rivers in Massachusetts are the primary focus of the study, the scope of the study was expanded to include streamflow-gaging stations in southern New England. The study also provides:

1. Annual hydrographs and tables of median monthly flow statistics, normalized by drainage area and prepared from streamflow records for the period of record (POR) for 85 streamflow-gaging stations in southern New England;
2. An assessment of the statistical properties of daily streamflows by using L-moment ratios, based on streamflow records from the POR for a subset of 61 streamflow-gaging stations;
3. Streamflow statistics determined by the Indicators of Hydrologic Alteration (IHA) program and the Hydrologic Index Tool (HIT) that describe the magnitude, frequency, magnitude and duration of annual extremes, timing of annual extremes, and rate of change of streamflow for 61 index stations, prepared from streamflow records that included some simulated flows for a concurrent period from 1960 through 2004;
4. Regression equations for calculating long-term median monthly streamflows from basin and climate characteristics;
5. A hydrologic classification of index stations in southern New England, developed on the basis of a multivariate statistical analysis of IHA and HIT hydrologic indices by using principal-components analysis (PCA) and cluster analysis (CLA); and
6. An evaluation of fish communities near selected stations in Massachusetts by using fish-community data from the MDFW.

Description of Study Area

The study area (fig. 1) in southern New England includes mainland Massachusetts and Rhode Island and portions of Connecticut, southern New Hampshire, southern Vermont, and eastern New York. The physiography, topography, and regional soil characteristics of the study area are closely tied to geology (Foster and Aber, 2004). The western and north-central portions of Massachusetts are the most hilly and mountainous areas in the state. The landscape to the west and north has the greatest topographic relief and includes the Taconic Highlands, the Vermont Valley, and the Berkshire Hills physiographic regions (Denny, 1982). High elevations and the presence of metamorphic carbonate rocks (dolomite and marble) are two of the distinguishing features of this area.

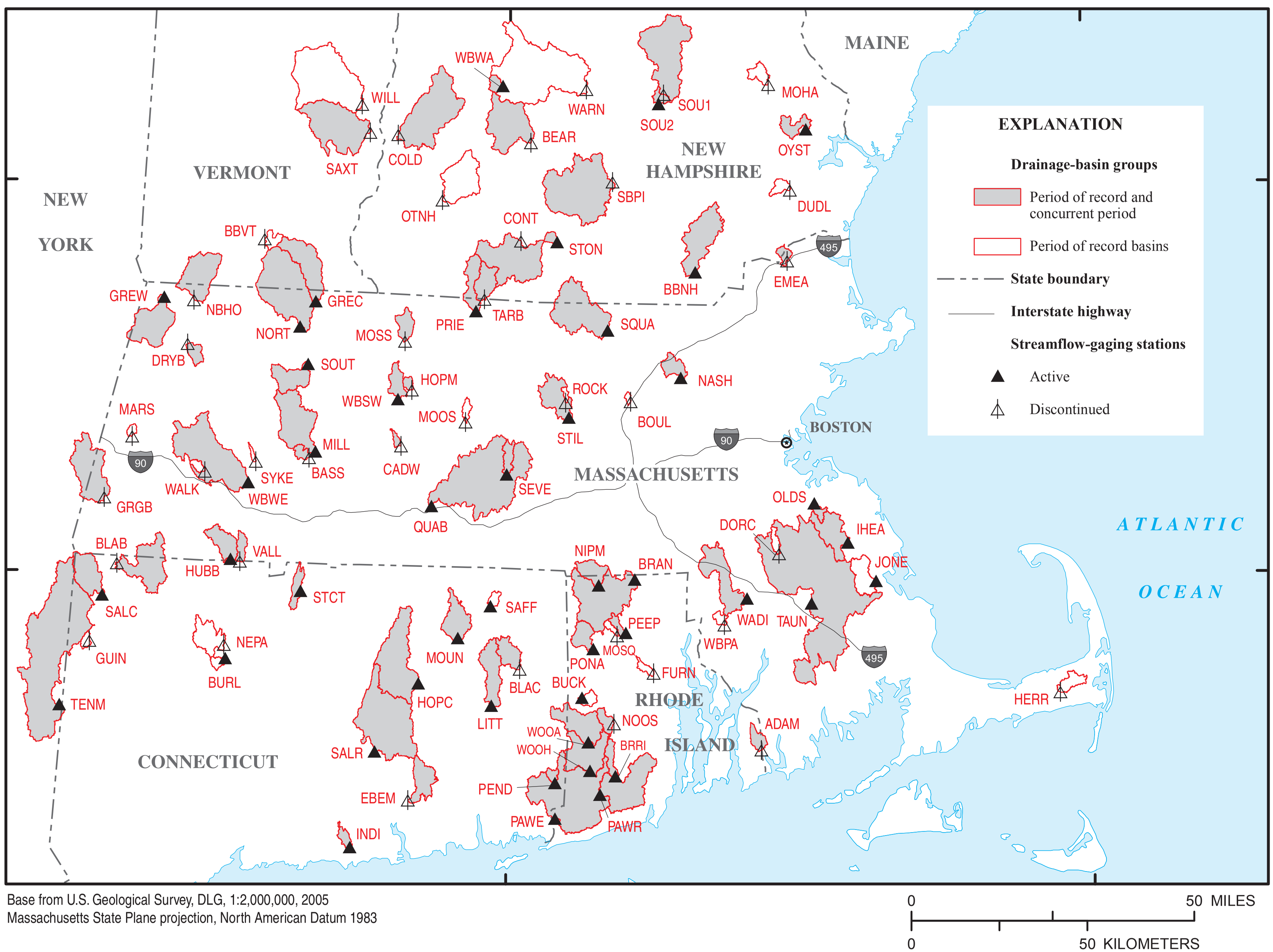


Figure 1. Streamflow-gaging stations used to characterize and classify streamflows in southern New England. Periods of record for all stations were used in the monthly flow-duration analysis; a concurrent period (1960–2004) was used for classification of stations. Station names are given in table 1.

This area is bordered to the east by the broad Connecticut Valley, which narrows northward from Connecticut across Massachusetts, and by the Central Highlands, a region of moderate relief composed of broad valleys, hills, and low mountains. The landscape in eastern and southern Massachusetts is characterized by rolling topography and broad lowlands. This area is distinguished by sand and gravel glacial deposits that are generally more extensive and thicker than those to the west.

Glaciation modified the topography and drainage patterns in southern New England and left most of the landscape covered with deposits of till and glaciofluvial sand and gravel (Randall, 2001). The distribution of these hydrologically different glacial deposits greatly influences the flow characteristics of streams and rivers. In many areas of southern New England, bedrock in upland areas is covered with glacial till, and river valleys and lowland areas contain glacial sand and gravel deposits. Till is a poorly sorted mixture of clay, silt, sand, gravel, and boulders, generally in a matrix of fine sand and silt, that was deposited directly by glaciers with little or no modification by meltwater (Sutphin and others, 2002; Stone and others, 2006). Till is thickest in drumlins and on the northwest slopes of bedrock hills (Stone and others, 2006). In some upland areas, till deposits are discontinuous, and depths to bedrock are shallow. The low hydraulic conductivity and low storage characteristics of till and bedrock, combined with greater topographic relief in upland areas, typically cause streams in till uplands to have relatively rapid runoff rates and low base flows. Fractured bedrock can also contribute small amounts of ground-water discharge to streams. Ground-water discharge from areas of fractured carbonate bedrock in western Massachusetts and northwest Connecticut can be higher than from areas of fractured crystalline igneous and metamorphic bedrock, such as found throughout most of southern New England. Most substantial ground-water discharge to streams and rivers in southern New England, however, is from coarse-grained sand and gravel aquifers. These aquifers are primarily glaciofluvial deposits. The thickness and hydraulic properties of these sand and gravel deposits differ locally. In a few coastal areas of southeastern Massachusetts and Rhode Island, the entire landscape is covered by sand and gravel outwash and glaciolacustrine deposits. In many river valleys throughout southern New England, the sand and gravel deposits are composed of morphosequences—bodies of stratified glaciofluvial deposits that can be graded over short distances (several miles) from coarse-grained ice-contact and glaciodeltaic sediments to coarse- and fine-grained glaciolacustrine deposits (Randall, 2001; Stone and others, 2006). The high hydraulic conductivity and storage of sand and gravel, combined with lower topographic relief, typically cause rivers in these areas to have higher base flows and slower runoff rates than those in upland till areas.

The climate of southern New England is temperate, with a wide range of diurnal, seasonal, and annual temperatures. Weather and climate conditions of inland portions of New England are influenced by conditions of the continental airmasses to the west as a result of the predominant flow direction of the mid-latitude westerlies (Zielinski and Keim, 2003). Weather and climate conditions near the coast are influenced by maritime airmasses, which influence precipitation and temper summer and winter temperature extremes. Because New England is within the fluctuating track of the jet stream, which affects the movement of polar and tropical air masses and their associated cold and warm fronts, day-to-day weather patterns in New England have a high degree of changeability (Zielinski and Keim, 2003; Dupigny-Giroux, 2003). In addition, shifts in circulation patterns caused by global climate-forcing factors such as the El Nino-Southern Oscillation and the North Atlantic Oscillation influence climate variability in winter (Bradbury and others, 2002) and result in climate conditions that recur roughly every 3 to 7 years and persist for a year or two (Zielinski and Keim, 2003). Because of these variations in weather and climate conditions over time, precipitation and streamflow can vary considerably in any given month or season and from year to year.

Average annual precipitation in the study area is evenly distributed throughout the year and ranges from about 40 to 50 in/yr (Gadoury and Wandle, 1986; Hammond and Cotton, 1986; Johnston, 1986; Weiss and Cervione, 1986). The year-to-year variability of annual total precipitation can range from about 10 in. between normal years to as much as 40 in. between extremely wet and dry years. For example, from 1960 through 2004, the median annual total precipitation for the National Oceanic and Atmospheric Administration (NOAA) National Weather Service station at the Worcester Municipal Airport was 46.5 in., but during 1965, an extremely dry year, annual precipitation was about 32 in.; and during 1983, an extremely wet year, annual precipitation was about 71 in. Average annual precipitation is distributed rather evenly across southern New England, although there are local differences of up to about 10 in/yr. Precipitation is highest in the high-elevation areas in western Massachusetts and southern Vermont (48 to 50 in.) and in southeastern Connecticut, Rhode Island, and southeastern Massachusetts (48 to 50 in.) (Randall, 1996). Precipitation is lowest in north-central Massachusetts and in southern New Hampshire (40 to 48 in.).

In southern New England rivers, seasonally high streamflows generally occur during spring in March or April, and seasonally low streamflows generally occur during late summer in August or September. Although prolonged droughts are infrequent in southern New England, low flows or seasonal droughts may occur during any season, not just during the summer period. Likewise, annual peaks in streamflow may occur in any season because of intense or successive rainstorms of long duration, snowmelt runoff, or, during late summer and fall, as a result of tropical storms and hurricanes.

Runoff measured as streamflow per unit area, a measure of flow that eliminates drainage area as a variable, is a useful measure for illustrating streamflow variability over a year. Typically, monthly runoff is lowest in July, August, and September because of the combined effects of evapotranspiration and depletion of ground-water storage. Runoff increases in October and November as evapotranspiration declines

(Gadoury and Wandle, 1986). In interior areas, runoff declines in the winter months because precipitation remains on the ground as snow and ice, and runoff is normally highest in April as a result of the melting snowpack and concurrent precipitation. In southern and coastal areas of southern New England, where winter rains are more common and the snowpack does not typically persist through the winter, runoff continues to increase through December, January, and February and tends to be highest in March. Runoff declines in May and June as evapotranspiration increases (Gadoury and Wandle, 1986).

Few, if any, areas in southern New England are without any human alterations; even areas classified as mostly forest have some roads, low-density housing, or remnants of historic alterations to the land and waterways. The mosaic of forested, urban, and agricultural land in southern New England reflects the history of settlement in the region. Coastal areas and river valleys were settled first, and the landscape was progressively cleared and broken up into small farms and closely spaced town centers (Zimmerman and others, 1996). Small dams and impoundments were built on many rivers in southern New England to power sawmills and gristmills. By the mid-1800s, more than half the land was cleared of forest (Foster and Aber, 2004). During the industrial revolution in the late 1800s, manufacturing industries that required water power became established along New England's major rivers. As the populations in these mill towns grew, upland farms were abandoned and began to revert back to woodland. Growth centered in large metropolitan areas during the mid-1900s, and land use in surrounding areas changed from rural to suburban (Zimmerman and others, 1996). Woodland and agricultural lands have become increasingly fragmented in the 20th and 21st centuries by the expansion of suburban areas, especially in eastern Massachusetts in areas bordering major metropolitan areas, in small cities, and near the junctions of major highways. These changes in land use coincided with alterations to the streamflow regimes of many rivers in southern New England.

Previous Studies

The USGS began a series of studies in 1995 to determine the spatial distribution of and correlation among parameters related to aquatic habitats and flow conditions of Massachusetts rivers. These studies, done in cooperation with the MDCR Office of Water Resources (formerly the Massachusetts Department of Environmental Management), the Massachusetts Department of Environmental Protection (MDEP), and the MDFW have evaluated median daily mean flows for August (Ries, 1997); assessed application of wetted-perimeter measures at streamflow-gaging stations (Mackey and others, 1998); investigated relations among stream habitat, fish communities, and hydrologic conditions in the Ipswich River Basin (Armstrong and others, 2001), Charles and Assabet Basins (Parker and others, 2004), and Sudbury River Basin (G. Parker, U.S. Geological Survey, written commun., August 2006); and evaluated streamflows and methods for determining streamflow requirements for aquatic habitat at index stations in southern New England (Armstrong and others, 2004).

Streamflows for a common period from 1976 through 2000 were characterized for 23 active index streamflow-gaging stations in southern New England (Armstrong and others, 2004), using monthly flow durations and streamflow statistics determined with the IHA Program (The Nature Conservancy, 2005). Analysis indicated that median monthly flows during the high-flow months of November through May differed regionally across southern New England and that differences in median monthly flows for the low-flow months of June through October were related to the areal percentage of surficial sand and gravel in the drainage basins and to an IHA base-flow index. Classification of the index stations and delineation between stations with different flow regimes were difficult, however, because of the small number of stations available for use in the study.

The current study closely follows an approach for classifying rivers developed at Colorado State University. Initial studies by Poff and Ward (1989) and Poff (1996) identified seven perennial stream types across the continental United States. Subsequent studies (Olden and Poff, 2003; Poff and others, 2006) presented an approach for developing a hydrologic classification of rivers that used PCA to reduce a set of 171 ecologically relevant hydrologic statistics, including the 33 flow statistics determined by the IHA program, to a smaller set of statistically significant, nonredundant indices that characterize the ecologically relevant components of the flow regime. CLA was then used to classify rivers into different flow-regime types. This approach has been used successfully to classify rivers, examine hydrologic variability, and identify similarities and differences in streamflows at the national scale (Olden and Poff, 2003) and the global scale (Poff and others, 2006). In the United States, hydrologic classifications are currently being applied at the regional scale in New Jersey, where 10 primary hydrologic indices and 4 stream classes were used to classify streamflows at 94 streamflow-gaging stations (Henriksen and others, 2006; Kennen and others, 2007); in Colorado, Oregon, and Washington, where 84 hydrologic indices were used to characterize the range of flow at 150 stations (Sanborn and Bledsoe, 2006); and in Missouri, where 53 nonredundant indices are being used to evaluate the range of flows at 169 sites (J. Kennen, U.S. Geological Survey, written commun., 2007).

Henriksen and others (2006) described a Hydroecological Integrity Assessment Process to assist in the establishment of flow standards protective of aquatic-ecosystem integrity. This process involves four steps: (1) develop a hydrologic classification of relatively unmodified streams in a geographic area by using long-term streamflow records and ecologically relevant indices; (2) identify statistically significant, nonredundant, ecologically relevant indices associated with the major flow components for each stream class; (3) develop an area-specific stream-classification tool for placing streams not used in the classification analysis into one of the identified stream classes, and (4) develop an area-specific hydrologic assessment tool to establish a reference time period and environmental flow standards and to evaluate past and proposed hydrologic modifications for a stream reach. Steps 1 and 2 of the Hydroecological Integrity Assessment Process are accomplished in this study.

The Natural-Flow Regime

Discharge, along with basin geomorphology, is one of the dominant variables that determines the form and function of a river and ultimately the biotic integrity of a river ecosystem (Poff and others, 1997; Annear and others, 2004; Molnar and others, 2002; Benda and others, 2004). A river ecosystem is said to have a high biotic integrity when the structure, composition, and natural processes of its aquatic communities and physical environment are intact, resilient to disturbance, and sustainable for the long term. Discharge determines the type and amount of habitat that are available in a stream and, as an agent of disturbance, affects the distribution of species (Doyle and others, 2005). Discharge also influences many processes important to aquatic life, such as the transport of sediment and solutes, nutrient uptake, primary production, and decomposition. Every river has a characteristic flow regime and associated biotic community (Naiman and others, 2002; Petts and Kennedy, 2005). A flow regime is the long-term fluctuation in the hydrograph that can be represented by the frequency, duration, magnitude, rate of change, and timing of streamflow (Poff and others, 1997; Richter and others, 1997). Streamflow regimes can differ among rivers with different basin and climatic characteristics, from upstream to downstream within a river network, and can vary over time.

Hydrologic variability promotes self-sustaining riverine ecosystems by creating and maintaining a wide range of habitat features and affecting geomorphic and ecosystem processes critical to supporting the abundance and diversity of fish and other aquatic life (Poff and Ward, 1989; Hill and others, 1991; Richter and others, 1997; Postel and Richter, 2003). Maintenance of seasonal streamflow variability is important for supporting a healthy ecosystem. Many aquatic species have life cycles that are, in part, adapted to the seasonal timing of streamflow. Predictable high and low streamflows provide cues for certain life-cycle events, such as spawning movements; fish feeding, egg hatching and rearing; and seasonal upstream and downstream migrations. In addition, some species or life stages do better during high-flow years and others do better during years with normal flows or low flows.

The riverine landscape constantly adjusts to variations in streamflow. High streamflows include flows that exceed the river banks (flood flows) and flows near bankfull that remain within the river channel. These high flows form and maintain channels, flood plains, and valley features; provide connections between the river and the flood plain, other off-channel water bodies, and habitat areas; recruit and transport beneficial woody debris; and alter riparian habitat. Flow pulses at or near bankfull can mobilize streambed sediment, restore and enhance aquatic habitat, maintain active channel width, and maintain streambanks. High-flow pulses caused by the rapid runoff of precipitation following storm events provide a series of natural disturbances to the river channel. Moderate flows provide more stable, diverse habitat in the forms of riffles, runs, and pools and provide important cover, nesting, spawning, and rearing habitats. Flows can be moderate at any point in time throughout the year, including periods when streamflows recede at the ends of higher flow pulses caused by storms. Base flow, the slower, sustained discharge of ground water that helps maintain streamflow between storms, provides essential habitat and stream temperatures for the support of diverse native aquatic communities and maintains streamside ground-water levels that support riparian vegetation. Without base flow, summer runoff would not provide flow or aquatic habitat sufficient to sustain many aquatic ecosystems.

Heavily regulated rivers rarely have streamflows that resemble natural-flow regimes (Ward and Stanford, 1983), and the water needed to sustain the native aquatic ecosystem in these rivers is in direct competition with human water needs, such as for water supply, wastewater dilution, power generation, and recreation. Flow modifications that alter habitat availability, complexity, and stability and that disrupt natural patterns of connectivity are among the most widespread disturbances of stream environments (Ward and Stanford, 1983; Bain and others, 1988; Petts and Kennedy, 2005; Guenther and Spacie, 2006; Shea and Peterson, 2007). Alteration of flow regimes and fragmentation of river connectivity can be significant factors in the decline of fish populations (Bauer and Ralph, 1999; Armstrong and others, 2001; Annear and others, 2004; Freeman and Marcinek, 2006; Guenther and Spacie, 2006) and in the invasion and success of exotic and introduced species (Petts and Kennedy, 2005).

A principal tenet of the natural-flow paradigm (Poff and others, 1997) is that the biodiversity and integrity of river ecosystems and the structure and function of aquatic ecosystems in regulated rivers can only be maintained if flows resemble a natural-flow regime. A single minimum-flow requirement is not sufficient to meet the needs of all species or maintain biologic diversity (Stalnaker, 1990), whereas variable flows that more closely resemble a natural, unaltered flow regime will, in most circumstances, meet the ecological needs of many aquatic species. Regional information about the natural range of variability for key flow metrics and for different classes of streams would facilitate the development of scientifically defensible environmental flow guidelines (Arthington and others, 2006).

Characteristics at Selected Stations

Streamflow records for 85 continuous-record streamflow-gaging stations were selected for use in this study. These records embody flow conditions for least altered gaged rivers in southern New England. The stations used in the study include 40 active and 45 discontinued stations: 36 from Massachusetts, 18 from Connecticut, 14 from New Hampshire, 14 from Rhode Island, and 3 from Vermont (table 1). Although streamflows in Massachusetts are the primary focus of the study, the study includes streamflow information from stations in adjacent states in southern New England. Additional stations in those states would have been included if the focus of the study had included all of southern New England. The stations used in this study have PORs ranging from 9 to 92 years in length. Daily mean streamflow data for the stations were obtained from the USGS National Water Information System (NWIS), which is available at *http://water-data.usgs.gov/nwis*.

The majority of stations used in the study are on small perennial streams and rivers: 51 stations have drainage areas less than 30 mi^2, 25 are between 30 and 100 mi^2, and only 9 have drainage areas greater than 100 mi^2. The predominance of small drainage basins in the study partly reflects the small size of streams and rivers in Massachusetts, but also is a function of the withdrawals, returns, alterations from impoundments, and history of land use along many of the large rivers in the region that precluded use of stations on these rivers as index stations.

Records from two sets of streamflow-gaging stations were used to evaluate streamflow regimes for different parts of this report. The number of records was maximized for the analysis of median monthly flows; to accomplish this goal, records from 85 stations were analyzed on the basis of their entire PORs. POR data were also used for L-moment analysis for a smaller set of 61 stations (table 1). This subset of 61 of the 85 stations was also used for the concurrent-period analyses. This subset was selected to keep the dataset from being biased toward records for stations with very small drainage areas or records for stations outside of Massachusetts. The records excluded were for 17 stations that had drainage areas less than 8 mi^2 and 6 stations in Vermont, New Hampshire, and Connecticut in areas outside of Massachusetts that could be represented by other stations. The records for many of the stations with small drainage areas also had short PORs that made record extension less reliable. Streamflow records were extended for 46 of the 61 stations by using maintenance of variance extension (MOVE) to develop a dataset of records with a concurrent POR from 1960 through 2004. Streamflow statistics, determined for this concurrent-record 61-station dataset by the IHA and HIT programs, were used in the multivariate statistical analysis to develop a hydrologic classification of least altered streamflows in southern New England.

Station Selection

Most of the stations used in this study were selected according to the following criteria: (1) the rivers were perennial for all but extreme drought years; (2) the station's records in the USGS Annual Water Data Reports (Kiah and others, 2005; Morrison and others, 2005; Socolow and others, 2005) indicated minimal effects from regulation; (3) the station could be either active or discontinued; (4) the record for the station included a minimum of 10 years of streamflow data. There were no absolute date restrictions for the POR analysis, but stations were required to have flow records between October 1959 and September 2004 for the concurrent-period analysis.

A large area of eastern and central Massachusetts did not have many streamflow-gaging stations that could be used to characterize natural flows. In particular, this area included much of the Boston metropolitan area and its suburbs extending outward to beyond the Route 495 corridor and an area of south-central Massachusetts extending roughly along the Massachusetts Turnpike corridor from Route 495 westward into central Massachusetts. This area included parts of the Ipswich, Sudbury, Assabet, Charles, Neponset, Taunton, Blackstone, Quinebaug, and French River Basins (Simcox, 1992). To increase the number of stations in the analysis and to give a better representation of rivers with a wide range of basin characteristics, exceptions to the selection criteria were made to include stations that were in areas where few index stations existed. These stations included (1) 12 stations with differing degrees of flow alteration caused by withdrawals, regulation, impoundment, or urban land use—stations on the Jones, Mill, Quaboag, Taunton, and Wading Rivers in Massachusetts; the Pawcatuck River stations in Rhode Island; and Stony Brook, Salmon Creek, and the Blackberry, Hop, and Salmon Rivers in Connecticut; (2) 3 stations with only 9 years of record—Bucks Horn, Furnace Hill, and Mosquitohawk Brooks in Rhode Island; and (3) 2 stations on small basins that occasionally produced zero flows during dry years—Dorchester Brook and the West Branch Palmer River in Massachusetts. The streamflow records for these 17 stations were included in this study because moderate and high flows for these stations were thought to be more representative of least altered flow conditions than of highly altered flow conditions.

Drainage-Basin Characteristics

A geographic information system (GIS) was used to collect physiographic, geographic, geologic, climatic, and land-use characteristics for the contributing drainage areas to the stations from a variety of GIS data sources and clearinghouses (table 2, in back of report). The suite of basin characteristics was also used to characterize differences in potential flow alteration among index stations and to describe the characteristics among station groups classified during the CLA.

Small differences in the drainage areas listed in tables 1 and 3 (in back of report) are a result of differences in the source elevation data used to derive the basin areas. Drainage-basin areas listed in table 1 are those published by the USGS in the Annual Data Reports for the respective states (Socolow and others, 2005). Drainage-basin areas listed in table 3 (in back of report) were determined for this study by using GIS (P. Steeves, U.S. Geological Survey, written commun., 2007). Spatial data needed for delineating the drainage areas of the 85 basins used in this study included

Table 1. Descriptions and period of record of selected streamflow-gaging stations used to characterize and classify streamflows in southern New England.

[USGS station number: Locations shown in figure 1. Station numbers for active streamflow-gaging stations are in **boldface** type; all others are discontinued stations. Latitude and longitude: In degrees, minutes, and seconds. Period of record: Present is 2004. USGS, U.S. Geological Survey; mi^2, square mile; POR, period of record; CP, concurrent period (1960–2004)]

USGS station number	Station name	Station code	Longitude	Latitude	Drainage area (mi^2)	Period of record (range of years)	POR (number of years)	Period of statistics used in analysis
01072850	Mohawk River near Center Stafford, NH	MOHA	-71 05 48.23	43 15 47.29	7.47	1964–77	13	POR
01073000	**Oyster River near Durham, NH**	OYST	-70 57 54.22	43 08 55.30	12.1	1934–present	70	POR, CP
01073600	Dudley Brook near Exeter, NH	DUDL	-71 01 18.21	42 59 35.31	5.85	1962–85	24	POR
01082000	Contoocook River at Peterborough, NH	CONT	-71 57 33.29	42 51 45.30	68.1	1945–77, 2001–present	35	POR, CP
01084500	Beard Brook near Hillsboro, NH	BEAR	-71 55 34.29	43 06 51.29	55.3	1945–70	25	POR, CP
01085800	**West Branch Warner River near Bradford, NH**	WBWA	-72 01 33.30	43 15 33.28	5.91	1962–present	42	POR, CP
01086000	Warner River at Davisville, NH	WARN	-71 43 56.28	43 15 04.28	146	1939–78, 2001–present	42	POR
01089000	Soucook River near Concord, NH	SOU1	-71 27 43.25	43 14 19.29	76.8	1951–87	36	POR
01089100	**Soucook River, at Pembroke Road, near Concord, NH**	SOU2	-71 28 49.25	43 12 49.29	81.9	1988–present	17	POR, CP
01091000	South Branch Piscataquog River near Goffstown, NH	SBPI	-71 38 29.26	43 00 53.30	104	1940–78	38	POR, CP
01093800	**Stony Brook Tributary near Temple, NH**	STON	-71 49 58.28	42 51 36.30	3.60	1963–present	41	POR, CP
01095000	Rocky Brook near Sterling, MA	ROCK	-71 48 08.26	42 26 57.33	1.95	1946–67	21	POR
01095220	**Stillwater River near Sterling, MA**	STIL	-71 47 28.26	42 24 39.33	31.6	1994–present	10	POR, CP
01096000	**Squannacook River near West Groton, MA**	SQUA	-71 39 28.25	42 38 03.32	63.7	1949–present	55	POR, CP
01096910	Boulder Brook at East Bolton, MA	BOUL	-71 34 37.24	42 27 04.33	1.60	1971–83	12	POR
010965852	**Beaver Brook at North Pelham, NH**	BBNH	-71 21 13.23	42 46 58.32	47.8	1986–present	18	POR, CP
01097300	**Nashoba Brook near Acton, MA**	NASH	-71 24 15.22	42 30 45.33	12.8	1963–present	41	POR, CP
01100700	East Meadow River near Haverhill, MA	EMEA	-71 01 57.20	42 48 41.32	5.47	1962–74	12	POR, CP
01105600	**Old Swamp River near South Weymouth, MA**	OLDS	-70 56 41.16	42 11 25.36	4.50	1966–present	38	POR, CP
01105730	**Indian Head River at Hanover, MA**	IHEA	-70 49 21.15	42 06 02.37	30.3	1966–present	38	POR, CP
01105870	**Jones River at Kingston, MA**	JONE	-70 44 01.14	41 59 27.37	15.7	1966–present	38	POR
01105880	Herring River at North Harwich, MA[1]	HERR	-70 06 25.07	41 42 00.40	9.40	1966–present	22	POR
01106000	Adamsville Brook at Adamsville, RI	ADAM	-71 07 45.16	41 33 30.37	8.01	1940–87	39	POR, CP
01107000	Dorchester Brook near Brockton, MA	DORC	-71 03 57.17	42 03 41.36	4.67	1962–74	12	POR
01108000	**Taunton River near Bridgewater, MA**	TAUN	-70 57 23.15	41 56 02.37	261	1929–76, 1985–88, 1996–present	58	POR, CP
01109000	**Wading River near Norton, MA**	WADI	-71 10 36.18	41 56 51.36	43.3	1925–present	79	POR, CP
01109200	West Branch Palmer River near Rehoboth, MA	WBPA	-71 15 14.40	41 52 46.36	4.35	1962–74	12	POR
01111300	**Nipmuc River near Harrisville, RI**	NIPM	-71 41 09.24	41 58 52.35	16.0	1964–91, 1993–present	39	POR, CP
01111500	**Branch River at Forestdale, RI**	BRAN	-71 33 45.23	41 59 47.35	91.2	1940–present	65	POR, CP
01115098	**Peeptoad Brook at Elmdale Road near Westerly, RI**	PEEP	-71 36 22.23	41 51 09.36	4.96	1994–present	10	POR, CP

Table 1. Descriptions and period of record of selected streamflow-gaging stations used to characterize and classify streamflows in southern New England.—Continued

[USGS station number: Locations shown in figure 1. Station numbers for active streamflow-gaging stations are in **boldface** type; all others are discontinued stations. Latitude and longitude: In degrees, minutes, and seconds. Period of record: Present is 2004. USGS, U.S. Geological Survey; mi^2, square mile; POR, period of record; CP, concurrent period (1960–2004)]

USGS station number	Station name	Station code	Longitude	Latitude	Drainage area (mi^2)	Period of record (range of years)	POR (number of years)	Period of statistics used in analysis
01115100	Mosquitohawk Brook near North Scituate, RI	MOSQ	-71 37 22.23	41 51 05.36	3.06	1965–74	9	POR
01115187	**Ponaganset River at South Foster, RI**	PONA	-71 42 18.24	41 49 07.36	13.7	1994–present	11	POR, CP
01115630	Nooseneck River at Nooseneck, RI[1]	NOOS	-71 37 57.23	41 37 36.36	8.23	1963–81	18	POR, CP
01116300	Furnace Hill Brook at Cranston, RI	FURN	-71 29 50.22	41 45 23.36	4.19	1965–74	9	POR
01117468	**Beaver River near Usquepaug, RI**	BRRI	-71 37 41.23	41 29 33.36	8.87	1974–present	30	POR, CP
01117500	**Pawcatuck River at Wood River Junction, RI**	PAWR	-71 40 51.23	41 26 42.36	100	1940–present	64	POR, CP
01117800	**Wood River near Arcadia, RI**	WOOA	-71 42 59.24	41 29 53.36	35.2	1964–81, 1982–present	39	POR, CP
01118000	**Wood River at Hope Valley, RI**	WOOH	-71 43 14.24	41 34 26.36	72.4	1941–present	64	POR, CP
01118300	**Pendleton Hill Brook near Clarks Falls, CT**	PEND	-71 50 03.25	41 28 29.36	4.02	1958–present	46	POR, CP
01118500	**Pawtucket River at Westerly, RI**	PAWE	-71 49 59.25	41 23 01.36	295	1940–present	64	POR, CP
01120000	Hop Brook near Columbia, CT	HOPC	-72 18 08.29	41 43 39.36	73.9	1932–71	39	POR, CP
01120500	Safford Brook near Woodstock Valley, CT	SAFF	-72 03 25.27	41 55 35.35	4.15	1950–81	31	POR
01121000	**Mount Hope River near Warrenville, CT**	MOUN	-72 10 08.28	41 50 37.35	28.6	1940–present	64	POR, CP
01123000	**Little River near Hanover, CT**	LITT	-72 03 08.27	41 40 18.35	30.0	1951–present	53	POR, CP
01126200	Bucks Horn Brook at Greene, RI	BUCK	-71 44 36.25	41 41 35.36	5.52	1965–74	9	POR
01126600	Blackwell Brook near Brooklyn, CT	BLAC	-71 57 23.26	41 45 55.35	17.0	1963–76	13	POR, CP
01153500	Williams River at Brockway Mills, VT	WILL	-72 31 03.32	43 12 31.27	102	1940–84	44	POR
01154000	Saxtons River at Saxtons River, VT	SAXT	-72 29 17.32	43 08 15.28	72.1	1940–82, 2001–present	46	POR, CP
01155000	Cold River at Drewsville, NH	COLD	-72 23 25.32	43 07 54.28	83.3	1940–78	38	POR, CP
01158500	Otter Brook near Keene, NH	OTNH	-72 14 03.31	42 57 55.29	42.3	1924–58		POR
01161500	Tarbell Brook near Winchendon, MA	TARB	-72 05 07.29	42 42 45.31	17.8	1916–83	67	POR, CP
01162500	**Priest Brook near Winchendeon, MA**	PRIE	-72 06 54.29	42 40 57.31	19.4	1916–35, 1936–present	86	POR, CP
01165500	Moss Brook at Wendell Depot, MA	MOSS	-72 21 34.31	42 36 10.31	12.1	1909–82	67	POR, CP
01167800	Beaver Brook at Wilmington, VT	BBVT	-72 51 04.35	42 51 38.29	6.36	1963–77	15	POR
01169000	**North River at Shattuckville, MA**	NORT	-72 43 30.33	42 38 18.30	89.0	1939–present	65	POR, CP
01169900	**South River near Conway, MA**	SOUT	-72 41 37.33	42 32 31.31	24.1	1966–present	38	POR, CP
01170100	**Green River near Colrain, MA**	GREC	-72 40 14.33	42 42 12.30	41.4	1967–present	37	POR, CP
01171500	**Mill River at Northampton, MA**	MILL	-72 39 54.33	42 19 08.32	54.0	1938–present	66	POR, CP
01171800	Bassett Brook near North Hampton, MA	BASS	-72 41 14.33	42 18 09.32	5.56	1963–74	12	POR, CP
01173260	Moose Brook near Barre, MA	MOOS	-72 08 49.29	42 23 52.33	4.63	1962–74	12	POR

Table 1. Descriptions and period of record of selected streamflow-gaging stations used to characterize and classify streamflows in southern New England.—Continued

[USGS station number: Locations shown in figure 1. Station numbers for active streamflow-gaging stations are in **boldface** type; all others are discontinued stations. Latitude and longitude: In degrees, minutes, and seconds. Period of record: Present is 2004. USGS, U.S. Geological Survey; mi^2, square mile; POR, period of record; CP, concurrent period (1960–2004)]

USGS station number	Station name	Station code	Longitude	Latitude	Drainage area (mi^2)	Period of record (range of years)	POR (number of years)	Period of statistics used in analysis
01174000	Hop Brook near New Salem, MA	HOPM	-72 20 03.30	42 28 42.32	3.39	1947–82	35	POR, CP
01174565	**West Branch Swift River near Shutesbury, MA**	WBSW	-72 22 54.31	42 27 18.32	12.6	1983–85, 1995–present	11	POR, CP
01174900	Cadwell Creek near Belchertown, MA	CADW	-72 22 10.30	42 20 08.33	2.55	1961–97	36	POR, CP
01175670	**Sevenmile River near Spencer, MA**	SEVE	-72 00 17.27	42 15 54.33	8.81	1960–present	44	POR, CP
01176000	**Quaboag River at West Brimfield, MA**	QUAB	-72 15 49.29	42 10 56.34	150	1912–present	92	POR, CP
01180000	Sykes Brook at Knightville, MA	SYKE	-72 52 13.35	42 17 27.32	1.73	1945–74	29	POR
01180800	Walker Brook near Becket Center, MA	WALK	-73 02 46.37	42 15 49.32	2.94	1962–77	15	POR
01181000	**West Branch Westfield at Huntington, MA**	WBWE	-72 53 44.35	42 14 14.32	94.0	1935–present	69	POR, CP
01184100	**Stony Brook near West Suffield, CT**	STCT	-72 42 37.33	41 57 38.35	10.4	1981–present	23	POR, CP
01187300	**Hubbard River near West Hartland, CT**	HUBB	-72 56 20.37	42 02 14.34	19.9	1938–55, 1956–present	65	POR, CP
01187400	Valley Brook near West Hartland, CT	VALL	-72 55 47.37	42 02 03.34	7.03	1940–72	32	POR, CP
01187800	Nepaug River near Nepaug, CT	NEPA	-72 58 12.36	41 49 14.35	23.6	1921–55, 1957–72		POR
01188000	**Burlington Brook near Burlington, CT**	BURL	-72 57 53.37	41 47 10.35	4.10	1931–present	73	POR
01193500	**Salmon River near East Hampton, CT**	SALR	-72 26 57.30	41 33 08.36	100	1928–present	76	POR, CP
01194500	East Branch Eightmile River near North Lyme, CT	EBEM	-72 20 03.30	41 25 40.35	22.4	1937–81, 2001–present	47	POR, CP
01195100	**Indian River near Clinton, CT**	INDI	-72 31 52.33	41 18 21.36	5.68	1981–present	23	POR, CP
01197300	Marsh Brook at Lenox, MA	MARS	-73 17 54.39	42 20 59.31	2.12	1962–74	12	POR
01198000	Green River near Great Barrington, MA[1]	GRGB	-73 23 26.41	42 11 31.32	51.0	1951–71, 1994–96	23	POR, CP
01198500	Blackberry River at Canaan, CT	BLAB	-73 20 30.41	42 01 26.34	43.8	1949–71	22	POR, CP
01199050	**Salmon Creek at Lime Rock, CT**	SALC	-73 23 27.43	41 56 32.34	29.4	1961–present	43	POR, CP
01199200	Guinea Brook at West Woods Road at Ellsworth, CT	GUIN	-73 25 48.44	41 49 27.34	3.50	1960–80	21	POR
01200000	**Ten Mile River, CT**	TENM	-73 31 42.45	41 39 32.34	203	1930–88, 1988–89, 1990–present	70	POR, CP
01331400	Dry Brook near Adams, MA	DRYB	-73 06 46.36	42 35 20.31	7.67	1962–74	12	POR, CP
01332000	North Branch Hoosic River at North Adams, MA	NBHO	-73 05 35.37	42 42 08.29	40.9	1931–90	55	POR, CP
01333000	**Green River at Williamstown, MA**	GREW	-73 11 48.38	42 42 32.29	42.6	1949–present	59	POR, CP

[1] These stations were active as of 2007.

1:100,000-scale spatial data from the National Hydrography Dataset (NHD) (U.S. Geological Survey, 1999b); the National Elevation Dataset (NED) (U.S. Geological Survey, 1999a); georeferenced digital files consisting of terrain elevations for exposed or submerged ground positions at regularly spaced 30-m horizontal intervals; and the National Watershed Boundaries for 12-digit hydrologic unit watersheds delineated by the Natural Resources Conservation Service (NRCS) (D. Richard and R. Sims, Natural Resources Conservation Service, written commun., 2000).

The variable *coastdistance* was developed to represent basin and climatic characteristics that roughly vary from southeast to northwest across southern New England, such as elevation, slope, percent sand and gravel, winter temperatures, and seasonal maximum snow depth. The measure represents the distance of a streamflow-gaging station from a regional coastline, measured in a roughly northwest direction, and is not a measure of the straight-line distance between a station and the local coastline. The *coastdistance* variable was defined as the difference, in meters, between two distances: the distance between each station and a point far offshore, the point (1,000,000, 0) in the Massachusetts State Plane coordinate system, approximately 150 mi northeast of Bermuda, and the approximate distance from the offshore point to landfall on Nantucket (1.07×10^6 m). Distances were measured from a point far offshore so that the radially measured distances would always be positive and would increase with distance in the northwesterly direction. Once the distance to landfall is subtracted, the *coastdistance* variable represents a distance from an arc that roughly parallels the northeast Atlantic coast. In addition, *coastdistance* is measured in a direction that is roughly perpendicular to the trend of the Appalachian Mountains; thus, the definition of the variable is based on two continental-scale features that influence regional climate.

Soils are classified into four Hydrologic Soil Groups on the basis of the runoff and infiltration potential of the soil and depth to the water table or an impermeable layer (Natural Resources Conservation Service, 2007). The four Hydrologic Soil Groups are A, B, C, and D and range from well drained to poorly drained soils. Soils in Group A tend to be sandy with greater depths to the water table and to have the lowest runoff potential and highest infiltration rate. Soils in Group D tend to be clayey or have shallow depths to the water table and to have the highest runoff potential and slowest infiltration rate.

Additional characteristics of the contributing drainage areas to the 61 stations are provided in table 3 (in back of report). The stations represent a wide range of drainage areas and topographic-, geologic-, climatic-, and land-use conditions. Boxplots of selected basin and climate characteristics illustrate the range of characteristics of the basins used in the study (fig. 2).

Evaluation of Flow Alteration

Ideally, natural flows would be described for reference or benchmark stations with long periods of unmodified streamflow, in basins with natural forest and wetland landcover with no water withdrawals, return flows, dams, or development. Few stations in southern New England meet these criteria, however, given the population density and history of land use in the region. GIS data for water withdrawals, water returns, dams, and land-use characteristics were evaluated to indicate differences in potential flow alteration in records for selected stations in Massachusetts.

Data were obtained by first determining, with a GIS, the contributing drainage areas associated with streamflow-gaging stations in Massachusetts. Coverages for drainage areas were then intersected with spatial datasets for volume of water withdrawals and returns (2000–2004), number of dams, and land-use characteristics. These data were obtained from MDEP, the Massachusetts Geographic Information System (MassGIS), and U.S. Army Corps of Engineers (USACE) databases. Data electronically available from MDEP for 2000–2004 water withdrawals from water-supply sources in Massachusetts under Water Management Act jurisdiction (ground-water and surface-water sources withdrawing more than 100,000 gal/d), were obtained from the Massachusetts Sustainable-Yield Estimator (SYE) Water-Use Database (S.A. Archfield, U.S. Geological Survey, written commun., 2007). The SYE Water-Use Database also provided MDEP data for National Pollutant Discharge Elimination System (NPDES) discharges, which include return flows from wastewater-treatment plants. Data for the number of dams higher than 6 ft were obtained from the USACE. Land-use data are based upon 30-m scale Thematic Mapper images from the National Land Cover Dataset (U.S. Geological Survey, 1992).

The water-withdrawal, return-flow, dam, and land-use data are summarized for the drainage basins to 29 streamflow-gaging stations in Massachusetts in figure 3. The plots indicate that few of the index stations can be considered to be reference stations with natural flows. The stations associated with the fewest alterations, which include Cadwell Creek, Valley Brook, and West Branch Swift River, are in small basins in rural areas. These areas are predominantly forest or wetland, have no water withdrawals or dams, and have less than 1 percent low-density residential, high-density residential, or commercial land use. A few large drainage areas, such as the Taunton and Quaboag Rivers, were associated with a mix of water withdrawals and returns, dams, and land-use alterations that cumulatively alter flow. Most of the index stations have some flow alterations, but the type and degree of alteration differ among stations. Further work would be necessary to quantify the effects of land-use alterations on streamflow and to calibrate an index of potential flow alteration.

Flow alterations and land uses in the contributing areas to streamflow-gaging stations are not constant over time. Over years or decades, impoundments may be constructed, abandoned, or removed; and mills or other water infrastructures

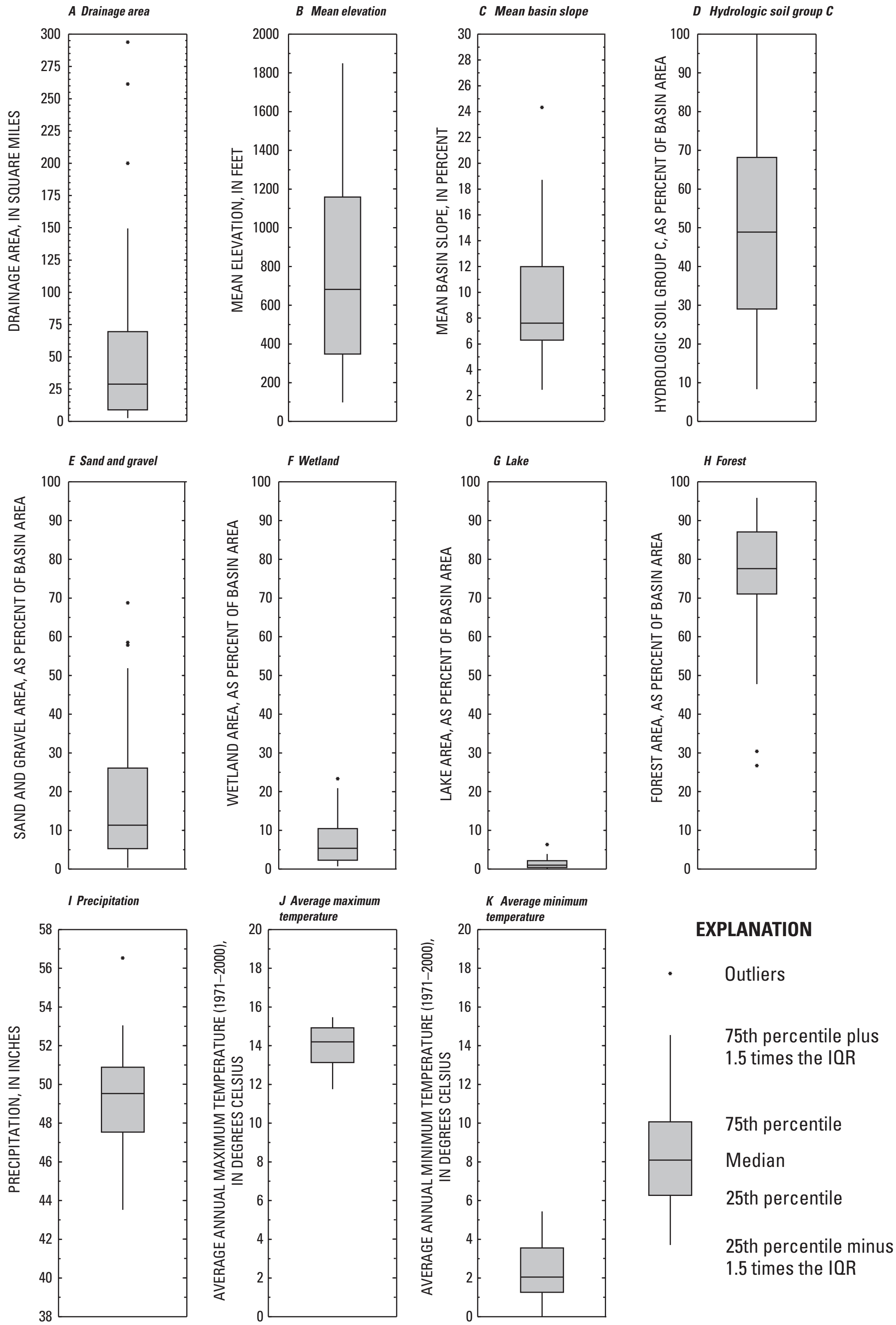
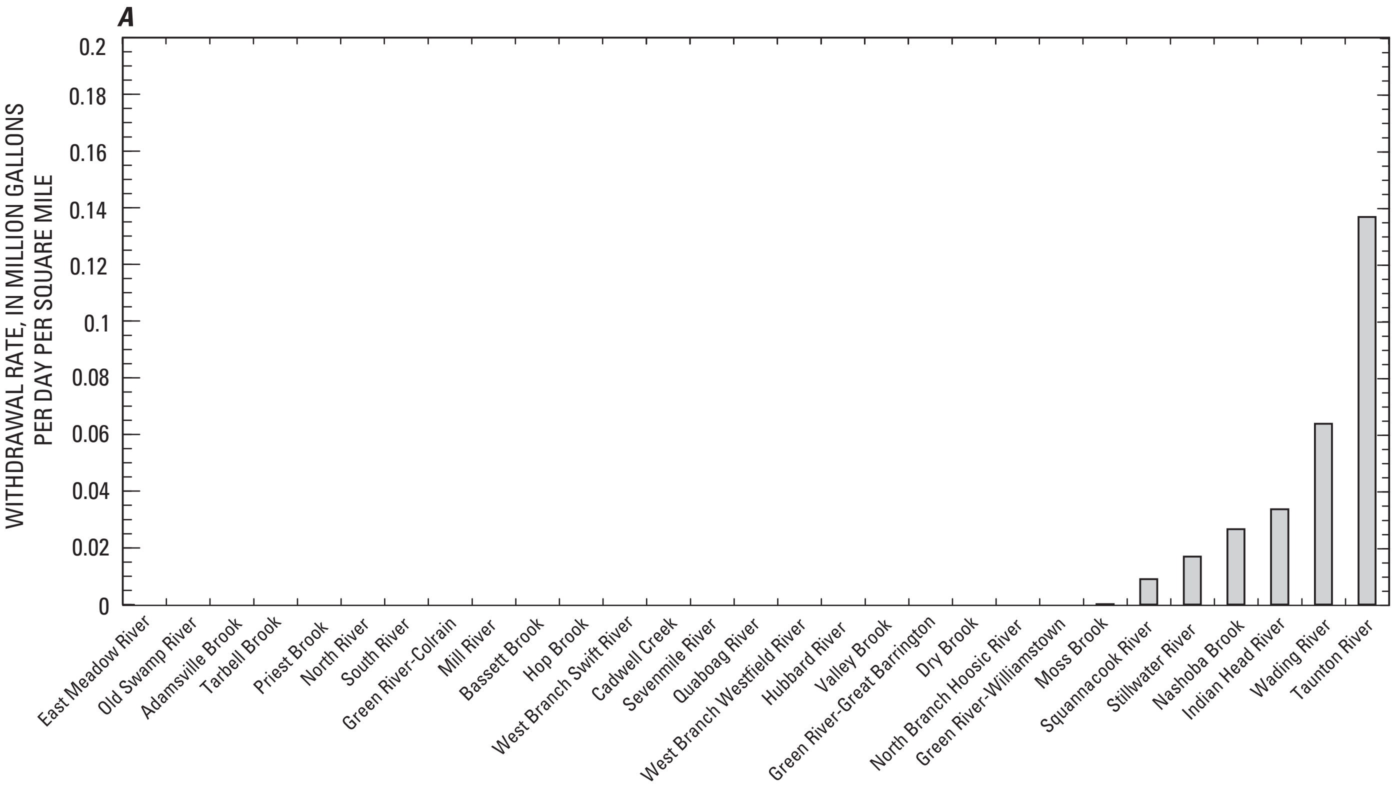


Figure 2. Basin and climate characteristics for contributing areas to 61 streamflow-gaging stations in southern New England: *(A)* drainage area, *(B)* mean elevation, *(C)* mean basin slope, *(D)* hydrologic soil group C, *(E)* sand and gravel area, *(F)* wetland area, *(G)* lake area, *(H)* forest area, *(I)* precipitation, *(J)* average annual maximum temperature, and *(K)* average annual minimum temperature. IQR, interquartile range, is the difference between the 75th- and 25th-percentile values.



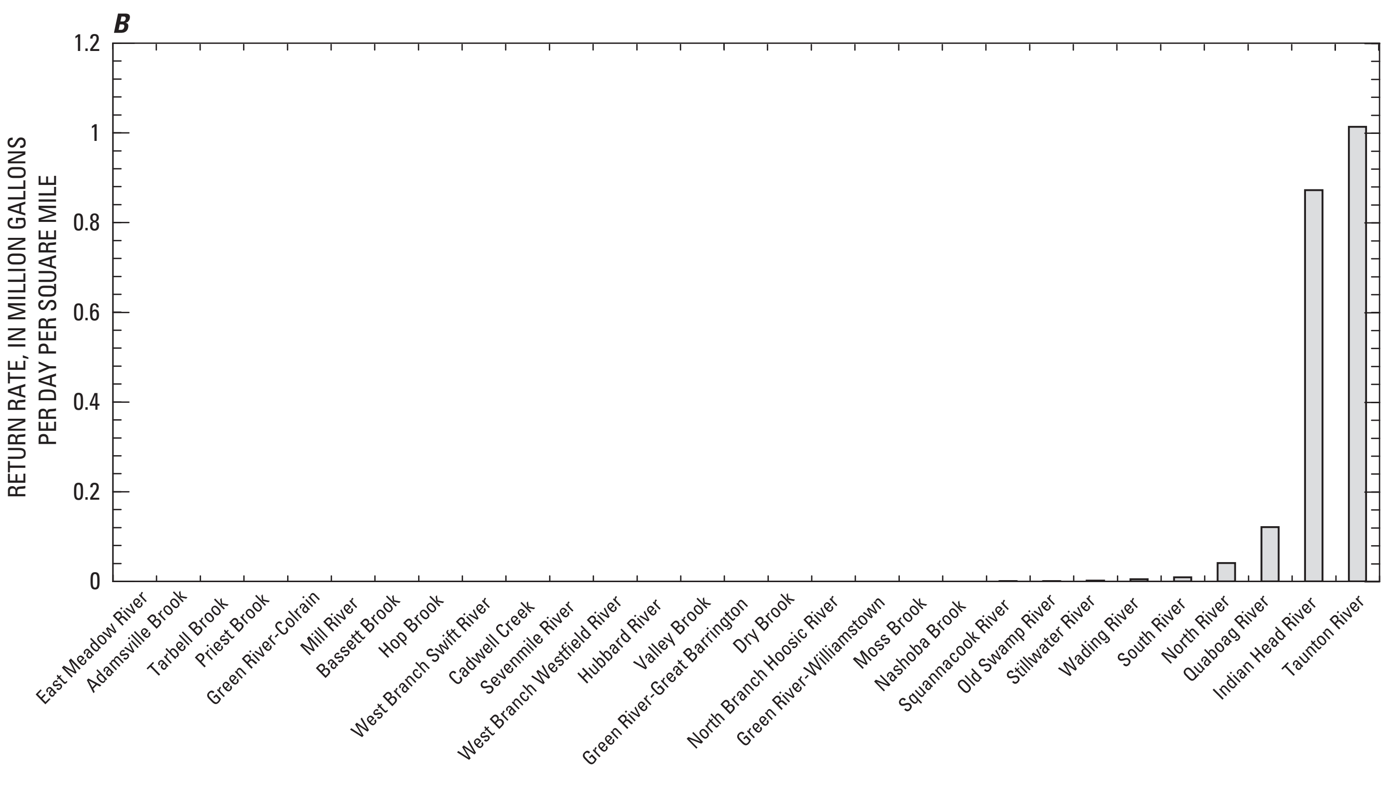


Figure 3. *(A)* Water-withdrawal rate, *(B)* return rate, *(C)* number of dams per square mile, and *(D)* land-use characteristics for selected streamflow-gaging stations in Massachusetts. Land-use data from Office of Geographic and Environmental Information (MassGIS).

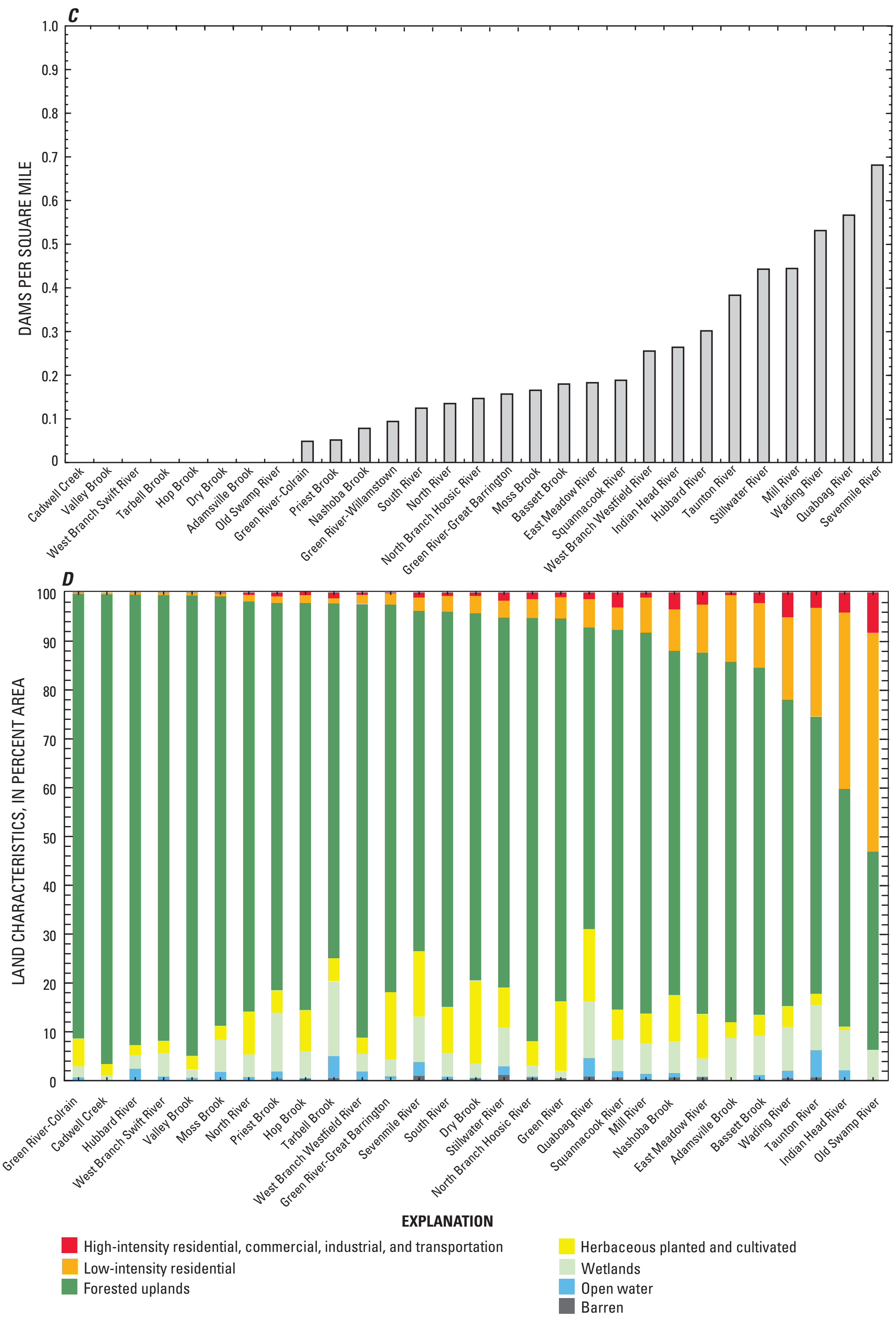


Figure 3. *(A)* Water-withdrawal rate, *(B)* return rate, *(C)* number of dams per square mile, and *(D)* land-use characteristics for selected streamflow-gaging stations in Massachusetts. Land-use data from Office of Geographic and Environmental Information (MassGIS).—Continued

regulating flows may change operating procedures. Water withdrawals change as new sources become available or as the magnitude or timing of withdrawals changes. Changing land-use conditions over time also can affect streamflows. Many forested and agricultural areas in eastern Massachusetts have become increasingly fragmented as they are converted to suburban or commercial land use. Because of these changing conditions, some stations used in this study may no longer meet criteria to be considered index stations in the near future.

Fish-Community Sampling

Fisheries information, obtained from the MDFW Statewide Fisheries Assessment Program, was available for reaches near 15 of the streamflow-gaging stations used in this study. This information was used to assess whether the fish-community composition in reaches near the stations supported their designation as having minimally altered flows. For the purposes of analysis, inclusion of fish-community samples was limited to collections by backpack and barge electroshocking in free-flowing reaches of streams near the stations.

Descriptions of sampling methodologies and data-collection sheets used by the MDFW are in appendix 1. Fish collection consisted of sampling at least 100 m of stream during the summer base-flow season (typically mid-June to mid-September). Backpack electroshocking (pulsed, direct current) was the primary method used for fish collection and is best suited to shallow, wadeable streams. A single upstream pass was made by a three-to-five-person team using the electroshocking equipment. Electroshocking temporarily stuns fish so they can be captured, identified, measured, and released. The total number of each species captured was recorded, and the lengths of the first 100 individuals of each species were measured. One or two representatives of each species captured were preserved for confirmation of identification as a voucher sample.

Field data included sampling date, stream name, town name, site description, location, length of sampling reach, and sampling gear type (appendix 1). Coordinates for sampling reaches were obtained by using a Global Positioning System (GPS) or by recording locations on USGS 1:25,000 topographic maps and georeferenced orthophotographs that were marked in meters above the river mouth. Information on electrofishing equipment and use were also recorded, including backpack- and battery-identification numbers, numbers of amperes and volts used, pulse frequency and width settings, and electrofishing effort (defined as the length of time during which current is sent through the water). The latter was recorded to enable standardization and comparison of results by calculation of catch per unit effort (CPUE). To determine the adequacy of the sample, observations of air and water temperatures, water clarity, and general weather conditions were recorded in addition to habitat quality (described on U.S. Environmental Protection Agency (USEPA) rapid-bioassessment-protocol forms). The fish-community data include only data collected by using consistent sampling methods from 1998 through 2005 in free-flowing stream reaches. Three fish-community samples were not used because the samples were collected from streams that were part of the Atlantic salmon-restoration effort.

Fish were assigned a Habitat Use Classification (HUC): macrohabitat generalist (MG), fluvial dependent (FD), or fluvial specialist (FS) (table 4) (Bain and Meixler, 2000; M. Kearns, Riverways, written commun., 2004). Macrohabitat generalists, such as pumpkinseed and redfin pickerel, use a broad range of habitats; they include species commonly found in lakes, reservoirs, and rivers and can complete their life cycle in any one of these systems. Fluvial dependents, such as common shiners and white suckers, require access to streams or flowing-water habitats for a specific life stage, but otherwise can be found in lakes, reservoirs, and rivers. Fluvial specialists, such as blacknose dace and fallfish, are common only to streams or rivers and require flowing-water habitats throughout their life cycle (Bain and Travnichek, 1996). HUC percentages were calculated for each fish-community summary (table 5). If multiple samples were collected upstream of a station, the data were pooled.

Fish-community summaries associated with each station are provided in appendix 2. Nine of the 15 summaries included more than 90 percent fluvial dependents and specialists combined. A few summaries show very low proportions of fluvial fish; two summaries show a fish community with less than 50 percent of fluvial dependents and specialists combined. These summaries were for fish sampled near stations whose drainage areas included a high percentage of land-use alterations. In general, however, most fish communities near the index stations showed a high percentage of fluvial individuals; this finding supported their use as index stations (Armstrong and others, 2004).

Table 4. Habitat-use classifications for fish collected from Massachusetts study streams.

[HUC, habitat-use classification; --, not classified; MG, macrohabitat generalist; FD, fluvial dependent; FS, fluvial specialist; A, anadronous; C, catadromous; R, resident; HUCs provided by M. Bain, Cornell University, written commun., 2000; and modified by T. Richards, Massachusetts Division of Fisheries and Wildlife, written commun., 2007]

Common name	Family *genus*	Species	HUC	Life history
Lamprey	**Petromyzontidae**			
Sea lamprey	*Petromyzon*	*marinus*	--	A
Freshwater eel	**Anguillidae**			
American eel	*Anguilla*	*rostrata*	MG	C
Herring	**Clupeidae**			
Alewife	*Alosa*	*pseudoharengus*	--	A
Carps and Minnow	**Cyprinidae**			
Common shiner	*Notropis*	*cornutus*	FD	R
Golden shiner	*Notemigonus*	*crysoleucas*	MG	R
Blacknosed dace	*Rhinichthys*	*atratulus*	FS	R
Longnose dace	*Rhinichthys*	*cataractae*	FS	R
Creek chub	*Semotilus*	*atromaculatus*	FS	R
Fallfish	*Semotilus*	*corporalis*	FS	R
Sucker	**Catostomidae**			
Longnose sucker	*Catostomus*	*catostomus*	FD	R
White sucker	*Catostomus*	*commersoni*	FD	R
Bullhead and Catfish	**Ictaluridae**			
Yellow bullhead	*Ameiurus*	*natalis*	MG	R
Brown bullhead	*Ameiurus*	*nebulosus*	MG	R
Pike and Pickerel	**Esocidae**			
Redfin pickerel	*Esox*	*americanus americanus*	MG	R
Chain pickerel	*Esox*	*niger*	MG	R
Salmon, Char, and Trout	**Salmonidae**			
Atlantic salmon	*Salmo*	*salar*	FS	A
Landlocked salmon	*Salmo*	*salar*	--	R
Brown trout	*Salmo*	*trutta*	FS	R
Brook trout	*Salvelinus*	*fontinalis*	FS	R
Sculpin	**Cottidae**			
Slimy sculpin	*Cottus*	*cognatus*	FS	R
Striped bass	**Moronidae**			
White perch	*Morone*	*americana*	MG	R
Sunfish and Bass	**Centrarchidae**			
Rock bass	*Ambloplites*	*rupestris*	MG	R
Banded sunfish	*Enneacanthus*	*obesus*	MG	R
Redbreast sunfish	*Lepomis*	*auritus*	MG	R
Pumpkinseed	*Lepomis*	*gibbosus*	MG	R
Bluegill	*Lepomis*	*macrochirus*	MG	R
Largemouth bass	*Micropterus*	*salmoides*	MG	R
Perch	**Percidae**			
Swamp darter	*Etheostoma*	*fusiforme*	MG	R
Tesselated darter	*Etheostoma*	*olmstedi*	FS	R
Yellow perch	*Perca*	*flavescens*	MG	R

Table 5. Number of fish sampled between 2001–2005 in flowing mainstem reaches near selected USGS streamflow-gaging stations in Massachusetts, and percentages of fish in each habitat-use classification.

[USGS, U.S. Geological Survey; MDFW, Massachusetts Division of Fish and Wildlife; FS, fluvial specialist; FD, fluvial dependent; MG, macrohabitat generalist]

USGS station number	Station name	Number of mainstem samples	MDFW sample identifier	Number of fish collected	FS (percent of total)	FD (percent of total)	MG (percent of total)
01095220	Stillwater River near Sterling, MA	4	272, 1261, 1262, 1264	1,086	55	41	4
01096000	Squannacook River near West Groton, MA	1	233	23	78.3	17.4	4.3
01105730	Indian Head River at Hanover, MA	1	481	143	0	10.5	89.5
01165500	Moss Brook at Wendell Depot, MA	1	202	87[1]	93.1	3.4	1.1
01169000	North River at Shattuckville, MA	2	201, 1356	360	92.8	6.9	0.3
01169900	South River near Conway, MA	6	203, 204, 1056, 1071, 1086, 1349	1,228	79.5	20.4	0.1
01170100	Green River near Colrain, MA	4	199, 1067, 1341, 1263	1,010	99.2	0.8	0
01174900	Cadwell Creek near Belchertown, MA	1	1211	61	100	0	0
01175670	Sevenmile River near Spencer, MA	3	789, 791, 1150	412	59.7	27.4	12.9
01176000	Quaboag River at West Brimfield, MA	3	876, 880, 886	176	24	11	65
01187300	Hubbard River near West Hartland, CT	1	1228	150	37	56	7
01198000	Green River near Great Barrington, MA	1	649	122	89	0	11
01331400	Dry Brook near Adams, MA	1	799	96	94.8	2.1	3.1
01332000	North Branch Hoosic River at North Adams, MA	1	801	145	76	23	1
01333000	Green River at Williamstown, MA	1	787	293	91	9	0

[1] Includes two sea lampreys, an anadromous species whose habitat use is unclassified.

Streamflow Statistics for Characterizing Flow Regimes

Streamflow statistics were calculated for both the POR for the stations and a concurrent period (1960–2004). Use of the POR for a station offers the advantages that the entire streamflow dataset is composed of observed streamflows and that more stations can be included in the analysis. A disadvantage of using POR data is that the records for different stations generally include streamflows from different time periods and thus could reflect different climatic conditions. For example, streamflow statistics determined from stations with different PORs may differ because some records may include extreme streamflows, such as low flows or floods, not represented in the records for other stations. For this study, the effect of using different PORs was minimized by limiting the analysis of POR data to the calculation of median monthly flows and by analysis of daily flows by using L-moment ratios. Median monthly flows are relatively robust statistics and, as a measure of central tendency, are much less affected by high and low flows than other flow statistics. L-moments also are robust to the presence of outliers and are unbiased for small samples (Hosking and Wallis, 1997). Concurrent streamflow records of equal length are considered best for a regional analysis (Fennessey and Vogel, 1990). Limiting the stations only to those with concurrent record, however, would have substantially reduced the number of stations used in the study. To increase the number of stations available for the concurrent-period analysis, record-extension techniques were used to simulate daily streamflows at selected streamflow-gaging stations.

Median Monthly Streamflows

Monthly flow-duration curves (FDCs) were prepared for 85 stations from daily mean streamflows for each month and each year for the POR at the station. For example, for a POR from 1960 through 2004, 12 monthly FDCs would be generated for each year, resulting in a total of 540 monthly FDCs for the entire POR. Although FDCs are traditionally constructed for the POR on an annual basis (Searcy, 1959; Vogel and Fennessey, 1994, 1995), FDCs were constructed for this study on a monthly basis so that the variability in the magnitude of median monthly streamflows could be assessed. To construct monthly FDCs, daily mean streamflow data for 85 streamflow-gaging stations (table 1) were obtained from the USGS NWIS. Monthly flow durations were calculated for each month of each year in the POR for the stations by an EXCEL Visual Basic Program (R.W. Dudley, U.S. Geological Survey, written commun., 2003), which ranks the daily mean streamflows for each day of a given month and year in ascending order of discharge. The exceedence probability of each streamflow was calculated by use of the Weibull formula (Helsel and Hirsch, 1992). The percentiles of monthly flow durations for all years were calculated using MINITAB release 14.12.0, 2004.

A single monthly FDC displays the variability of daily flows for a given month and year. The 50-percent flow duration (Q_{50}) is the flow that was equaled or exceeded 50 percent of the time during the month of interest in a given year and is a measure of the central tendency of all flows for that month. A 75-percent flow duration (Q_{75}) is equaled or exceeded 75 percent of the time during the month of interest in a given year and is considered a moderately low flow for that month. A 25-percent flow duration (Q_{25}) is equaled or exceeded 25 percent of the time in the month of interest for a given year and is considered a moderately high flow for that month. The percentage of time that flows are between two flow durations is indicated simply by the difference between the durations; thus, 50 percent of the daily mean flows are between the Q_{75} and the Q_{25} for that month, and 80 percent of the daily mean flows are between the Q_{90} and the Q_{10}. For this report, the term "median monthly flow" for the POR refers to the median of the Q_{50} monthly flow durations for that month over the POR.

The variability of flows for a given month over the POR for a station can be illustrated with a plot showing all the monthly FDCs, one for each year of record. For example, figures 4A and B show the 45 monthly FDCs for the POR for the Sevenmile River (01175670), normalized by drainage area, for April and August, respectively. Median streamflows for these months vary by slightly less than an order of magnitude in April (1 to 6 $ft^3/s/mi^2$), and by slightly more than an order of magnitude in August (0.05 to 1 $ft^3/s/mi^2$). Figure 4 also illustrates that in individual years a monthly FDC may vary considerably from the medians of selected monthly flow durations (long-term median monthly FDC, represented by the bold red lines in figs. 4A and B). For example, comparison of the long-term median monthly FDC in August (fig. 4B) with the monthly FDCs for individual years with high or low flows shows that in years with extremely high flows, most of the daily streamflows for August may be higher than the long-term median monthly FDC; and that during years with extremely low flows, all of the daily streamflows in August may be lower than the long-term median monthly FDC.

Boxplots can be used to quantify the variability of monthly flows between years. A boxplot is a useful and concise graphical display that summarizes the distribution of a dataset (Helsel and Hirsch, 1992). On a boxplot, the median,

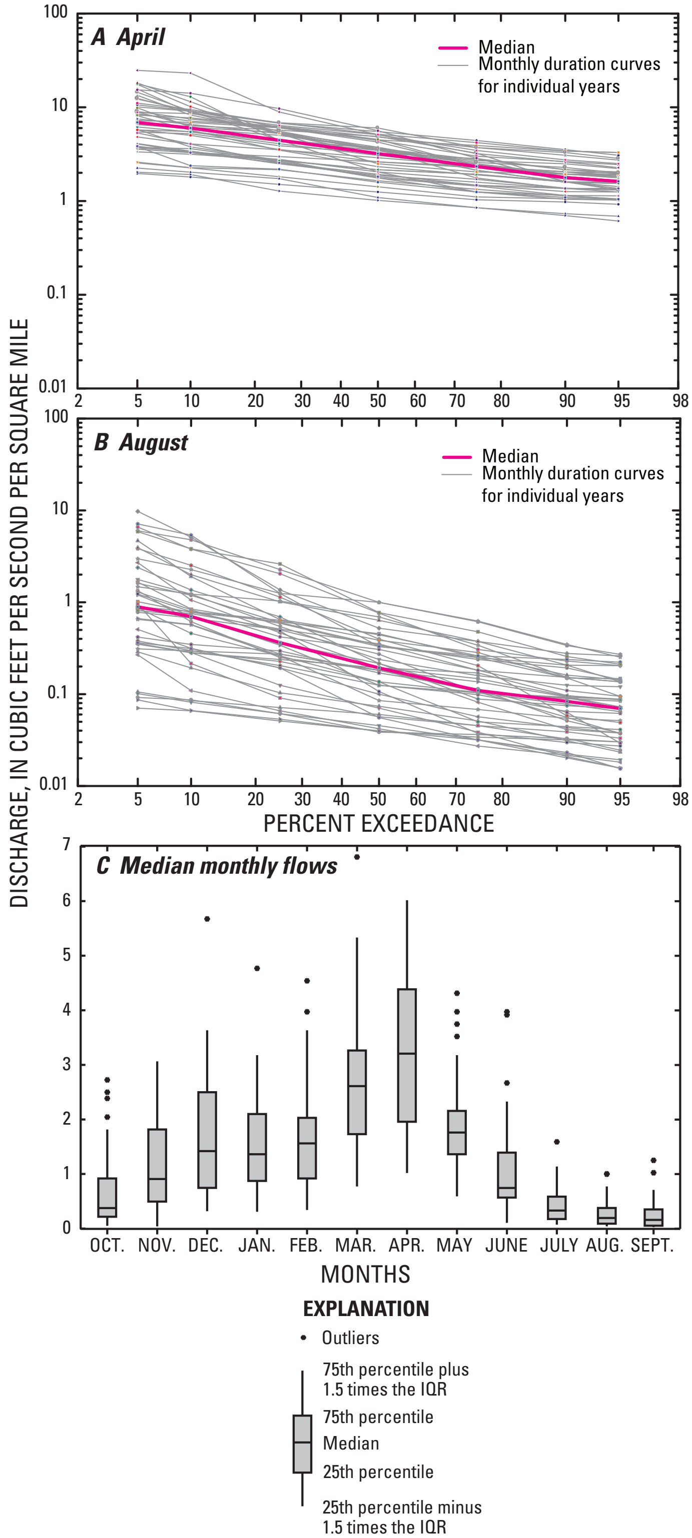


Figure 4. *(A)* Monthly flow-duration curves normalized by drainage area for April, *(B)* normalized monthly flow-duration curves for August, and *(C)* normalized median monthly flows for the Sevenmile River near Spencer, Massachusetts (01175670), 1961–2004.

or 50th percentile for a given monthly flow duration, is shown as the center line of the box. The variation, or spread of the data, is indicated by the bottom and top of the box, which are drawn to the 25th and 75th percentiles, respectively. The height of the box (between the 25th and 75th percentiles) is a common measure of variability known as the interquartile range (IQR). A boxplot (fig. 4C) of median monthly flows for each month of the POR at the Sevenmile River station indicates that median monthly flows are most variable during high flows in spring (April) and least variable during low flows in summer (July–September).

Note the differences between a percent exceedence on a FDC and a percentile on a boxplot of flows for a given monthly flow duration. For example, on a FDC, the Q_{75} represents a low flow for a specific month and year; this flow has a 75-percent probability of being equaled or exceeded during that month and year. On a boxplot showing the distribution of median flow durations (Q_{50}) for a given month over all the years, the 75th percentile represents a high median for that month (75 percent of all the Q_{50} values are less than or equal to this value).

Median monthly flows were calculated for the POR of each of the 85 stations in southern New England and were used to prepare annual hydrographs. Streamflows were divided (normalized) by drainage area because this characteristic was expected to explain most of the variability in flow between stations (Ries and Friesz, 2000) and because normalization allows comparisons to be made among basins with different drainage areas. The median monthly hydrographs for all 85 stations are shown together on a linear scale in figure 5A. The hydrographs show that the annual pattern of normalized median monthly flow exhibits similar seasonal patterns for most stations. Median monthly streamflows tend to rise during autumn (October, November) to moderate levels in winter (December, January, February); rise again in early spring to an annual peak (March, April); and decline through late spring and early summer (May, June) to low values in mid- to late summer (July, September). The magnitudes of median monthly flows differ among stations, with differences most pronounced in winter and spring (fig. 5A). A plot of median monthly flow per unit area on a log scale (fig. 5B), however, indicates a high degree of variability in low median monthly streamflows among stations during summer. The even distribution of median monthly flows for all the stations over a range of flows (figs. 5A and B) suggests that rivers in southern New England could potentially be classified into a single moderately heterogeneous hydrologic class.

Monthly flow durations were determined for the PORs of each of the 85 stations in southern New England. Boxplots of the normalized median monthly flows display the variability of median flows for the stations (fig. 5C). To quantify the magnitudes of monthly flow regimes for each station, the 25th percentiles, medians, and 75th percentiles for the Q_{25}, Q_{50}, and Q_{75} monthly flow durations are included for each station in appendix 3 (CD in back of report).

River-flow regimes can be classified by the shapes and magnitudes of the annual hydrographs of normalized median monthly flows (Harris and others, 2000; Hannah and others, 2000; Bower and others, 2004; Monk and others, 2006). The hydrographs differ among stations in different areas of southern New England (fig. 6), with the greatest differences apparent between stations in the northwest (figs. 6A and B) and southeast parts of southern New England (figs. 6E–H). The patterns of these hydrographs are controlled by a complex interaction of climatic and basin characteristics.

Median monthly flows calculated from stations in the northwest (fig. 6A) typically decrease from December into January and February as a result of winter conditions and snowpack buildup. Spring snowmelt causes high spring peaks in April with median monthly flows that range from about 4 to 6.5 $ft^3/s/mi^2$. Records from stations in north-central and northeastern Massachusetts and southeastern New Hampshire and in high relief areas of southwestern Massachusetts and northwestern Connecticut (figs. 6B and C) show median monthly flows that decline only slightly or remain at the same level during January and February. Median monthly flows at these stations peak in April, but the peaks are lower than those in records from stations in the northwest and range from about 2.5 to 4 $ft^3/s/mi^2$. Median monthly flows at stations in the south and east (figs. 6E–G) typically increase or remain constant from December through February and have earlier spring peaks in March or April as a result of milder winters and winter rains.

Median monthly flows in summer differ among stations primarily because of differences in the magnitude of groundwater discharge. Rivers with high median flows in summer, such as at the Herring, Pawcatuck, Beaver, and Wood River stations, generally drain areas that have extensive sand and gravel aquifers (figs. 6G and H). Because these aquifers are more common in southeastern than northwestern parts of southern New England, median monthly flows in summer for many southeastern stations tend to be higher than those for northwestern stations. Median monthly flows in July, August, and September at some stations in the southeast can be as high as 0.5 $ft^3/s/mi^2$ or higher, whereas median monthly flows for summer at most other stations are in the range of 0.2–0.4 $ft^3/s/mi^2$. Small basins that are predominantly in till areas (fig. 6F) may have normalized median monthly flows in summer that are as low as 0.1–0.2 $ft^3/s/mi^2$.

Streamflows in areas with very thick sand and gravel aquifers, such as Cape Cod and some areas of southeastern Massachusetts, differ very little throughout the year because of high rates of infiltration and ground-water discharge. Streamflows in these areas tend to reflect seasonal variations in the elevation of the water table. For example, median monthly flows at the Herring River station (01105880), the only station on Cape Cod used in this analysis (figs. 6H and 7), increase gradually from 0.6 $ft^3/s/mi^2$ in November to 0.9 $ft^3/s/mi^2$ in February, 1.3 $ft^3/s/mi^2$ in March, and 1.7 $ft^3/s/mi^2$ in May, and then gradually decline to about 1.3 $ft^3/s/mi^2$ in June, 0.9 $ft^3/s/mi^2$ in July, and 0.6 $ft^3/s/mi^2$ in October.

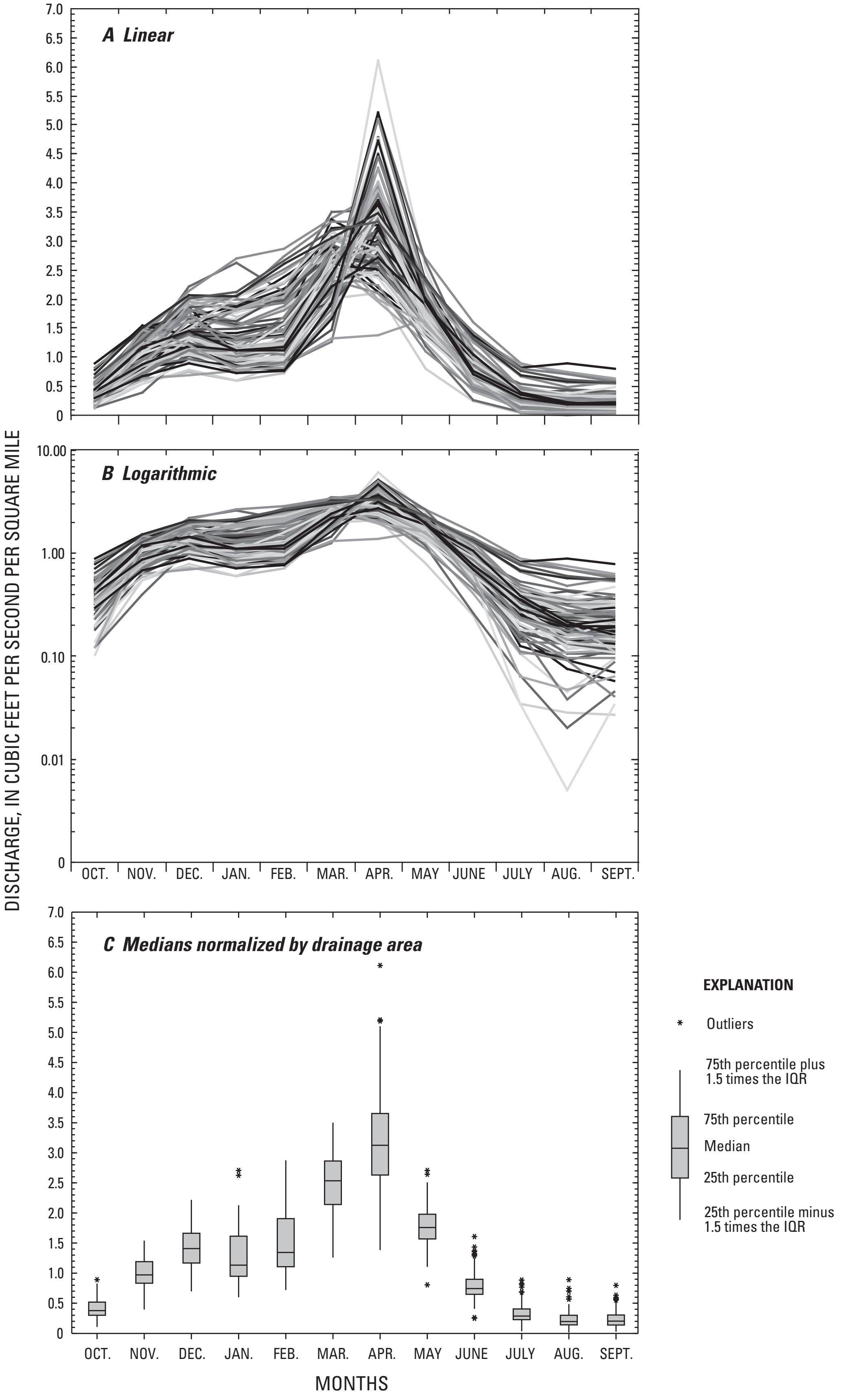


Figure 5. *(A)* Hydrographs, linear scale; *(B)* hydrographs, logarithmic scale; and *(C)* boxplots showing medians of monthly flow, normalized by drainage area, for the periods of record for 85 stations in southern New England.

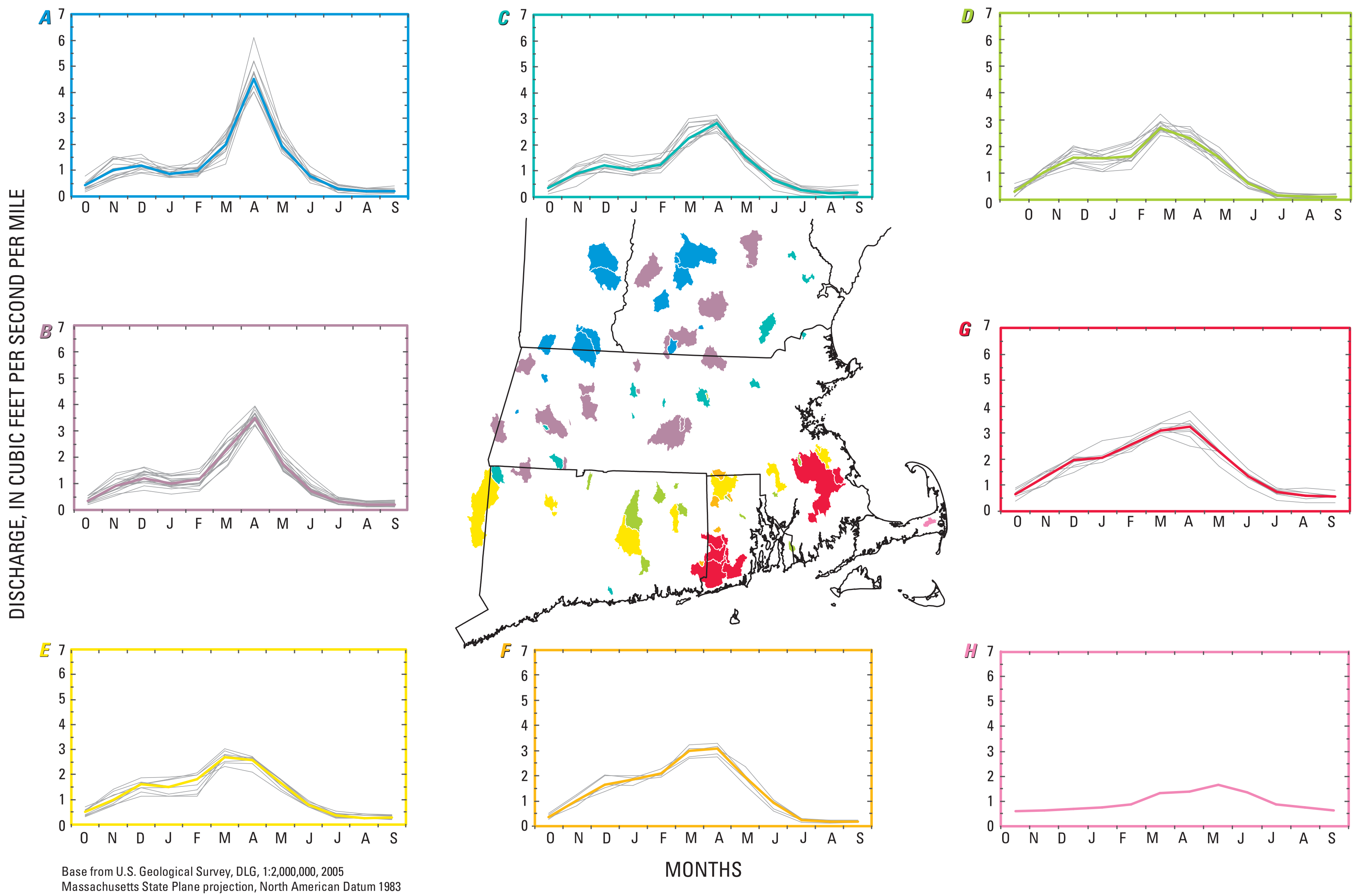


Figure 6. Median monthly flows normalized by drainage area for groups of stations in southern New England. The thick colored line on each graph represents the median for each group. The basins Letters A through H denote the different groups. The streamflow-gaging stations in each group are identified on the map by coloring the contributing areas to the stations to correspond with the color of the median line on the graph.

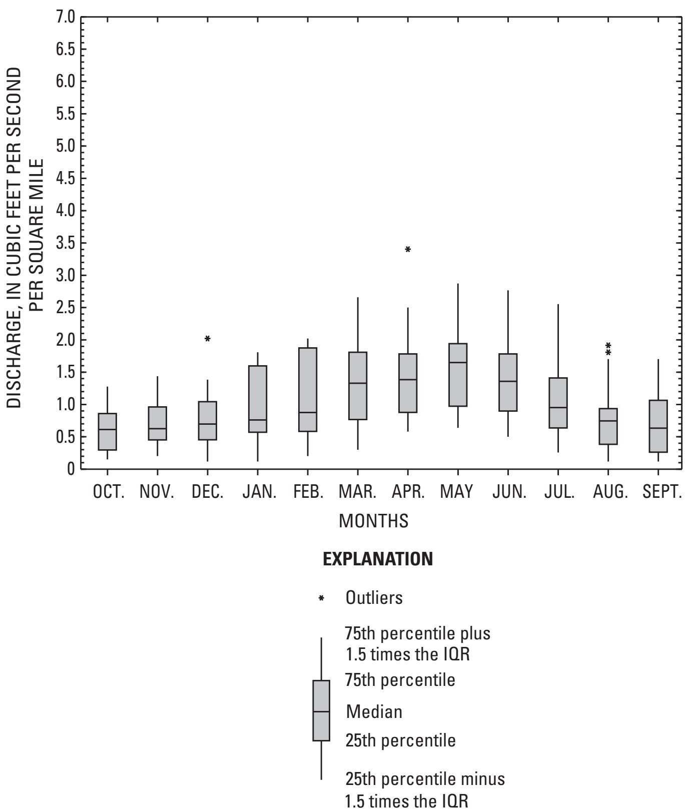


Figure 7. Median monthly flows for the Herring River at North Harwich, Massachusetts (01105880), 1966–1988.

In many years, the shape and magnitude of the annual median monthly flow hydrograph at a station are similar to the shape and magnitude of the graph of the long-term median. Streamflows can vary considerably among years, however, and the hydrograph will not resemble the pattern of the long-term median every year. For example, figure 8A, shows normalized median monthly streamflows for the West Branch Westfield River (01181000) for years when the median monthly hydrographs peaked in April. April peaks likely occurred in years when winters were cold enough for snow and ice to remain on the ground until spring. In other years, large-scale climatic controls caused median monthly flows to peak in months other than April (fig. 8B).

In any given year, the annual hydrographs of normalized median monthly flow were similar for stations with similar drainage areas and basin characteristics and that were in close proximity to one another. Figures 9A–D show median monthly hydrographs for the Green-Colrain (01170100), North (01169000), South (01169900), and West Branch Westfield (01181000) Rivers for 4 years with very different streamflow conditions. For example, figure 9 illustrates years for which normalized median monthly flows were very high in spring (2001; fig. 9A), low in spring (1968; fig. 9B), low in winter (2002; fig. 9C), or high in winter (2004; fig. 9D). The graphs indicate that the differences in the normalized median monthly streamflow among the four stations generally differed by only a few tenths of a cubic foot per second per square mile, even in years with different conditions.

Regression equations for predicting medians of monthly flow on the basis of basin characteristics were developed by using multiple linear regression (appendix 4, back of the report). The equations should be useful for estimating long-term median monthly flows for an ungaged site but should not be used to estimate the median monthly flows for any given year.

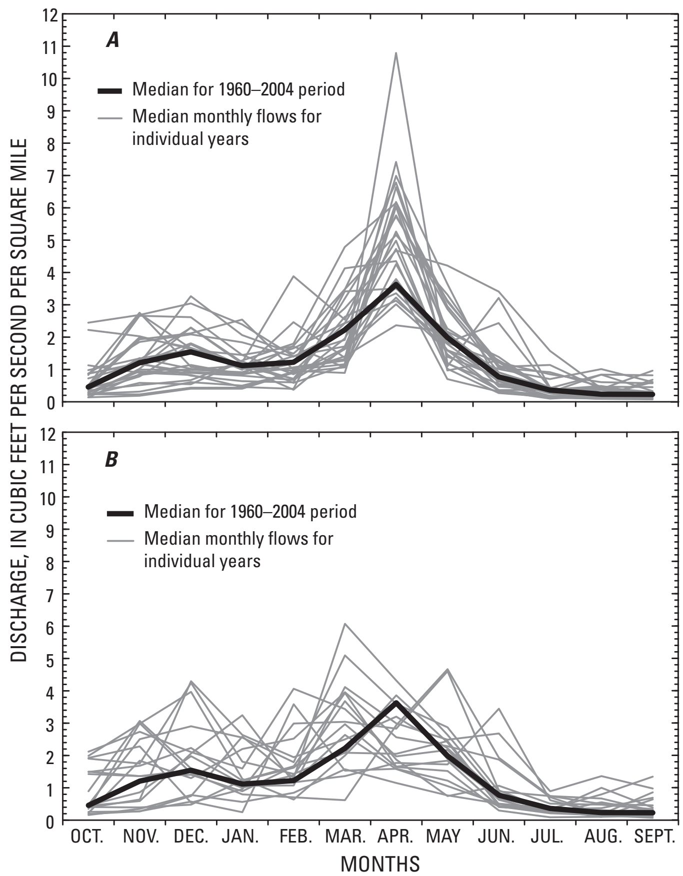


Figure 8. Medians of monthly flow normalized by drainage area for the West Branch Westfield River at Huntington, Massachusetts (01181000), for *(A)* years with median peaks in April and *(B)* years with median peaks in other months.

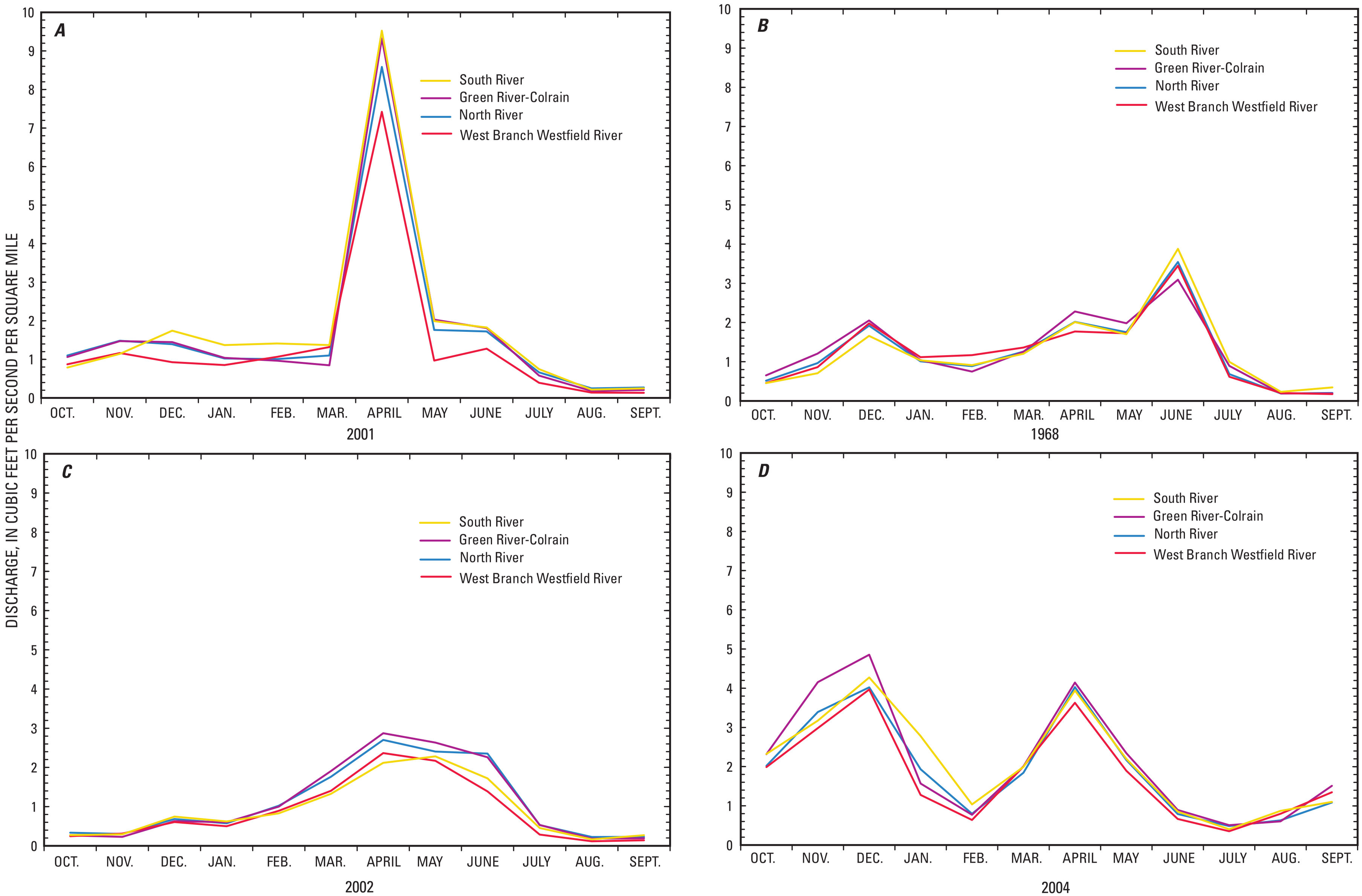


Figure 9. Median monthly flow for the Massachusetts stations Green River near Colrain (01170100), North River at Shattuckville (01169000), South River near Conway (01169900), and West Branch Westfield River at Huntington (01181000) during *(A)* 2001, *(B)* 1968, *(C)* 2002, and *(D)* 2004.

Assessment of Daily Streamflows by Using L-Moments

Daily streamflows were used to construct L-moment ratio diagrams for the PORs of 61 stations in southern New England. The “L” in L-moments refers to linear combinations of order statistics (Hosking and Wallis, 1997). Interpretation of L-moments ratios is roughly analogous to that of conventional product moments in that the first moment, the mean, provides information about the central value or location of a distribution; the second moment, L-CV, provides information about whether the distribution is widely dispersed or bunched (known as scale or dispersion); the third moment, L-skewness, provides information about whether the distribution is skewed to the right or left (symmetry); and the fourth moment, L-kurtosis, can be thought of as providing information about how far extreme values are from the central values (peakedness).

L-moment ratios (such as L-skewness and L-kurtosis) have many uses in regional frequency analysis such as for frequency analysis of floods, droughts, and rainfall. L-moment ratios are dimensionless versions of L-moments that summarize the main features of a probability distribution independent of its scale of measurement (Hosking and Wallis, 1997). Equations for the use of L-moments for parameter estimation for different probability distributions, such as the normal, lognormal, exponential, Gumbel, generalized pareto, generalized extreme value, generalized logistic, Pearson type III, and Wakeby distributions, are given in Hosking and Wallis (1997). Scatterplots of L-CV and L-skewness against L-kurtosis, known as L-moment ratio diagrams, can be used to characterize frequency distributions. L-moment ratio diagrams show compact groupings when the data are homogeneous (Hosking and Wallis, 1997). On an L-moment ratio diagram, a two-parameter distribution plots as a single point, and two- and three-parameter distributions are shown as points and lines, respectively.

An L-moment ratio diagram plotting L-skewness and L-kurtosis for the daily streamflow records for the 61 stations (fig. 10A) indicates the plotted points fall roughly along a wide line, indicating a similar underlying probability distribution for the stations and, thus, a statistical similarity among sites. The L-kurtosis and L-skewness ratios for the stations show a range of values across southern New England. L-moment ratios to the northwest tend to be generally higher than those to the southeast. One possible explanation for this trend is that both basin and climate characteristics (such as topographic relief, extent of sand and gravel aquifers, heating degree days, snowpack depth) differ from southeast to northwest across southern New England.

The stations occupy two groups distinguished from each other by both basin characteristics and geographic location (fig. 10B). The group with low L-skewness and L-kurtosis includes rivers in the southeast part of the study area. Drainage areas to these stations are characterized by large sand and gravel aquifers, low channel gradients, and many wetlands and impoundments that have a stabilizing effect on the range of daily flows and result in lower values of L-skewness and L-kurtosis. Stations in this base-flow-dominated group include the Pawcatuck River-Wood River Junction (01117500) and the Pawcatuck River-Westerly (01118500), Wood River-Arcadia (01117800) and Wood River-Hope Valley (01118000), Beaver (01117468), Nooseneck (01115630), Taunton (01108000), Wading (01109000), and Quaboag (01176000) Rivers.

Most stations within the group with high L-skewness and L-kurtosis values (colored blue in fig. 10B) are runoff-dominated rivers. Stations with values of L-skewness and L-kurtosis that plot at the upper end of the group, such as the North (01169000) and Hubbard (01187300) Rivers are in high-gradient basins that generate rapid runoff. Stations at the lower end of the group, such as Pendleton Hill Brook (01118300) and Branch River (01111500), are in lower relief basins where runoff processes are slower.

Streamflows at stations that are geographically adjacent to one another or even in the same basin do not necessarily have similar L-moment ratio values. For example, the plotted point for Pendleton Hill Brook, a Pawcatuck River tributary, is in the group with the runoff-dominated stations and not with the other base-flow-dominated stations in the Pawcatuck basin that have low L-skewness and L-kurtosis. Pendleton Hill Brook is a small headwater stream in an area of moderate relief that is predominantly till. Consequently, daily streamflows in Pendleton Hill Brook are more variable and have higher ratios of L-skewness and L-kurtosis than streamflows in downstream basins that have higher amounts of sand and gravel. The differences in the L-kurtosis and L-skewness ratios for adjacent sites indicate that geographic location alone does not explain differences in L-moments among the sites.

Although the plotted points occupy two groups on the L-skewness and L-kurtosis ratio diagram, the gap between the two groups may, in part, be a function of the stations used in the analysis. For example, streamflow records from many river basins in eastern and east-central Massachusetts were not well represented in this study because of flow alterations. Some of these basins may have had runoff and summer base-flow characteristics under a natural-flow regime that would have fallen between those of the stations for the two groups on the L-moment ratio diagram. Under such conditions, the diagram might have shown one gradually varying continuum instead of the two groups.

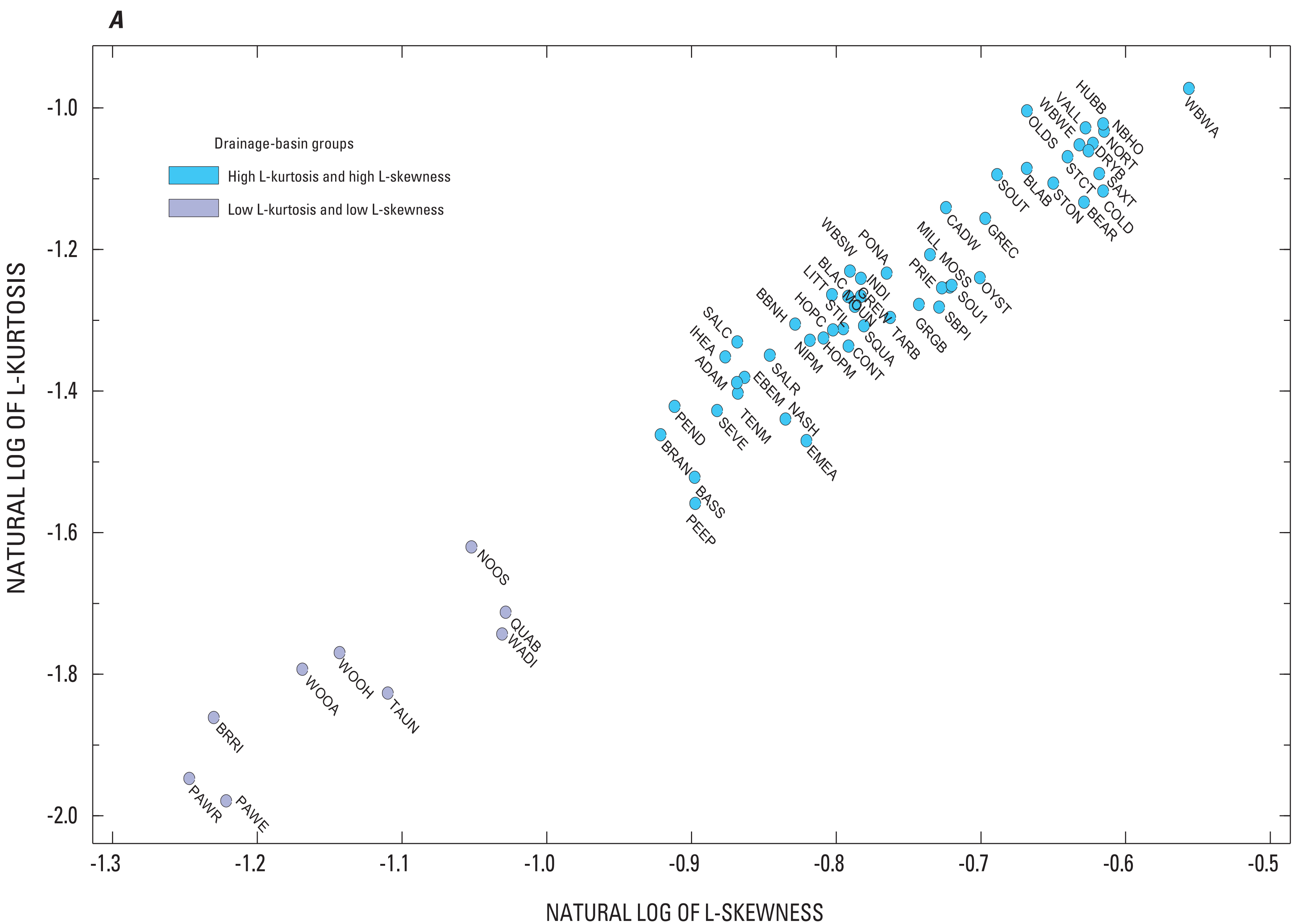


Figure 10. *(A)* L-moment ratio diagram and *(B)* map showing groups of stations with high L-kurtosis and high L-skewness ratios and low L-kurtosis and low L-skewness ratios for 61 streamflow-gaging stations in southern New England. Code names for the streamflow-gaging stations are listed in table 1.

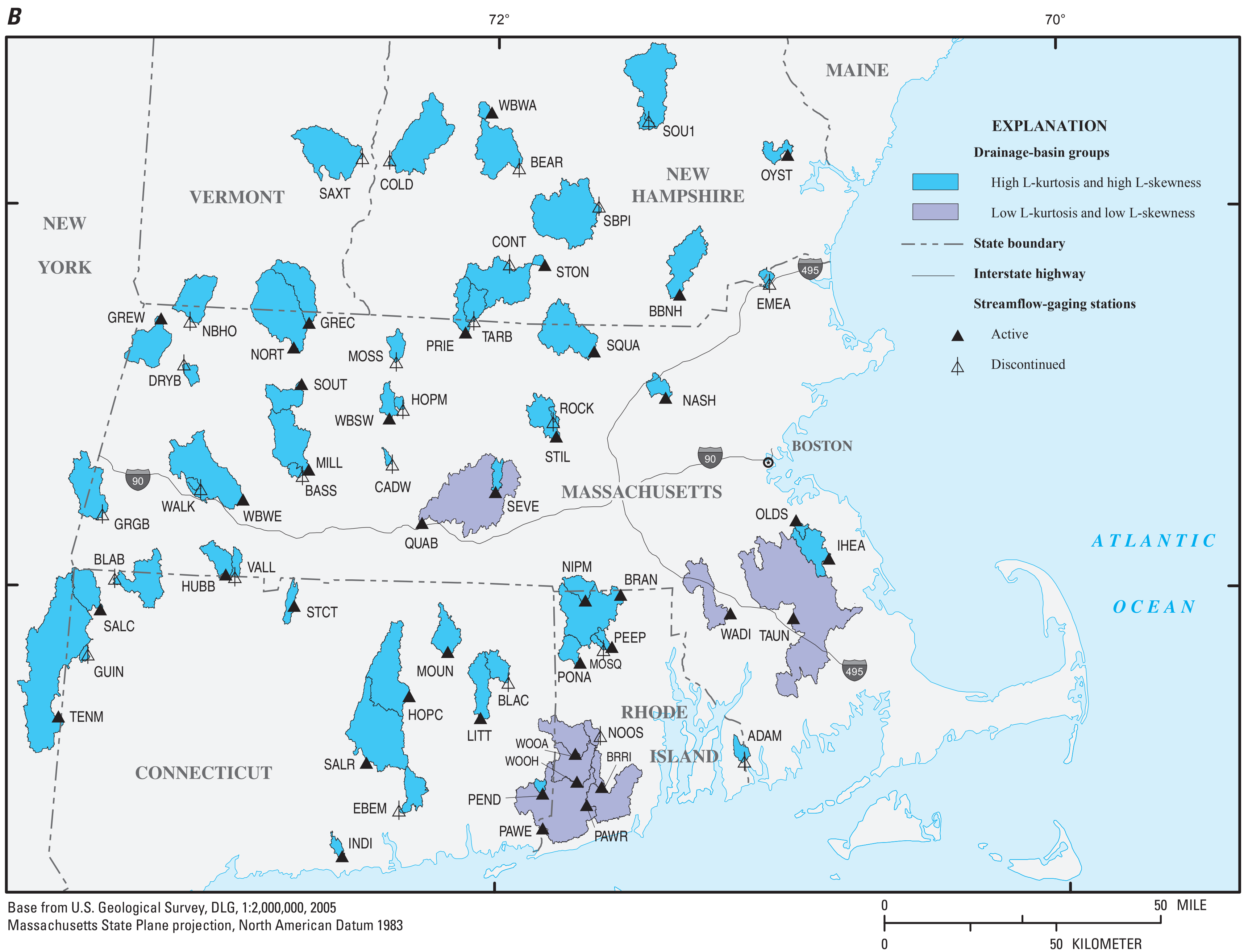


Figure 10. *(A)* L-moment ratio diagram and *(B)* map showing groups of stations with high L-kurtosis and high L-skewness ratios and low L-kurtosis and low L-skewness ratios for 61 streamflow-gaging stations in southern New England. Code names for the streamflow-gaging stations are listed in table 1.—Continued

Streamflow Statistics Determined for a Concurrent Period (1960–2004)

Streamflow statistics were calculated for 61 stations for a concurrent 45-year period from 1960 through 2004. Selection of the record length for the concurrent-period analysis required balancing the number of stations available for analysis with the needs to represent long-term climate conditions and minimize the effects of land-use change on streamflow. In general, streamflow statistics determined for a longer POR tend to be more representative of long-term climate conditions, whereas statistics based on a short term POR may be biased by wet or dry climate cycles if those cycles compose a large part of the POR. The longer the POR, however, the lower the likelihood that current land-use conditions represent the land-use conditions during the period when flows were measured.

Different PORs have been recommended to characterize the flow variability of the high- and low-flow portions of the flow regime. Bulletin 17B (Interagency Advisory Committee on Water Data, 1982) recommended a 25-year POR for flood-frequency analyses. Gan and others (1991) suggest that as many as 40 years of streamflow record may be required to characterize high-flow variability, and Huh and others (2005) suggest that as many as 60 years of streamflow record may be required to characterize low-flow variability. The 1960–2004 time period was selected to include the 1960s drought, considered to be the modern drought-of-record in Massachusetts. Streamflows prior to 1960 were not used to limit the amount of land-use change represented by the POR and the number of years of record that needed to be simulated. Because of constraints in time, cost, and data availability, an analysis to quantify relations between trends in streamflows and changes in climate, land use, water withdrawals, and water returns was not conducted. Land use in the contributing areas to the stations chosen for this analysis changed during the concurrent period. Additional analysis would have been needed to quantify the effects of the type and extent of land-use change on flow statistics.

Record Extension

Record-extension techniques were used to estimate missing streamflow data for 46 of the 61 stations to increase the number of records that could be used in the concurrent-period analysis. Record extension is a technique of extending the historical record at a short-term streamflow-gaging station by correlation with concurrent flows at a nearby long-term station. A maintenance of variance extension (MOVE) technique developed by Hirsch (1982) and modified by Vogel and Stedinger (1985) was used to simulate missing records for the 1960–2004 period. MOVE techniques use the relation between two streamflow records for their common data period to produce a time series for the missing record that has variances similar to those of the existing record for the short-term station. The MOVE technique used in this study was Maintenance Of Variance Extension, type 3 (MOVE.3) (Vogel and Stedinger, 1985). The MOVE.3 process requires a long-term station that has several years of record coincident with those of the short-term station. The long-term station should be minimally regulated or have flow alterations that are limited to small, constant withdrawals or return flows. Concurrent daily streamflows in the common periods for the short and long-term stations must be highly correlated. Correlation coefficients were computed between the base-10 logarithms of daily mean streamflow for the concurrent periods of the short-term and candidate long-term stations. Because log values cannot be calculated for flows with values of zero, zero flows were replaced with a small discharge value of 0.001 ft^3/s prior to record extension. As a consequence, the extended datasets do not include zero discharges in either their measured or extended parts of the record. The long-term record with the highest correlation with the short-term record was generally selected for record extension. As a rule-of-thumb, the measure of the correlation between the logs of streamflows at the short- and long-term stations should be at least 0.80 for the long-term record to be used for record extension, and a correlation of greater than 0.90 or higher is preferred (R. Vogel, Tufts University, oral commun., 2004). The best stations for record extension turned out to be stations with similar drainage areas and similar basin characteristics near to the short-term station.

Plots of stations with base-10 logarithms greater than or equal to 0.90 indicated a general pattern of more stations with high correlations to the northeast or southwest from one another than to the northwest or southeast. Possible explanations for this pattern may be that multiple basin and climate characteristics—such as elevation, sand and gravel deposits, and the maximum depth of winter snowpack—differ more from southeast to northwest across southern New England than from southwest to northeast and that the predominant direction of storm tracks across southern New England is from west to east and northeast along the coast. The pattern may also be a function of the spatial distribution of the stations. The lack of index stations in eastern and central Massachusetts created a gap that extends from Boston into central Massachusetts, and records from only a few stations correlated highly across this gap.

The MOVE techniques are based on the assumption that a linear relation exists between the concurrent flows at the short-term and long-term stations. Streamflow regulation can cause nonlinearity in the relation between the low streamflows at two stations. Stations with nonlinear relations were identified visually by plotting the log-transformed short- and long-term streamflow data, fitting a linear regression line to the data, and looking for deviations from the regression line. Examples of good and poor linear relations are shown in figures 11A and B, respectively. Occasionally, the long-term record with the highest correlation of daily flows did not have a good linear relation for extreme high or low flows, and other sites needed to be identified. In addition, records for some short-term stations required records from two or more long-term stations for extension to the full 45-year period. The long-term stations used to extend the streamflow record are shown in table 6 with the correlations between the daily flows (in log space) at the short- and long-term stations.

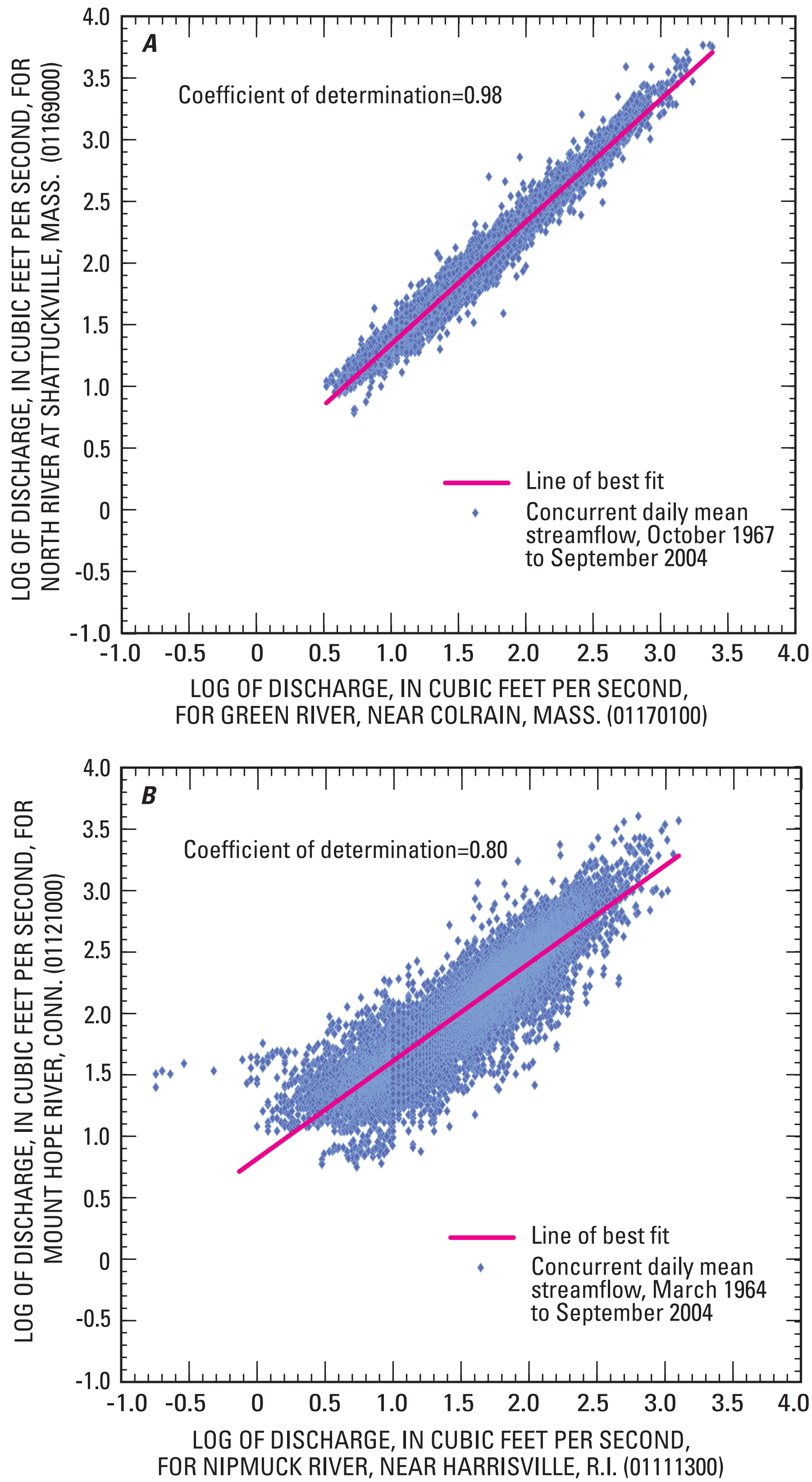


Figure 11. Comparison of the log of daily mean discharges for common periods for *(A)* Massachusetts stations Green River near Colrain (01170100) and North River at Shattuckville (01169000), 1967–2004; and *(B)* Nipmuc River near Harrisville, Rhode Island (01111300), and Mount Hope River near Warrenville, Connecticut (01121000), 1964–2004.

Table 6. Streamflow-gaging stations used for MOVE.3 Record Extensions, southern New England, 1960–2004.

[USGS, U.S. Geological Survey; MOVE.3, Maintenance of Variance Extension, type-3; --, coefficient not calculated]

USGS station number	Station name	Station(s) used for MOVE.3 record extension	Correlation coefficient	Period of extension
01082000	Contocook River near Peterborough, NH	Squannacook River (01096000)	0.92	1978–2000
01084500	Beards Brook near Hillsboro, NH	West Branch Warner River (01085800)	.95	1971–2004
01085800	West Branch Warner River near Bradford, NH	Warner River (01086000)	.93	1960–1961
01086000	Warner River near Davisville, NH	Soucook River near Concord (01089000)	.95	1979–1987
		Soucook River near Pembroke (01089100)	.97	1988–2001
		Squannacook River (01096000)	.92	1987–1988
01089000	Soucook River near Concord, NH	Soucook River at Pembroke Road, near Concord (01089100)	--	1988–2004
01091000	South Branch Piscataquog River near Goffstown, NH	Squannacook River (01096000)	.96	1979–2004
01093800	Stony Brook Tributary near Temple, NH	South Branch Piscataquog River (01091000)	.95	1960–1962
01095220	Stillwater River near Sterling, MA	Cadwell Creek (01174900)	.88	1961–1994
		Sevenmile River (01175670)	.87	1961
		Squannacook River (01096000)	.94	1960
010965852	Beaver Brook at North Pelham, MA	Oyster River (01073000)	.94	1960–1985
01097300	Nashoba Brook near Acton, MA	Squannacook River (01096000)	.95	1960
		Sevenmile River (01175670)	.88	1961–1963
01100700	East Meadow River near Haverhill, MA	Squannacook River (01096000)	.91	1960–1961, 1975–2004
01105600	Old Swamp River near South Weymouth, MA	East Branch Eightmile River (01194500)	.87	1960–1965
01105730	Indian Head River at Hanover, MA	Taunton River (01108000)	.95	1960–1965
01106000	Adamsville Brook at Adamsville, RI	Pendleton Hill Brook (01118300)	.90	1988–2004
01108000	Taunton River near Bridgewater, MA			
01111300	Nipmuc River near Harrisville, RI	Mount Hope River (01121000)	.92	1960–1963, 1992
01115098	Peeptoad Brook at Elmdale Road near Westerly, RI	Wading River (01109000)	.94	1960–1993
01115187	Ponaganset River at South Foster, RI	Nipmuc River (01111300)	.94	1964–1991
		Wading River (01109000)	.93	1960–1963, 1991–1993
01115630	Nooseneck River at Nooseneck, RI	Wood River Acadia (01117800)	.92	1960–1962
		Pendleton Hill Brook (01118300)	.93	1982–2004, 1981
01199050	Salmon Creek at Lime Rock, CT	Tenmile River (01200000)	.93	1960
01117468	Beaver River near Usquepaug, RI	Wood River at Hope Valley (01118000)	.96	1960–1973
01118000	Wood River near Arcadia, RI	Wood River at Hope Valley (01118000)	.99	1981
01120000	Hop Brook near Columbia, CT	Mount Hope River (01121000)	.95	1972–2004
01126600	Blackwell Brook near Brooklyn, CT	Mount Hope River (01121000)	.95	1960–1962, 1977–2004
01154000	Saxtons River at Saxtons River, VT	North River (01169000)	.92	1983–2000

Table 6. Streamflow-gaging stations used for MOVE.3 Record Extensions, southern New England, 1960–2004.—Continued

[USGS, U.S. Geological Survey; MOVE.3, Maintenance of Variance Extension, type-3; --, coefficient not calculated]

USGS station number	Station name	Station(s) used for MOVE.3 record extension	Correlation coefficient	Period of extension
01155000	Cold River at Drewsville, NH	Green River near Colrain (01170100)	0.93	1983–2000
01161500	Tarbell Brook near Winchenden, MA	Priest Brook (01162500)	.92	1984–2004
01165500	Moss Brook near Winchenden, MA	Otter River (01163200)	.93	1983–2004
01169900	South River near Conway, MA	North River (0116900)	.96	1960–1965
01170100	Green River near Colrain, MA	North River (0116900)	.99	1960–1966
01171800	Bassett Brook near North Hampton, MA	Mill River (01171500)	.96	1960–1962, 1975–2004
01174000	Hop Brook near New Salem, MA	Sevenmile River (01175670)	.93	1983–2004
01174565	West Branch Swift River near Shutesbury, MA	Cadwell Creek (01174900) Mill River (01171500)	.95 .92	1961–1982 1986–1994, 1960
01174900	Cadwell Creek near Belchertown, MA	West Branch Swift River (01174565) Hubbard River (01187300)	.94 .93	1998–2004 1960
01175670	Sevenmile River near Spencer, MA	South Branch Piscataquog River (01091000)	.92	1960
01180000	Sykes Brook at Knightville, MA	West Branch Westfield River (01181000)	.97	1975–2004
01184100	Stony Brook near West Suffield, CT	Hubbard River (01187300)	.92	1960–1980
01187400	Valley Brook near West Hartland, MA	Hubbard River (01187300)	.96	1973–2004
01194500	East Branch Eightmile River near North Lyme, CT	Mount Hope River (01121000)	.92	1982–2000
01195100	Indian River near Clinton, CT	Pendleton Hill Brook (01118300)	.90	1960–1980
01198000	Green River near Great Barrington, MA	West Branch Westfield River (01181000)	.93	1972–1993, 1997–2004
01198500	Blackberry River at Canann, CT	Hubbard River (01187300)	.94	1972–2004
01199050	Salmon Creek at Lime Rock, CT	Blackberry River (01198500)	.93	1960
01200000	Tenmile River near Gaylordsville, CT	Salmon Creek (01199050)	.93	1988, 1991–2004
01331400	Dry Brook near Adams, MA	Green River at Williamstown (01133000)	.90	1960–1961, 1975–2004
01332000	North Branch Hoosic River at North Adams, MA	Green River at Williamstown (01133000)	.93	1991–2004

Hydrologic Indices

Streamflow statistics that characterize the variability in the natural-flow regime were determined for 61 stations for the concurrent period (1960–2004) dataset, by using the IHA (The Nature Conservancy, 2005) and the HIT (Olden and Poff, 2003; Henrikson and others, 2006) programs. The IHA program calculates 67 hydrologic indices, while the HIT program calculates 171 indices. The hydrologic indices determined by the IHA and HIT programs can be used to characterize and compare hydrologic regimes in ecologically meaningful terms (Richter and others, 1996, 1997; Olden and Poff, 2003).

The IHA and HIT indices can be divided into five classes that describe the magnitude, frequency, magnitude and duration of annual extremes, timing of annual extremes, and rate of change of streamflow. Magnitude indices measure the size of a high, low, or statistically defined streamflow within a fixed time period. Magnitude indices may be measures of average flow conditions, such as annual means or monthly means or medians, or measures of low- or high-flow events, such as monthly minimums or maximums. Frequency indices are counts of the number of times a streamflow rises above or falls below a specified low- or high-flow threshold during a fixed time period. Duration statistics are measures of the magnitude of streamflow during a specified time period, such as the minimum average streamflow for a 7-day or 30-day period. Timing refers to measures of the dates of specific flows, such as the Julian dates of annual minimum or maximum flows. Rates of change refer to the rates at which streamflows rise or fall and were calculated for this study as the rates of rise and fall of daily mean discharges.

The 67 hydrologic indices produced by the IHA program include 33 indices that quantify the major components of hydrologic regimes: 24 that measure the magnitude of monthly flows, 2 that measure the timing of extreme flows, 4 that measure the frequency and duration of high and low flows, and 3 that measure the rate of change of flow. IHA streamflow statistics were calculated for the annual period of a water year (October–September), except for the long-period *n*-day low flows (30- and 90-day low flows), which were calculated for a climate year (April–March). In New England, the April–March time period generally allows better representation of the magnitudes of the long-period low flows (30-day and 90-day) because, in some years, summer low-flow conditions extend into autumn of the next water year. In addition to the original 33 indices, IHA version 7 also includes a set of 34 indices that describe high- and low-flow conditions; these indices are referred to as Environmental Flow Components (EFCs). The EFCs include 12 indices that measure monthly low flows; 4 that measure the magnitude, duration, timing, and frequency of extreme low flows; and 18 that measure the magnitude, duration, timing, frequency, and rate of change of high flows. For this study, the EFCs were defined by using IHA default values that approximate 2-year and 10-year return periods.

The 171 hydrologic indices determined by the HIT program are described in Olden and Poff (2003) and Henriksen and others (2006). Like the indices developed by the IHA, the HIT hydrologic indices can be divided into five classes describing the magnitude, frequency, duration, timing, and rate of change of streamflow. The HIT program calculates some indices not included in the IHA, such as the skewness of daily flow; indices that measure low-flow and high-flow volumes; and additional indices that measure flow variability, such as the coefficient of variation (CV) of daily flows and the CV of monthly mean flows. The 171 HIT hydrologic indices include 94 that measure magnitude, 14 that measure frequency, 44 that measure duration, 10 that measure timing, and 9 that measure the rate of change of streamflow (Olden and Poff, 2003; Henricksen and others, 2006).

The hydrologic indices used in this analysis were determined with earlier versions of the HIT and IHA software. In the currently available (2007) versions of the HIT and IHA, the hydrologic indices provided by HIT can be selected to include statistics identical to those determined by the IHA program (J. Henriksen, U.S. Geological Survey, oral commun., 2005). For this study, however, central-tendency values were calculated as medians by the IHA program and as means by the HIT program. Consequently, there was no duplication between the statistics from the two programs, and all indices from the HIT and IHA programs were used in the initial analysis with the following 14 exceptions: 3 HIT indices and 1 IHA index that describe the frequency and variability of zero flows for intermittent streams, 6 HIT indices that require peak-flow data, 2 IHA indices describing peak flows of small and large floods, and 2 HIT indices related to seasonal predictability of flows. The indices related to zero flow were not used in the analysis because the extended records do not include zero flows; the indices related to peak flows were not used because instantaneous peak-flow data were not available for the records that required extension.

The IHA and HIT flow indices are provided for 61 streamflow-gaging stations in appendix 5 and appendix 6, respectively, on the CD in the back of the report. The statistics were calculated from the extended-record dataset for the stations for the concurrent period 1960–2004. The IHA discharge indices are reported in units of both cubic feet per second and cubic feet per second per square mile to facilitate comparisons among basins.

Hydrologic Classification of Stations

A two-step multivariate statistical approach (Olden and Poff, 2003; Poff and others, 2006; Henriksen and others, 2006; Kennen and others, 2007) was used to develop a hydrological classification of streams in southern New England. In the first step, the streamflow statistics and hydrologic indices determined using the IHA and HIT programs are used in a PCA to reduce data redundancy and to identify the variables in the dataset that account for the most variation. The second step uses a hierarchical CLA to classify the data for the stations according to their similarity.

Data Screening and Standardization

The initial dataset consisted of 224 hydrologic indices determined by the IHA and HIT programs for the 61 stations. The dataset was arranged into a matrix consisting of 61 rows (stations) and 224 columns (hydrologic indices). Prior to the PCA analysis, indices measuring discharges in cubic feet per second were standardized by dividing the discharge values by the drainage areas to the stations. The IHA and HIT statistics include indices measured in different units, such as discharges, counts, durations, percentages, Julian dates, and rates of rise and fall. Because it can be difficult to compare the variability of indices measured in different units, all hydrologic indices were normalized to Z scores, using PC-ORD, to give each of the indices equal weight in the analysis (Haan, 2002; McCune and Grace, 2002; Clarke and Warwick, 2001). A Z-score is the number of standard deviations each observation is from its own mean. Normalization to Z-scores gives each column of hydrologic indices a mean of zero and a standard deviation of one.

Outliers can have a large influence on the results of multivariate analyses. An outlier analysis of the hydrologic-index data, by using PC-ORD software (McCune and Mefford, 1999; McCune and Grace, 2002), identified outliers more than two standard deviations away from the mean. Hydrologic indices identified as potential outliers included a measure of the maximum daily flow, four measures of the variability of rise and fall rates, and several measures of the timing of extreme high and low flows. These potential outliers were flagged and removed later in the analysis once additional variables were identified that were highly correlated (collinear) with the potential outliers.

Principal-Components Analysis (PCA)

PCA is an ordination technique—a method of creating a map of samples, in two or more dimensions, in which relations among samples can be defined by the relative position of the stations. A PCA simplifies the interpretation of a complex dataset by organizing variables along gradients that represent the maximum variation within a dataset. These gradients, called principal components, are weighted linear combinations of the original variables and are relatively independent of one another (McGarigal and others, 2000; Tabachnick and Fidell, 2001).

A detailed description of a PCA, which involves eigenanalysis and matrix algebra, is beyond the scope of this report. Briefly, PCA involves the following steps (McCune and Grace, (2002). First, a correlation matrix is calculated. Next, the eigenvalues and the corresponding eigenvectors of the correlation matrix are computed and used to determine the linear combination of variables (the eigenvector) that explains the most variance in the matrix (the eigenvalue). An eigenvalue represents the proportion of the original total variance that is explained by a particular principal-components (PC) axis. The first principal components axis (PC1) explains the most variance, the second axis (PC2) the second most, and so on. Finally, the principal-components scores (which represent the number of standard deviations of each variable from the overall principal-components mean) and variable loadings (the correlation between each variable and each PC axis) are derived. The results of a PCA analysis are generally shown with an output table and a biplot. The top portion of the output table generally shows the eigenvalues of the principal components and the percent of variance explained by each of the principal components (usually only the first three or four principal components are shown). The loading values in the bottom portion of the table indicate the correlations of the original variables with each PC axis.

A PCA biplot is a scatter diagram that shows the relations between PC scores and loadings. On a biplot, the stations are plotted as points with the origin at the center and the axes representing the principal components scores. The distance between the stations on a biplot represents dissimilarity, that is, points that are close to one another are more similar than those that are far apart. A perpendicular line drawn from a station to a principal components axis indicates the ranking of that station relative to that principal component. Stations on the edge of the diagram (far from the origin) are the most important for indicating differences for that PC axis, and stations near the center are of minor importance. The hydrologic indices are indicated on the biplot by lines. Each line points in the direction of maximum variation for that hydrologic index, and eigenvector loadings determine the lengths of the lines. Lines that point in the same direction indicate indices with a positive correlation, lines pointing in opposite directions indicate indices with a negative correlation, and lines that are perpendicular to one another indicate indices that are relatively independent. By mentally rotating the axis to coincide with the vector for a specific hydrologic index, and drawing perpendicular lines from the stations to this vector, the ranking of the stations relative to that hydrologic index can be determined. Biplots can be rotated or flipped on their axes, without changing the information shown.

Initially, the data for the 61 stations and the 224 hydrologic indices generated by the IHA and HIT programs were input into the PCA program (McCune and others, 2002). The

PCA output was analyzed to identify statistically significant, non-redundant indices, prior to classification using cluster analysis. Unless removed, data redundancy (multicollinearity) can bias a cluster-analysis solution toward over-represented aspects of the flow regime (Puckridge, 1998; Olden and Poff, 2003; Sanborn and Bledsoe, 2006). To reduce the multicollinearity between indices while maintaining the significant indices in the dataset, indices with the highest absolute (positive and negative) eigenvector loadings were retained, and indices that accounted for very little variability were removed. To the extent possible, the variables with the highest eigenvector loadings were retained for use in the CLA. In certain circumstances, however, indices with slightly lower loadings were selected. Indices were selected on the basis of the following guidelines: (1) one or more indices were selected within each of the five major flow categories (magnitude, frequency, duration, rate of change, and timing); (2) for cases where the IHA and HIT programs produced similar indices that covaried, only one of the indices was retained; (3) the total number of hydrologic indices used in the PCA was limited to 20 to maintain a 3:1 ratio of stations to indices (McGarigal and others, 2000), and (4) the number of indices retained for each principal-components axis, relative to the total number of indices, was selected to be roughly proportional to the variance explained by that principal component. Exploratory data analysis and data reduction in CANOCO (ter Braak, and Smilauer, 2002; Leps and Smilauer, 2003) facilitated the testing of different indices in the PCA. For consistency, however, the final PCA and CLA were done using PC-ORD (McCune and others, 2002).

The 224 IHA and HIT hydrologic indices were reduced to a set of 20 indices (table 7) that had high eigenvector loadings on four principal-component (PC) axes. Flow statistics for the 20 hydrologic indices for each of the index stations are given in table 8 (in back of report). The PC eigenvalues for each axis were compared to those for a Broken Stick distribution (McGarigal and others, 2000) to determine the number of PC axes that accounted for more variation than might be expected from random data. The comparison indicated that four PC axes were significant. Eigenvector loadings for the first four axes are given in table 9. The four PCs explained approximately 92 percent of the total variability of the dataset, with the first four axes explaining 45, 20, 16, and 11 percent of the total variance, respectively.

Biplots of the 20 hydrologic indices on the first three PC axes are shown in figures 12A–C. The separation of the stations along each PC axis indicates distinct differences in the streamflow characteristics among stations, but the relatively even distribution of points on the biplots indicates a gradation of streamflow characteristics among stations. The plot of PC1 and PC2 (fig. 12A) indicated distinct differences between a group of stations in southern Rhode Island (the Wood, Pawcatuck, Nooseneck, and Beaver Rivers) and the rest of the stations in southern New England; this grouping is similar to that shown by the L-moments analysis.

Although the PC axes themselves were not used for further statistical analysis, the PCA ordination is useful in interpreting the dominant modes of variability within the dataset. The first principal component (PC1) distinguishes primarily between stations with records that have more stable flows and higher low flows (base-flow-dominated), and stations with records that have greater flow variability and lower low flows (runoff-dominated). Eigenvector variables with high loadings for PC1 include a base-flow-volume index (ML20), a base-flow index (ML17), and indices that indicate the variability of both monthly flows (MA35, MA33, MA27), and daily flows (MA3) (table 9). Stations that have records that show higher low flows and stable daily and monthly flows are predominantly in southern Rhode Island and southeastern Massachusetts basins that have extensive or thick deposits of sand and gravel, such as the Beaver (01117468), Pawcatuck (01117500, 01118500), and Wood (01117800, 01118000) Rivers. Stations that have records that show lower low flows and more highly variable flows are predominantly in high relief basins in till and bedrock upland areas, such as Hubbard River (01187300) and Valley Brook (01187400) in Connecticut, Cadwell Creek (01174900) in Massachusetts, and Beard Brook (01084500) and Stony Brook Tributary (01093800) in New Hampshire.

The second principal component (PC2) distinguishes primarily between stations with records that have differing magnitudes of daily flows (MA1), higher variability of monthly mean flows in autumn (MA20 and MA22), and greater fall rates (IHA_RF1) (table 9). This component separates many of the stations in New Hampshire, Vermont, and northern Massachusetts, such as Beaver Brook (010965852), Cold River (01155000), Oyster River (01073000), and Soucook River (01089100), from the remainder of the stations in the study.

The third principal component (PC3) distinguishes primarily between stations with records that have later annual maximum flows (IHA_JMAX), higher mean flows in April (MA15), and lower mean flows in January (MA12) from stations that have records with earlier maximums, lower April flows, higher flows in January, and a greater variability in a base-flow index (ML18) (table 9). This component separates records for stations in western Massachusetts, Vermont, and New Hampshire basins that have high elevations and gradients and more northern-style winters—such as the North (01169000) River and Green River-Colrain (01170100) stations—from stations in Connecticut, Rhode Island, and southern and eastern Massachusetts basins that have more southern-style winters—such as the Adamsville (01106000), Indian (01195100), Pendleton Hill (01118300) Brooks, and Ponaganset River (01115187) stations.

The fourth principal component (PC4) distinguishes primarily between stations with records that have greater frequencies of both high flows (FH9) and low flows (FL1) and lower magnitudes of 90-day high flows (IHA_HD5) (table 9) and stations with records that have lower frequencies of high-flow and low-flow events and greater magnitudes of 90-day high flows. This component distinguishes records for stations

Table 7. Hydrologic indices used to characterize and classify streamflows in southern New England.

[ft³/s, cubic feet per second; HIT, Hydrologic Index Tool; IHA, Indicators of Hydrologic Alteration]

Hydrologic indices	Code	Units	Program	Definition
				Magnitude
Mean of the daily mean flow	MA1	ft^3/s	HIT	Mean of the daily mean flow values for the entire flow record.
Mean of the coefficients of variation	MA3	Percent	HIT	Mean of the coefficients of variation (standard deviation/mean) for each year. Compute the coefficient of variation for each year of daily flows. Compute the mean of the annual coefficients of variation.
Mean of January flow	MA12	ft^3/s	HIT	Mean of January flow values. Compute the means for each month over the entire flow record. ML12 is the mean of all January flow values over the entire record.
Mean of April flow	MA15	ft^3/s	HIT	Mean of April flow values. Compute the means for each month over the entire flow record. ML15 is the mean of all April flow values over the entire record.
Mean of September flow	MA20	ft^3/s	HIT	Mean of September flow values. Compute the means for each month over the entire flow record. MA20 is the mean of all September flow values over the entire record.
Mean of November flow	MA22	ft^3/s	HIT	Mean of November flow values. Compute the means for each month over the entire flow record. MA22 is the mean of all November flow values over the entire record.
Variability of April flow	MA27	Percent	HIT	Variability (coefficient of variation) of April flow values. Compute the standard deviation for April in each year over the entire flow period. Divide the standard deviation by the mean for each April. Average the values for each April across all years.
Variability of October flow	MA33	Percent	HIT	Variability (coefficient of variation) of October flow values. Compute the standard deviation for October in each year over the entire flow period. Divide the standard deviation by the mean for each October. Average the values for each October across all years.
Variability of December flow	MA35	Percent	HIT	Variability (coefficient of variation) of December flow values. Compute the standard deviation for December in each year over the entire flow period. Divide the standard deviation by the mean for each December. Average the values for each December across all years.
Mean minimum flow for July	ML7	ft^3/s	HIT	Mean minimum flow for July across all years. Compute the minimum monthly flow for July over the entire flow record. Compute the mean of all the minimums.
Base-flow index	ML17	Dimensionless	HIT	Base flow. Compute the mean annual flows. Compute the minimum of a 7-day moving average flow for each year and divide them by the mean annual flow for that year. ML17 is the mean of those ratios.
Variability in base flow	ML18	Percent	HIT	Variability in base flow. Compute the standard deviation for the ratios of 7-day moving average flows to mean annual flows for each year. ML18 is the standard deviation times 100 divided by the mean of the ratios.
Base-flow volume	ML20	Dimensionless	HIT	Base flow. Divide the daily flow record into 5-day blocks. Find the minimum flow for each block. Assign the minimum flow as a base flow for that block if 90 percent of that minimum is less than the minimum flows for the blocks on either side. Otherwise set it to zero. Fill in the zero values using linear interpolation. Compute the total flow for the entire record and the total base flow for the entire record. ML20 is the ratio of total base flow to total flow.

Table 7. Hydrologic indices used to characterize and classify streamflows in southern New England.—Continued

[ft^3/s, cubic feet per second; HIT, Hydrologic Index Tool; IHA, Indicators of Hydrologic Alteration]

Hydrologic indices	Code	Units	Program	Definition
				Frequency
Low flood pulse count	FL1	Number of events/ year	HIT	Low flood pulse count. Compute the average number of flow events with flows below a threshold equal to the 25th-percentile value for the entire flow record. FL1 is the average number of events.
Flood frequency	FH9	Number of events/ year	HIT	Flood frequency. Compute the average number of flow events with flows above a threshold equal to the 75-percent exceedence value for the entire flow record. FH9 is the average number of events.
				Duration
90-day maximum flow	IHA_ HD5	ft^3/s	IHA	90-day maximum. Annual maxima 90-day means.
High-flow duration	DH18	Days	HIT	High-flow duration. Compute the average duration of flow events with flows above a threshold equal to three times the median flow value for the entire flow record. DH18 is the average duration of the events.
				Timing
Julian date of maximum flow	IHA_ JMAX	Julian date	IHA	Julian date of maximum flow.
				Rate of change
Negative change of flow	RA7	ft^3/s/day	HIT	Change of flow. Compute the base-10 logarithm of the flows for the entire flow record. Compute the change in log of flows for days in which the change is negative for the entire flow record. RA7 is the median of these log values.
Fall rate	IHA_RF1	ft^3/s/day	IHA	Fall rate. Mean of all negative differences between consequative daily values.

Table 9. Principal component loadings for the first four principal components and eigenvector loadings from a principal components analysis of 20 hydrologic indices measured at 61 streamflow-gaging stations in southern New England.

[Descriptions of the hydrologic-index codes are provided in table 7. PC, principal component]

Variance extracted, first four axes				
PC axis	Eigenvalue	Percentage of variance explained	Cumulative percentage of variance explained	Broken-stick eigenvalue
1	8.993	45.0	45.0	3.598
2	4.026	20.1	65.1	2.598
3	3.134	15.7	80.8	2.098
4	2.273	11.4	92.1	1.764
Eigenvectors, first four axes				
Indices	Eigenvectors 1	Eigenvectors 2	Eigenvectors 3	Eigenvectors 4
MA1	0.027	0.452	-0.064	0.249
MA3	0.313	-0.090	-0.093	0.088
MA12	-0.098	0.326	0.360	0.111
MA15	0.152	0.066	-0.412	0.289
MA20	-0.028	0.363	-0.203	-0.225
MA22	0.161	0.383	-0.118	0.127
MA27	0.320	-0.057	-0.084	-0.036
MA33	0.323	-0.025	0.039	0.006
MA35	0.324	0.003	-0.047	-0.004
ML7	-0.267	0.233	-0.157	-0.067
ML17	-0.275	0.149	-0.201	-0.156
ML18	0.135	-0.059	0.401	0.232
ML20	-0.322	0.076	0.023	-0.011
FL1	0.227	0.110	-0.054	-0.430
FH9	0.224	0.104	-0.044	-0.437
DH18	-0.077	-0.300	-0.200	0.379
RA7	-0.309	0.035	-0.177	0.039
IHA_HD5	0.147	0.287	-0.149	0.398
IHA_JMAX	0.081	-0.123	-0.493	-0.057
IHA_RF1	-0.175	-0.313	-0.234	-0.025

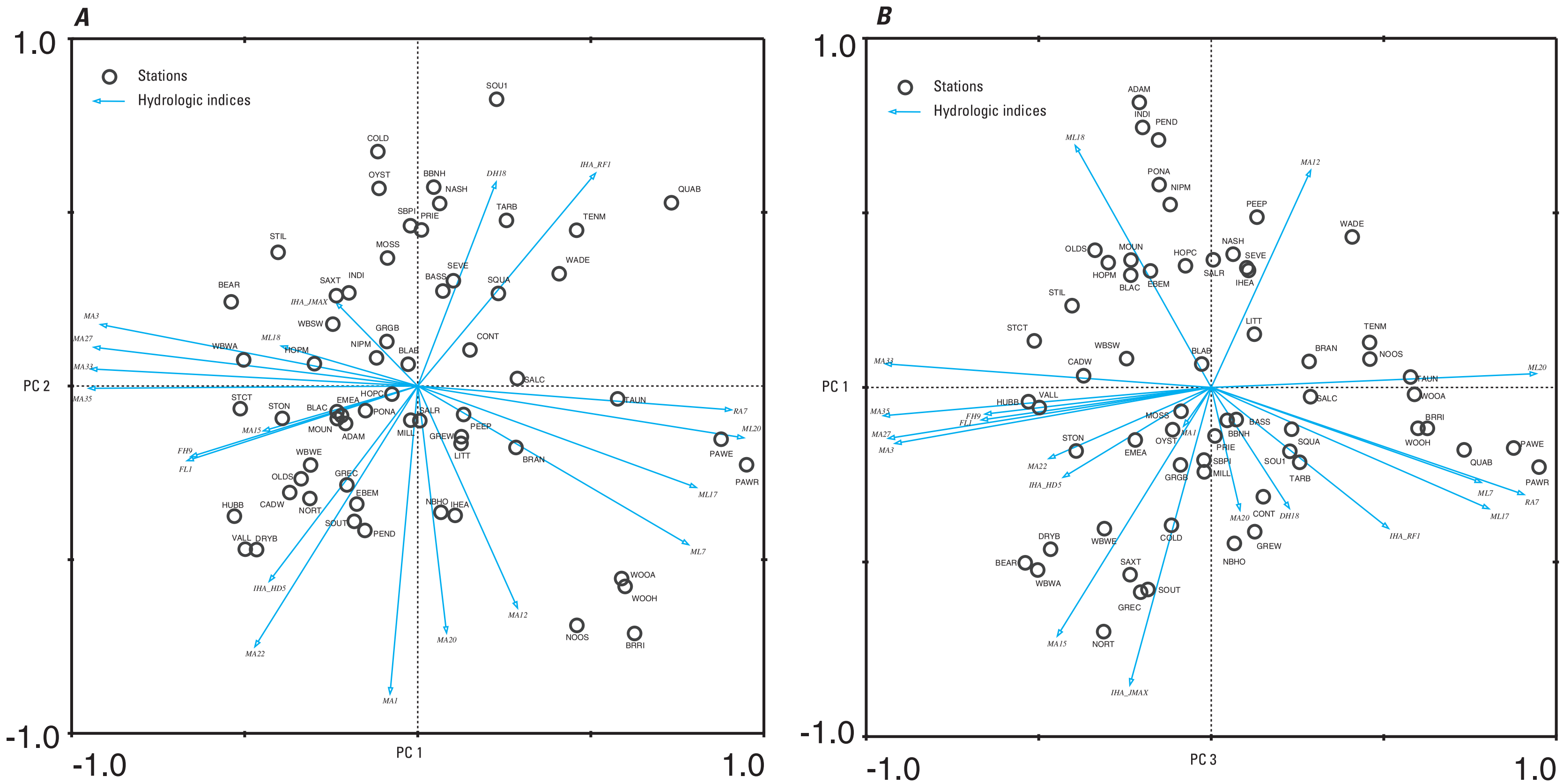


Figure 12. Principal-components-analysis biplots showing ordination of stations: *(A)* principal-components axes 1 and 2; *(B)* principal-components axes 1 and 3; and *(C)* principal-components axes 2 and 3. Descriptions of the hydrologic-index and station codes are provided in tables 7 and 1, respectively.

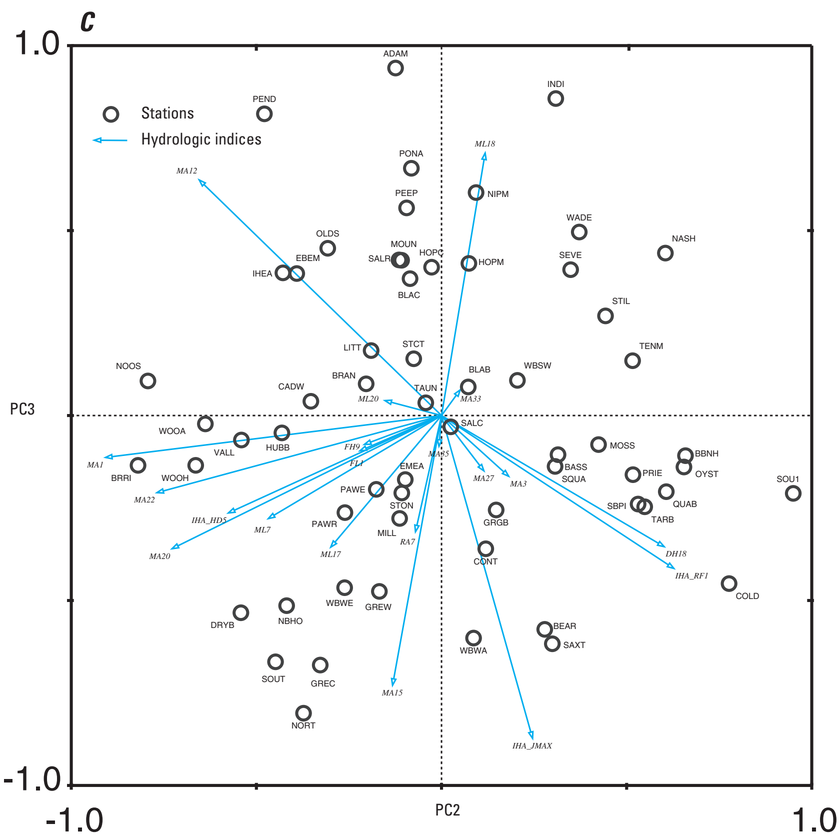


Figure 12. Principal-components-analysis biplots showing ordination of stations: *(A)* principal-components axes 1 and 2; *(B)* principal-components axes 1 and 3; and *(C)* principal-components axes 2 and 3. Descriptions of the hydrologic-index and station codes are provided in tables 7 and 1, respectively.—Continued

with small drainage areas that are predominantly till, such as Peeptoad (01115098) and Dry (01331400) Brooks, from stations with moderate-sized drainage areas, such as the Blackberry (01198500) and West Branch Swift (01174565) Rivers.

The streamflow characteristics describing most of the variability in the dataset are related primarily to differences in the magnitude of low-flow and to flow variability. Records that show higher low flows and stable flows tend to be those in drainage areas with high amounts of ground-water discharge, and records that show lower low flows and greater flow variability typically are for runoff streams with less ground-water influence. This pattern is similar to that previously identified by the L-moment analysis. Secondary modes of variability are largely a function of regional differences in streamflow related to differences in daily mean flows, the magnitudes of winter flows, and the magnitudes and timing of spring flows. PC2 indicates that geographic differences in flow characteristics may be associated with differences in climate and precipitation across southern New England. PC3 separates stations in northern or mountainous areas of western Massachusetts, Vermont, and New Hampshire with more northern-New England-style winters (more winter snowfall and accumulation of snowpack, lower winter flows, and snowmelt runoff in April) from stations in Connecticut, Rhode Island, and southern and eastern Massachusetts with more southern-New England-style winters (more winter rain and melting, higher winter flows, and earlier spring peaks in March).

Cluster Analysis (CLA)

The twenty indices identified in the PCA were used in a hierarchical CLA to classify stations into homogeneous groups. The CLA method used for this study is described as polythetic agglomerative hierarchical clustering (PAHC) (McGarigal and others, 2000). The CLA were computed by using PC-ORD (McCune and Mefford, 1999). A CLA consists of two steps. First, a dissimilarity matrix is computed. Second, the dissimilarity matrix is used with a predetermined clustering algorithm to group similar stations and station groups successively into a hierarchy of clusters. For this study, Euclidian distance (a form of the Pythagorean Theorem used for multidimensional space) was used as the measure of dissimilarity. Euclidian distance is appropriate for continuous or count data (McGarigal and others, 2000) such as the indices produced by the IHA and HIT programs. Ward's method (Ward, 1963) was used as the primary clustering algorithm. Ward's method uses an analysis of variance (ANOVA) approach to evaluate the merging of stations and clusters into new higher level clusters; stations or clusters of stations are combined if the increase in variance for the cluster (the sum of the squared Euclidian distances from each sample to the center of the cluster) is less than it would be if either of the two stations or clusters were joined with any other station or cluster. Results were compared to those determined using the Group Average method (also known as the unweighted pair-group method or UPGMA) (Sneath and Sokal, 1973).

In a hierarchical CLA, no assumptions are made about the number or structure of groups. The clustering process starts with individual stations and successively combines the most similar stations or clusters in accordance with the criteria established by the specified algorithm until only one cluster is left. Hierarchical clusters are shown in a dendrogram, also known as a tree diagram. A dendrogram shows the sequence in which the stations are combined into groups. The lengths of the branches on a dendrogram indicate the degree of dissimilarity between the stations in the cluster (McGarigal and others, 2000). Stations or groups of stations that are more similar are connected by shorter branches. A scale on the dendrogram shows the dissimilarity (distance) between station groups. PC-ORD adds a second scale, Wishart's objective function (Wishart, 1969), that is a measure of information remaining as the hierarchical clustering proceeds (McCune and Mefford, 1999). The branch lengths of dendrograms made by using different clustering algorithms, such as Ward's and UPGMA, are different because different clustering algorithms have different space contracting or space-dilating properties. For example, Ward's method is space-contracting. On a dendrogram, the exact sequence or order of observations along the bottom of a dendrogram is not important for interpretation. The clusters can be rotated at the juncture of the branches (links) without changing the information shown.

The number of clusters in a dataset is typically counted on a dendrogram after drawing a vertical line, or slice, through the plot at a selected distance or level of dissimilarity. A variety of methods or stopping rules can be used to determine the number of clusters in the dataset. For this study, the number of homogeneous clusters in the dataset was determined primarily by evaluating the change in interpretability of the composition of the station groups at different levels of clustering.

A dendrogram for the CLA done in this study is shown in figure 13. The cluster composition was interpreted primarily for two different classification levels, a two-cluster division and a four-cluster division, obtained by slicing the dendrogram at the dissimilarity levels for 25- and 50-percent information remaining, respectively. Station groups in the two-cluster and four-cluster classification were named for dominant characteristics of the clusters. Additional information about station-clustering characteristics also was obtained by evaluating the basin and climate characteristics of clusters obtained by slicing the dendrogram at dissimilarity levels representing 72- and 95-percent information remaining.

The Mann-Whitney and Kruskal-Wallis tests were used to determine the statistical significance of differences in hydrologic indices and basin characteristics among the station groups in the two-cluster and four-cluster classifications. The Mann-Whitney and Kruskal-Wallis tests are nonparametric tests; the tests are based on ranked data, and not on the assumption that the data have a particular distribution, such as a normal or lognormal distribution (Helsel and Hirsch, 1992). The Mann-Whitney test is used for the comparison of two

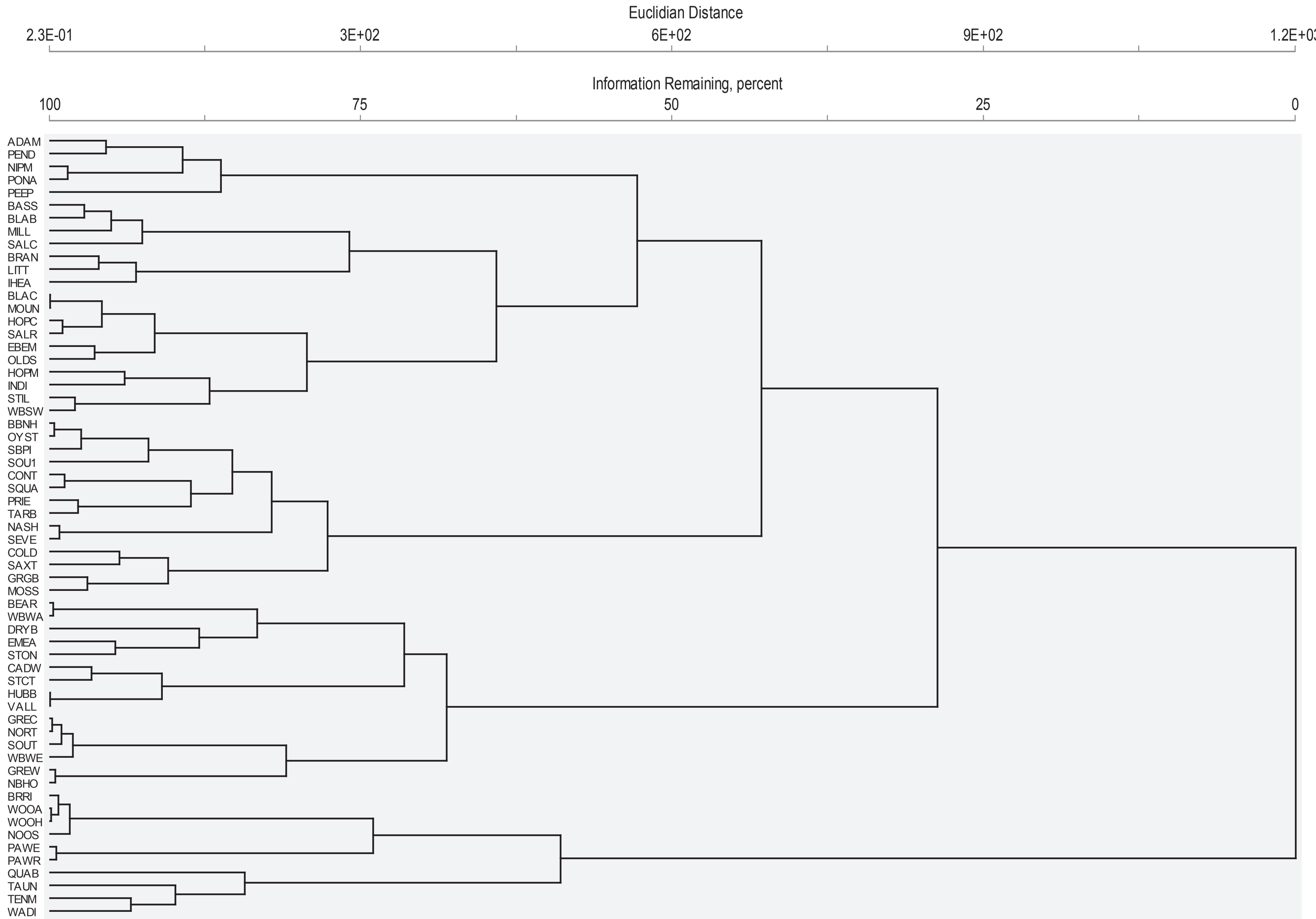


Figure 13. Cluster-analysis dendrogram made by using a Euclidian distance measure and Ward's method for classification of 61 streamflow-gaging stations in southern New England. Descriptions of station codes are provided in table 1.

groups. The Kruskal-Wallis test is used to compare three or more groups and is the nonparametric equivalent of a one-way ANOVA. Because the Kruskal-Wallis H statistic only tests the general hypothesis of whether the medians are equal for all groups compared, Dunn's post test (Dunn, 1964) was used for pairwise comparisons. The multiple comparisons were made by using a macro for Dunn's post test in MINITAB (Orlich, 2000).

Two-Cluster Classification

The stations in southern New England are grouped in two clusters on the dendrogram at about the level for 25-percent information remaining. The stations in these two clusters can be described as being on rivers that have high magnitudes of low flow and less flow variability (base-flow-dominated rivers), and rivers that have greater flow variability and lower magnitudes of low flow (runoff-dominated rivers) (fig. 14A). The base-flow-dominated rivers are primarily in the southeastern portion of southern New England (fig. 14B), and the dataset includes 10 stations on these rivers in Rhode Island and southeastern Massachusetts. In contrast, the dataset for the runoff-dominated rivers includes 51 stations in a wide geographic area across all five states in southern New England (fig. 14B). The stations in these two clusters are similar to those previously identified by the L-moment analysis.

Differences between the base-flow- and runoff-dominated groups for stations in the two clusters are illustrated by using boxplots of the hydrologic indices (fig. 15A). Hydrologic indices representing low-flow characteristics, such as a base-flow index (ML17), a base-flow volume index (ML20), and the mean minimum flow for July (ML7) indicate that the base-flow-dominated stations have a higher magnitude of low flows. Other indices, such as variability in base flow (ML18) and the mean of the coefficient of variation of daily flows (MA3), indicate that streamflows at the base-flow-dominated stations have less variability than streamflows at the runoff-dominated stations. The boxplots for runoff-dominated rivers show greater flow variability in April (MA27), October (MA33), and December (MA35). Significant differences between variables were determined by the Mann-Whitney test, ($p < 0.05$) (table 10). Boxplots of basin and climate characteristics (fig. 15B) indicate that base-flow-dominated rivers are primarily in areas with lower elevations (ELEVFT) and basin slopes (SLPPCT), higher percentages of sand and gravel in their contributing areas (SANDGRAVE), and a more southern-winter climate regime (less snowpack and melt) (TEMPMIN30). In comparison, the runoff-dominated rivers are primarily in areas that have higher elevations and basin slopes, and higher percentages of till and bedrock in their contributing areas.

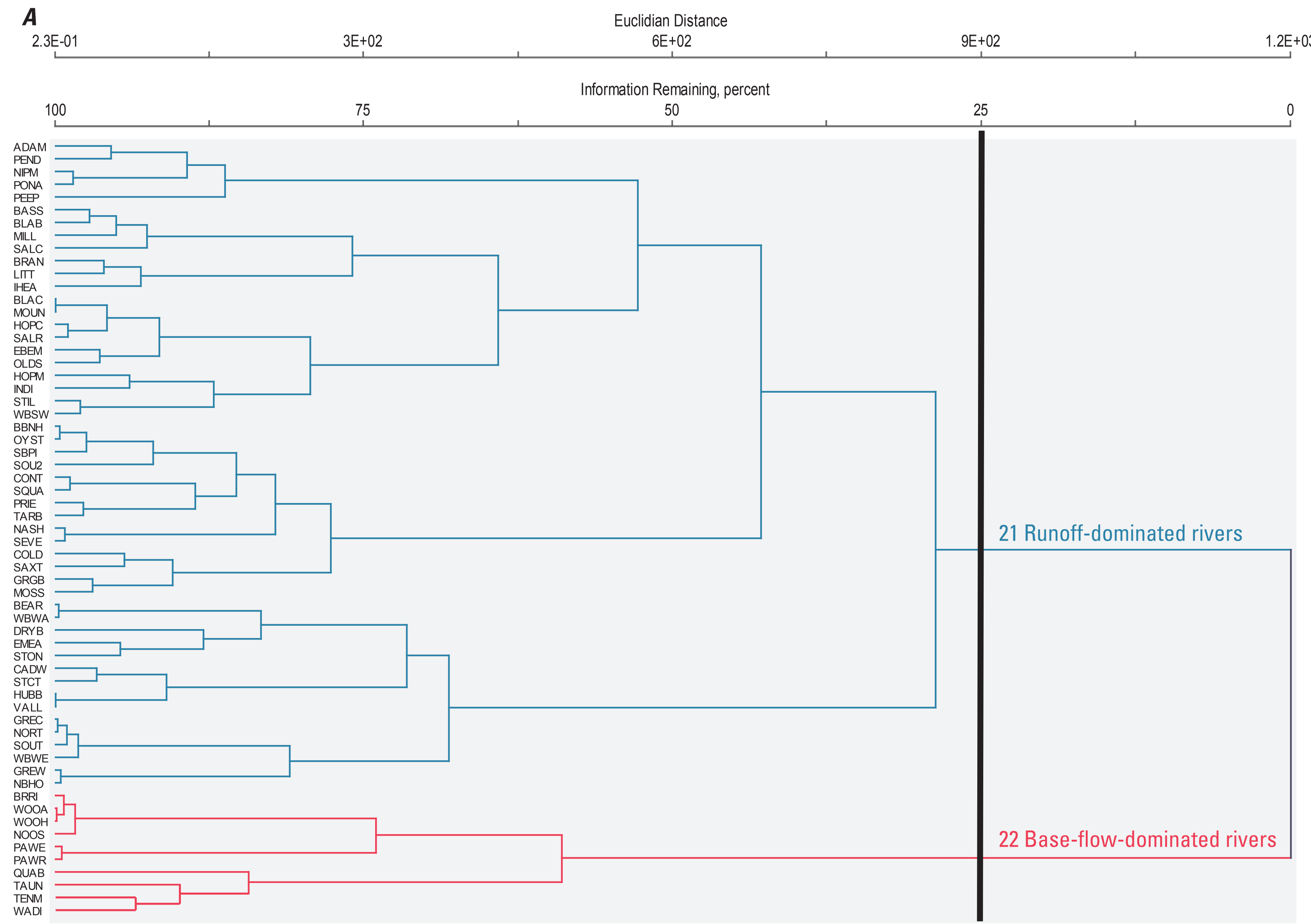


Figure 14. *(A)* Cluster-analysis dendrogram made by using a Euclidian distance measure and Ward's method and *(B)* map showing the two-cluster classification for 61 streamflow-gaging stations in southern New England. Cluster names are RO, runoff-dominated rivers (21); BF, base-flow-dominated rivers (22).

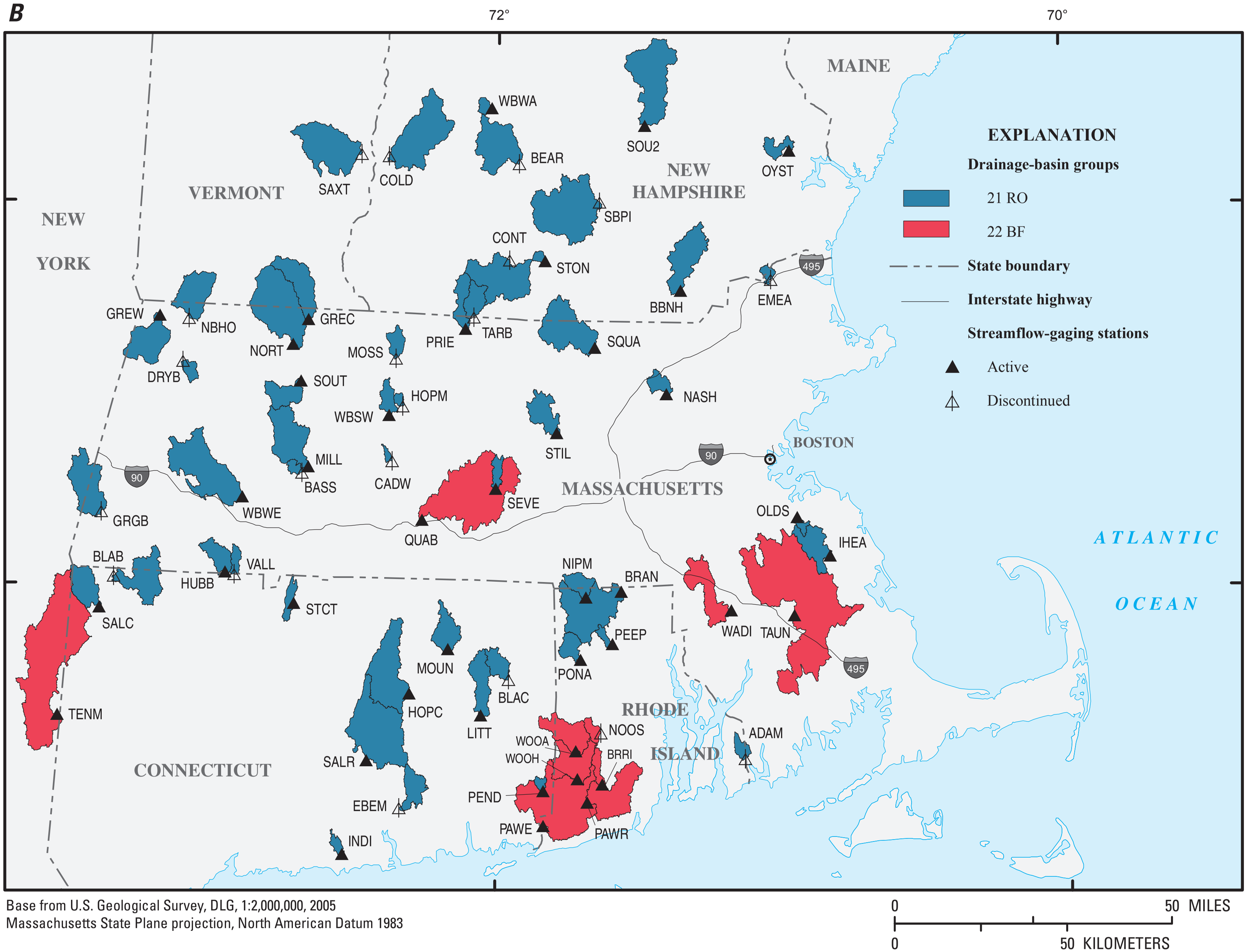


Figure 14. *(A)* Cluster-analysis dendrogram made by using a Euclidian distance measure and Ward's method and *(B)* map showing the two-cluster classification for 61 streamflow-gaging stations in southern New England. Cluster names are RO, runoff-dominated rivers (21); BF, base-flow-dominated rivers (22).—Continued

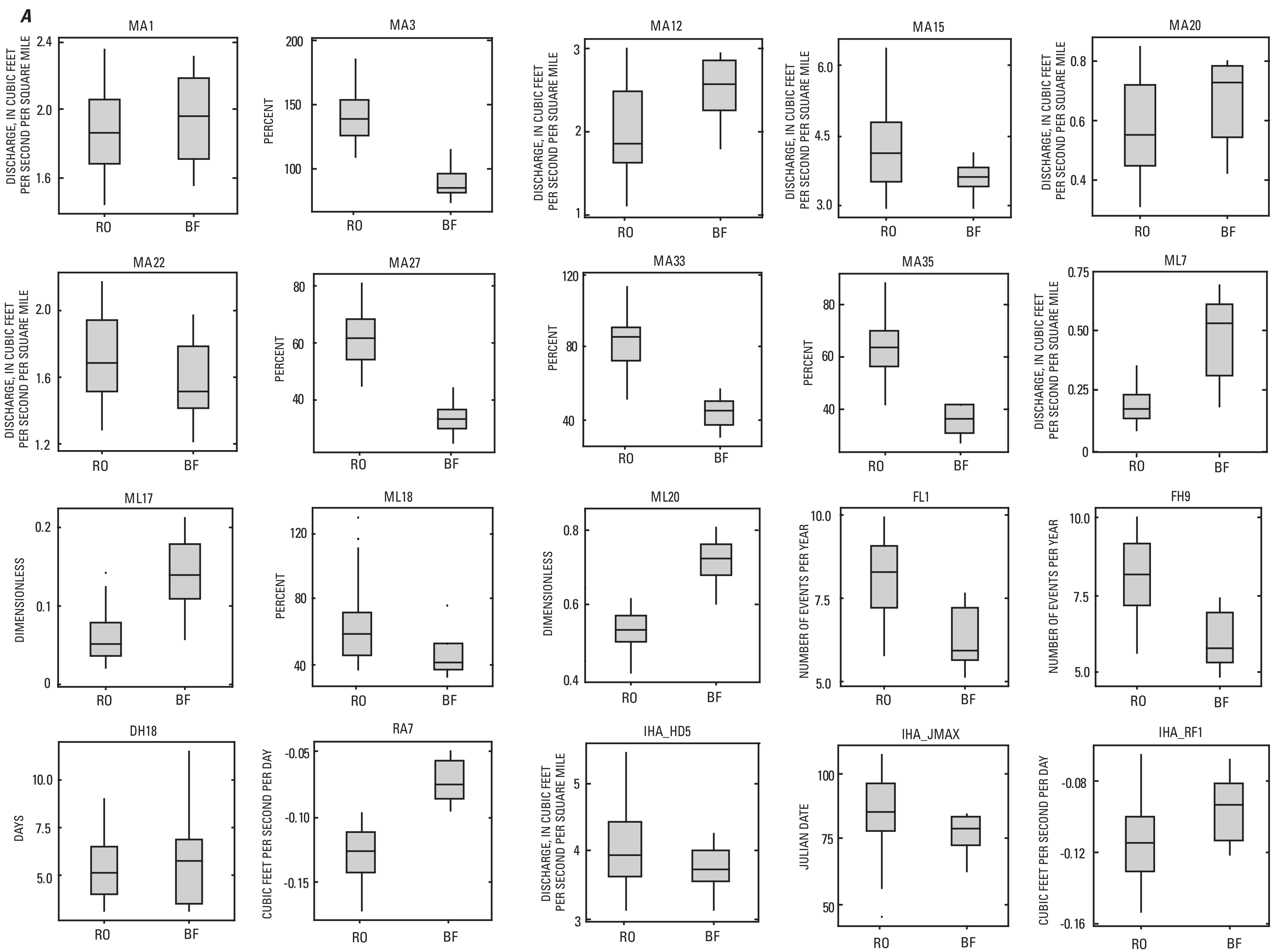


Figure 15. *(A)* Hydrologic indices and *(B)* selected basin characteristics for the two-cluster classification of streamflow-gaging stations in southern New England. RO, runoff-dominated rivers; BF, base-flow-dominated rivers. IQR, interquartile range, is the difference between the 75th- and 25th-percentile values. Names and definitions for hydrologic-index codes are given in table 7. Names and sources for basin-characteristic codes are given in table 2.

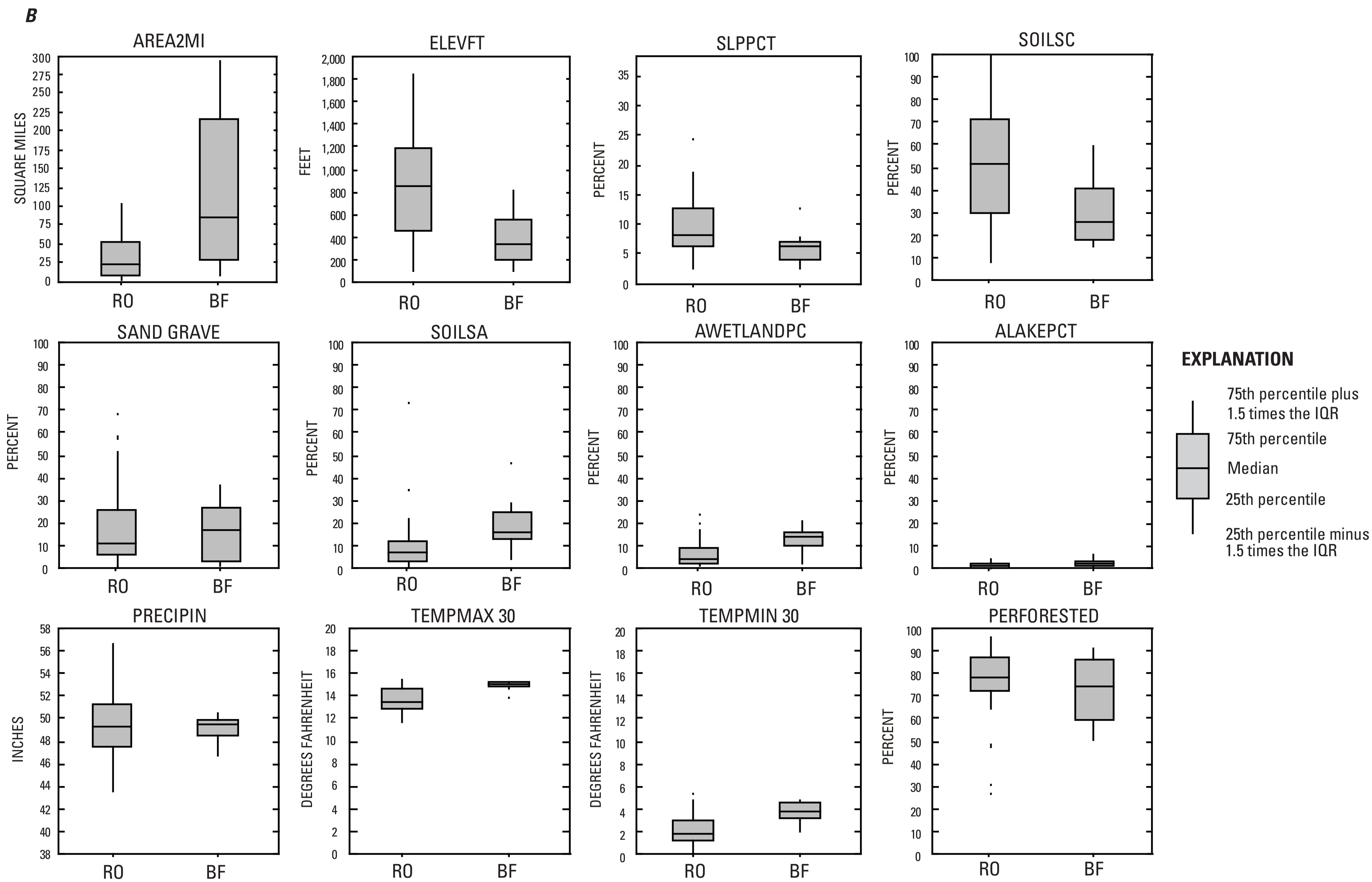


Figure 15. *(A)* Hydrologic indices and *(B)* selected basin characteristics for the two-cluster classification of streamflow-gaging stations in southern New England. RO, runoff-dominated rivers; BF, base-flow-dominated rivers. IQR, interquartile range, is the difference between the 75th- and 25th-percentile values. Names and definitions for hydrologic-index codes are given in table 7. Names and sources for basin-characteristic codes are given in table 2.—Continued

Table 10. Medians of selected hydrologic indices and results of the Mann-Whitney test for the two-cluster classification, for characterizing and classifying streamflows in southern New England.

[Descriptions of hydrologic-index codes are provided in table 7. $ft^3/s/mi^2$, cubic feet per second per square mile; $ft^3/s/d$, cubic feet per second per day]

Hydrologic-Index Code	Unit	Runoff-dominated stations	Base-flow-dominated stations	*p*-values	Statistically significant differences (*a* = 0.10)
			Magnitude		
MA1	$ft^3/s/mi^2$	1.87	1.97	0.1821	No
MA3	Percent	135	84.40	0.0000	Yes
MA12	$ft^3/s/mi^2$	1.87	2.58	0.0034	Yes
MA15	$ft^3/s/mi^2$	4.12	3.62	0.0270	Yes
MA20	$ft^3/s/mi^2$	0.55	0.73	0.1080	No
MA22	$ft^3/s/mi^2$	1.68	1.51	0.1637	No
MA27	Percent	61.5	32.7	0.0000	Yes
MA33	Percent	86.3	45.3	0.0000	Yes
MA35	Percent	63.5	37.10	0.0000	Yes
ML7	$ft^3/s/mi^2$	0.17	0.53	0.0000	Yes
ML17	Dimensionless	0.05	0.14	0.0000	Yes
ML18	Percent	58.5	40.9	0.0014	Yes
ML20	Dimensionless	0.48	0.67	0.0000	Yes
			Frequency		
FL1	Number of events/year	8.27	5.88	0.0001	Yes
FH9	Number of events/year	8.18	5.81	0.0000	Yes
			Duration		
DH18	Days	5.13	5.77	0.0000	No
IHA_HD5	$ft^3/s/mi^2$	3.95	3.73	0.2309	No
			Timing		
IHA_JMAX	Julian date	85	79	0.0199	Yes
			Rate of change		
RA7	$ft^3/s/d$	-0.13	-0.07	0.0000	Yes
IHA_RF1	$ft^3/s/d$	-0.11	-0.09	0.0078	Yes

Four-Cluster Classification

The stations in southern New England are grouped in four clusters on the dendrogram at the level for 50-percent information remaining (fig. 16A). At this level of clustering, the base-flow-dominated rivers (BF) remain classified as one cluster, and the runoff-dominated rivers are divided into three clusters. These clusters are referred to in this report as “high-gradient runoff-dominated rivers” (HRO), “northern runoff-dominated-rivers” (NRO), and “southern runoff-dominated rivers” (SRO). In general, the stations in the NRO and HRO clusters are predominantly in the northern and western portions of southern New England, whereas the SRO and BF clusters are predominantly in the southern and southeastern portion of southern New England (fig. 16B).

Differences in hydrologic indices and basin characteristics among the rivers in the clusters are illustrated in figure 17 (in back of report). Significant differences between the clusters were determined by the Kruskal-Wallis test ($p < 0.05$), and Dunn’s post test was used to show differences between pairs of groups. The results of the Kruskal-Wallis and Dunn’s post test are represented by a pair of graphs for each variable. On the left, a boxplot displays the data distribution for the selected variable for each of the four clusters. The red bars within the individual boxplots display the sign confidence intervals for the medians. The graph on the right displays the magnitudes and significances of the differences in the medians between the six possible combinations of clusters for the four boxplots. The two dotted red lines indicate the 90-percent confidence interval. The magnitudes of the differences in medians between each pair of clusters are shown by the lengths of the horizontal lines, which represent Bonferroni z-values. The difference between the medians of two clusters is significant if the horizontal line for that pairing extends outside the red dotted lines. The direction of the horizontal line indicates whether the differences are positive or negative for the pair of stations indicated by the cluster numbers along the Y-axis. The medians of the cluster groups and results of the Kruskal-Wallis tests are provided in table 11.

Rivers in the HRO cluster are primarily in the more mountainous areas of southern New England to the north and west (cluster number 43 indicated by the blue areas in fig. 16B). Relative to the other rivers, the 15 rivers in this cluster are characterized by streamflows that peak in April (MA15) and have a higher variability of flows in fall and early winter (MA27 and MA35, respectively) and lower base-flow volume (ML20) (fig. 17A, in back of report). Analysis of basin characteristics for this group of stations indicates that the rivers in this cluster are higher in elevation and slope, have lower maximum air temperatures, and a lower percentage of sand and gravel relative to the other runoff-dominated rivers (fig. 17B, in back of report).

Rivers in the NRO cluster are primarily in southern New Hampshire and Vermont and in northern Massachusetts (cluster number 42 represented by the green areas in fig. 16B). The 14 rivers in this cluster have characteristics that are similar to those of the high-gradient runoff-dominated rivers, with moderately high spring peaks in April (MA15) and low mean annual minimum temperatures (TEMPMIN_30) (fig. 17A, in back of report). They differ from the high-gradient river cluster, however, by having lower mean annual flows (MA1), lower average annual precipitation, and more moderate elevations and slopes (fig. 17B, in back of report).

Rivers in the SRO cluster are primarily in Connecticut, Rhode Island, and in southern Massachusetts (cluster number 41 represented by the yellow areas in fig. 16B). The 22 rivers in this cluster are characterized by high flows in winter (MA12) and earlier spring peaks, in March rather than April (IHA_JMAX) (fig. 17A, in back of report). Relative to the other runoff-dominated rivers (clusters 42 and 43), these basins have more moderate elevations and slopes, higher mean annual minimum and maximum air temperatures, and higher amounts of sand and gravel (fig. 17B, in back of report).

The Kruskal-Wallis tests (fig. 17, in back of report and table 11) indicate that many of the hydrologic indices are significantly different among two or three of the clusters in the four-cluster classification, but that there are no indices with values that are significantly different for all four clusters. Some indices, such as MA3, ML7, ML17, and ML20, clearly distinguish between base-flow and runoff clusters, whereas other indices, such as MA15, MA1, and MA22, distinguish among the three runoff clusters (table 11). Other indices may show differences only between two of the clusters or may be more effective at distinguishing clusters at different clustering levels. These characteristics reflect the multivariate nature of river-flow regimes and indicate why classifications based on a single variable or type of statistic, such as a monthly median, differ from classifications made with other statistics and do not result in the same clusters of stations as a classification made on the basis of multiple indices.

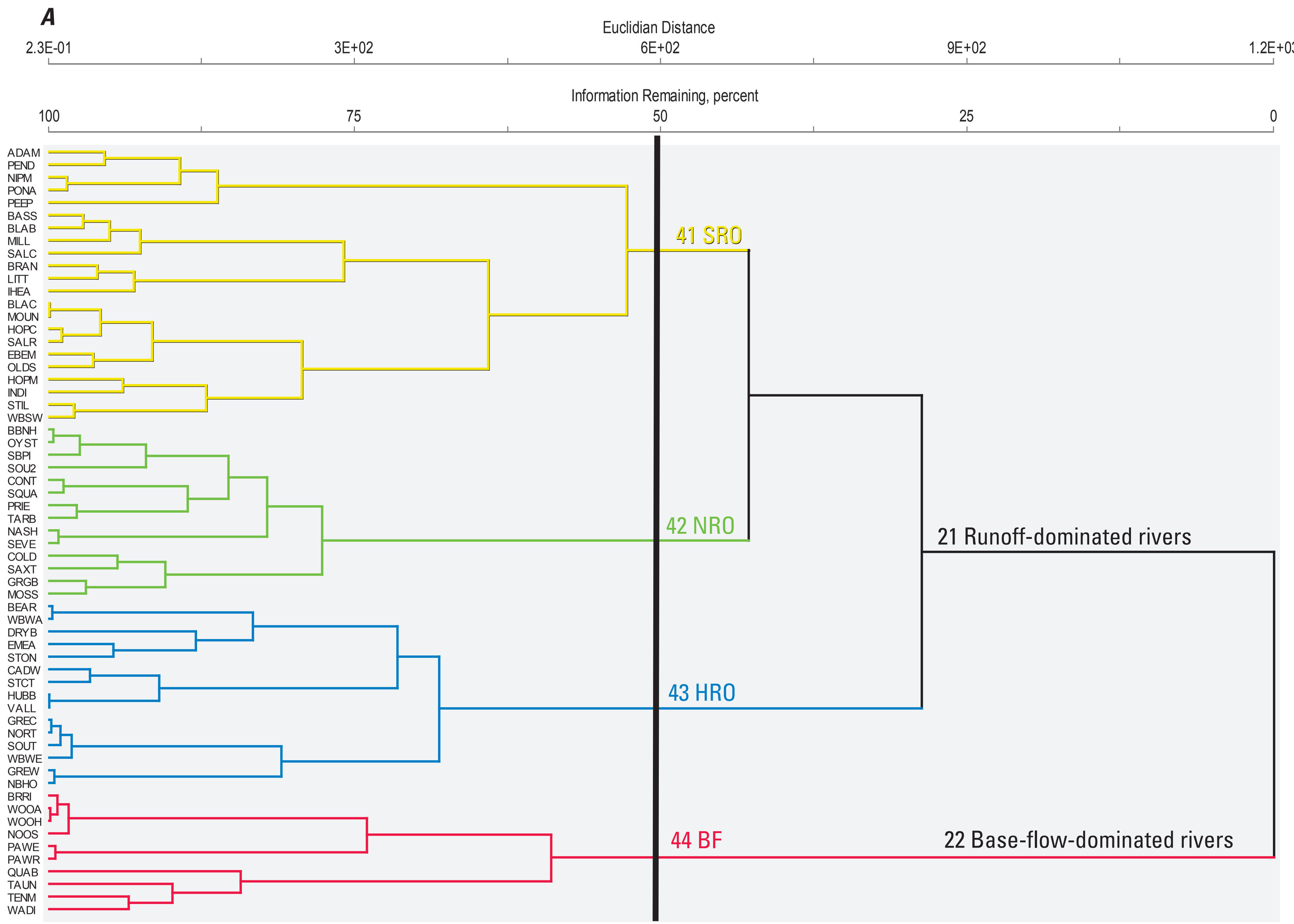


Figure 16. *(A)* Cluster-analysis dendrogram made by using a Euclidian distance measure and Ward's method and *(B)* map showing the four-cluster classification for 61 streamflow-gaging stations in southern New England. Cluster names are SRO, southern runoff-dominated (41); NRO, northern runoff-dominated (42); HRO, high-gradient runoff-dominated (43); and BF, base-flow-dominated (44).

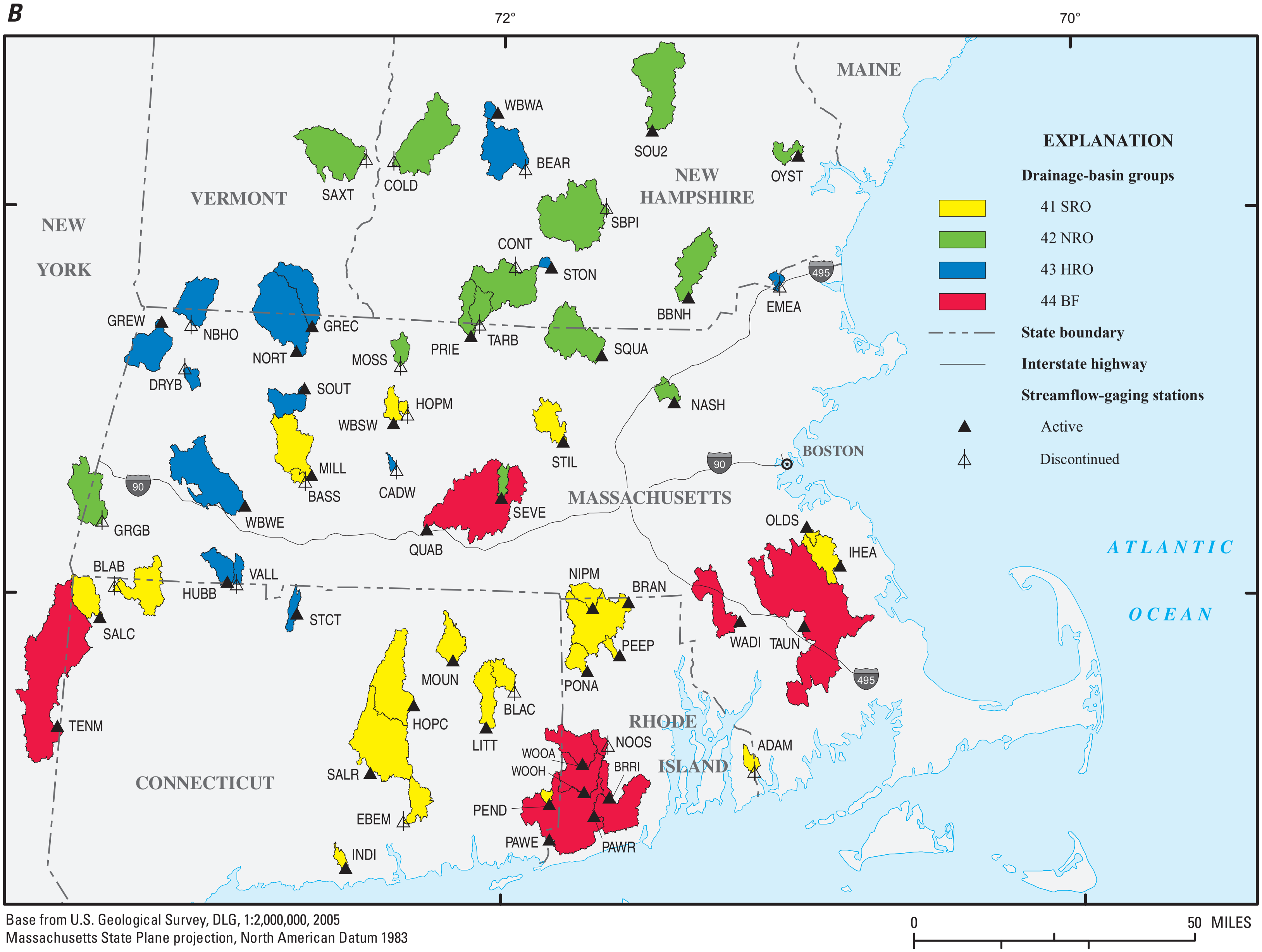


Figure 16. *(A)* Cluster-analysis dendrogram made by using a Euclidian distance measure and Ward's method and *(B)* map showing the four-cluster classification for 61 streamflow-gaging stations in southern New England. Cluster names are SRO, southern runoff-dominated (41); NRO, northern runoff-dominated (42); HRO, high-gradient runoff-dominated (43); and BF, base-flow-dominated (44).—Continued

Table 11. Medians of selected hydrologic indices and results of Kruskal-Wallis tests for the four-cluster classification, for characterizing and classifying streamflows in southern New England.

[Descriptions of hydrologic-index codes are provided in table 7. SRO, southern runoff-dominated; NRO, northern runoff-dominated; HRO, high-gradient runoff-dominated; vs, versus; BF, base-flow-dominated; --, *p* values greater than or equal to 0.05 are not considered statistically significant and are not shown]

Hydro-logic-index code	Unit	Group number									
		41 SRO	42 NRO	43 HRO	44 BF	41 SRO vs 42 NRO	41 SRO vs 43 HRO	41 SRO vs 44 BF	42 NRO vs 43 HRO	42 NRO vs 44 BF	43 HRO vs 44 BF
		Median	Median	Median	Median	Results of Kruskal-Wallis test (*p*-value)					
Magnitude											
MA1	$ft^3/s/mi^2$	1.86	1.66	2.08	2	0.0094	0.0029	--	0.0000	0.0007	--
MA3	Percent	133	133	159	84.4	--	0.0012	0.0006	--	0.0002	0.0000
MA12	$ft^3/s/mi^2$	2.5	1.54	1.9	2.58	0.0000	0.0123	--	--	0.0000	0.0037
MA15	$ft^3/s/mi^2$	3.44	4.33	5.52	3.62	0.0003	0.0000	--	--	0.0078	0.0000
MA20	$ft^3/s/mi^2$	0.558	0.457	0.772	0.734	--	0.0099	--	0.0001	0.0023	--
MA22	$ft^3/s/mi^2$	1.66	1.45	1.98	1.51	0.0081	0.0004	--	0.0000	--	0.0001
MA27	Percent	59	55.7	71.2	32.7	--	0.0043	0.0001	0.0060	0.0008	0.0000
MA33	Percent	84.9	77.2	93.5	45.2	--	--	0.0000	0.0028	0.0052	0.0000
MA35	Percent	62.5	56.9	73.4	37.1	--	0.0090	0.0000	0.0007	0.0045	0.0000
ML7	$ft^3/s/mi^2$	0.162	0.174	0.19	0.531	--	--	0.0001	--	0.0003	0.0006
ML17	Dimensionless	0.043	0.061	0.043	0.14	--	--	0.0000	--	0.0021	0.0002
ML18	Percent	61.3	49.6	60.4	40.9	--	--	0.0004	--	--	0.0114
ML20	Dimensionless	0.494	0.502	0.45	0.672	--	0.0087	0.0001	0.0102	0.0008	0.0000
Frequency											
FL1	Number of events/year	8.52	7.29	8.6	5.89	0.0051	--	0.0000	0.0066	0.0000	--
FH9	Number of events/year	8.83	7.23	8.49	5.81	0.0043	--	0.0000	0.0097	--	0.0000
Duration											
DH18	Days	4.09	6.86	5.61	5.77	0.0000	0.0114	--	0.0183	--	--
IHA_HD5	$ft^3/s/mi^2$	3.74	3.67	4.51	3.72	--	0.0000	--	0.0000	--	0.0002
Timing											
IHA_JMAX	Julian date	78	94.5	95	78.5	0.0000	0.0000	--	--	0.0007	0.0001
Rate of change											
RA7	$ft^3/s/day$	-0.136	-1.12	-0.134	-.074	--	--	0.0000	--	0.0025	0.0000
IHA_RF1	$ft^3/s/day$	-0.125	-0.0982	-0.124	-0.0921	0.0002	--	0.0008	0.0010	--	0.0024

Nine-Cluster Classification

The stations in southern New England are grouped into nine clusters on the dendrogram at about 72-percent information remaining (fig. 18A). At this level of clustering, the small number of rivers in some of the clusters (as few as four) limits the validity of statistical tests that can be done to identify significant differences among the clusters. A description of the dominant characteristics of the clusters is useful, however, to indicate streamflow variables and basin characteristics which could be used to classify stations further and to describe the variability among the stations that are grouped in the four-cluster classification. Boxplots showing the distribution of hydrologic indices within the nine-cluster classification and the basin and climate characteristics for the clusters are given in figure 19 (in back of report).

For the nine-cluster classification, the base-flow-dominated rivers are split into two clusters (fig. 18A). The first is a cluster of six stations in southern Rhode Island on the Beaver, Nooseneck, Pawcatuck, and Wood Rivers (cluster 98 in fig. 18B). These drainage areas to these stations have a higher percentage of stratified drift per unit of stream length than the rivers in the other base-flow-dominated cluster. The records for the second cluster of four basins—the Quaboag, Taunton, Tenmile, and Wading Rivers (cluster 99 in fig. 18B)—show slightly lower base flows (ML17 and ML18) and a greater variability of daily flows (MA3) (fig. 19A, in back of report), and their drainage areas have higher percentages of soils that have slow infiltration rates (hydrologic soils type D) (fig. 19B, in back of report). In addition, the Taunton and Quaboag Rivers have large drainage areas and were among those rivers known to be affected by some flow alterations. Return flows from wastewater-treatment plants could potentially have contributed to their clustering with the base-flow-dominated rivers.

At 72-percent information remaining, rivers in the northern runoff-dominated cluster (cluster 94 in fig. 18A) remained together as an intact cluster. Rivers in the southern runoff-dominated cluster were split into three clusters. One of these clusters included a set of five small till basins in northern Rhode Island, southeastern Massachusetts, and western Connecticut, including Adamsville, Pendleton Hill, and Peeptoad Brooks, and the Nipmuc and Ponaganset Rivers (cluster 91 in fig. 18B). Streamflows at these stations have earlier spring peaks (IHA_JMAX) and a greater variability of base flows (ML18) in comparison to the other southern runoff-dominated rivers (fig. 19A, in back of report); their drainage areas have lower elevations and slopes and higher percentages of wetland and forest land cover (fig. 19B, in back of report). The small drainage areas of these basins (median drainage area of 8 mi^2) may also be a factor in their clustering. In general, small basins are more likely to have homogeneous basin characteristics, (such as a surficial geology that is entirely till) or to have streamflows that are highly influenced by particular basin characteristics (such as a high percentage of wetlands); as a result, the flow regimes of small basins may differ from those of the larger basins to which they contribute.

A second cluster of southern runoff-dominated rivers includes a set of seven rivers in Connecticut and Massachusetts with moderate drainage areas (median drainage area 30 mi^2); these rivers include the Blackberry, Branch, Indian Head, Little, and Mill Rivers, Bassett Brook, and Salmon Creek (cluster 92 in fig. 18B). Compared to the other southern runoff-dominated rivers, rivers in this group have higher base flows (ML17) caused by higher percentages of sand and gravel in their contributing areas or, in the cases of Salmon Creek and the Blackberry River, possibly also because of ground-water discharge from solution-enlarged fractures in carbonate bedrock. The characteristics of this cluster demonstrate that some basin or climate characteristics may be important for distinguishing among stations at several different clustering levels. For example, base flows and low-flow variability were the predominant characteristics distinguishing between the base-flow-dominated and runoff-dominated clusters in the two-cluster classification and also were influential in distinguishing cluster 92 from the other subclusters of southern runoff-dominated rivers.

A third cluster of southern runoff-dominated rivers includes a set of ten rivers in central Connecticut and Massachusetts with moderate-sized basins (median drainage area 20 mi^2); these rivers include the East Branch Eightmile, Hop, Indian, Mount Hope, Old Swamp, Salmon, Stillwater, and West Branch Swift Rivers, and Blackwell and Hop Brooks (cluster 93 in fig. 18B). Relative to the other southern-runoff-dominated rivers, these rivers have a greater frequency of high flows (FH9) and low flows (FL1) (fig. 19A, in back of report), and their drainage areas have a higher percentage of soils that have slower infiltration rates (Hydrologic soils type D) and lower percentages of wetland area (fig. 19B, in back of report).

At 72-percent information remaining, the high-gradient runoff-dominated cluster also is split into three clusters (fig. 18A). Differences in climate and drainage area appeared to be factors distinguishing two of these clusters. One cluster includes a set of five small basins (median drainage area 7 mi^2) in the northern portion of the study area in southern New Hampshire and northern Massachusetts, including the Beard, West Branch Warner, and East Meadow Rivers, Dry Brook, and Stony Brook Tributary (cluster 95 in fig. 18B). A second high-gradient runoff-dominated cluster includes a set of four small rivers (median drainage area 9 mi^2) in the southern part of the study area in northern Connecticut and western Massachusetts; these rivers include Cadwell Creek, Stony and Valley Brooks, and Hubbard River (cluster 96 in fig. 18B). Records for the more northern high-gradient stations show a greater variability of daily flows (MA) and a lower frequency of both low and high flows (FL1 and FH9, respectively) than the stations in the southern high-gradient runoff-dominated cluster (fig. 19A, in back of report).

The third group of high-gradient runoff-dominated clusters is a set of six rivers in northwestern Massachusetts with moderate drainage areas (median drainage area 42 mi^2);

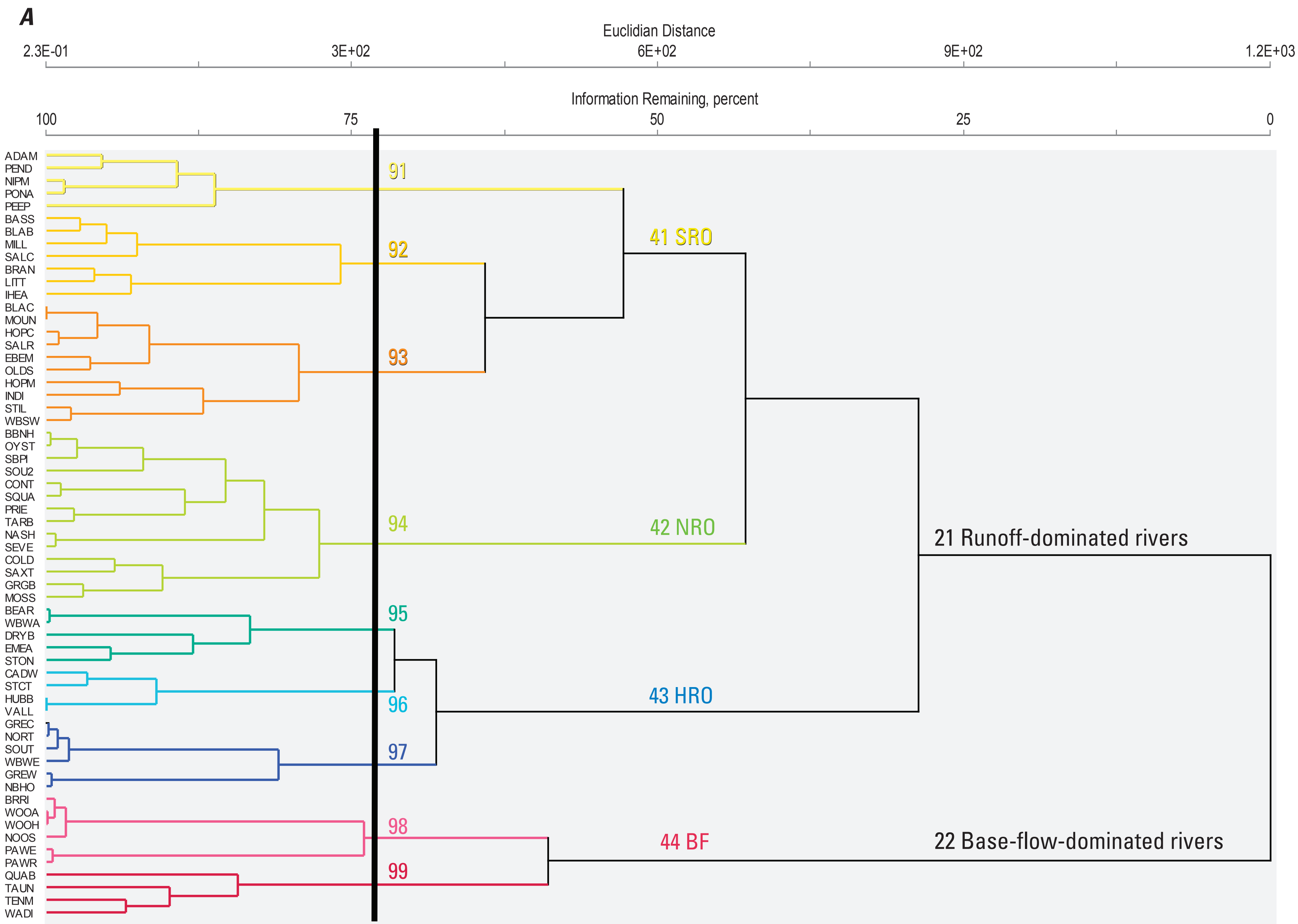
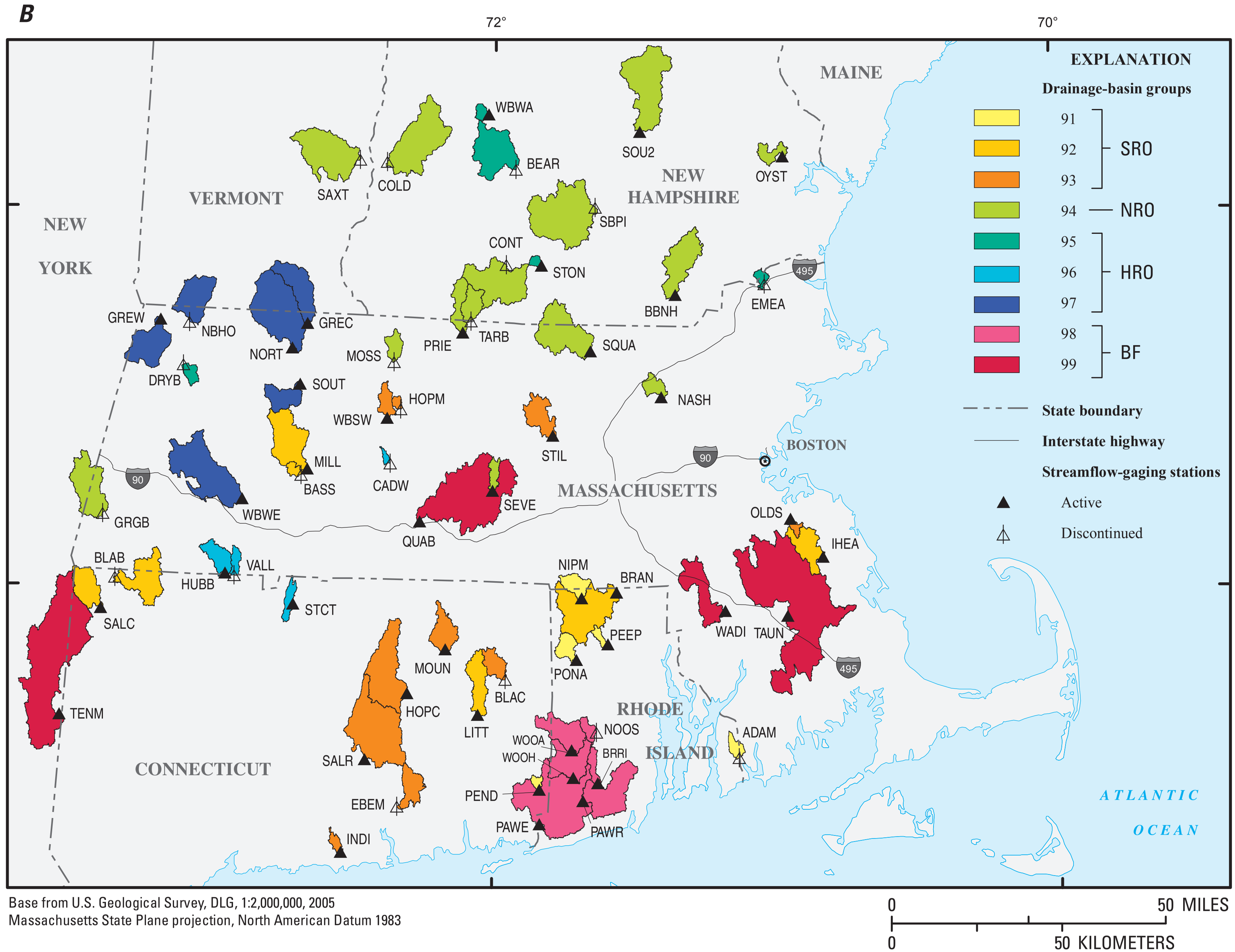


Figure 18. *(A)* Cluster-analysis dendrogram made by using a Euclidian distance measure and Ward's method and *(B)* map showing the nine-cluster classification for 61 streamflow-gaging stations in southern New England. Cluster names are SRO, southern runoff-dominated (41); NRO, northern runoff-dominated (42); HRO, high-gradient runoff-dominated (43); and BF, base-flow-dominated (44).



Base from U.S. Geological Survey, DLG, 1:2,000,000, 2005
Massachusetts State Plane projection, North American Datum 1983

Figure 18. *(A)* Cluster-analysis dendrogram made by using a Euclidian distance measure and Ward's method and *(B)* map showing the nine-cluster classification for 61 streamflow-gaging stations in southern New England. Cluster names are SRO, southern runoff-dominated (41); NRO, northern runoff-dominated (42); HRO, high-gradient runoff-dominated (43); and BF, base-flow-dominated (44).—Continued

these rivers include the Green-Colrain, North, South, West Branch Westfield, Green-Williamstown, and the North Branch Hoosic Rivers (cluster 97 in fig. 18B). Relative to the other high-gradient runoff-dominated rivers, these rivers show less variability of daily flows (MA1), lower variability of monthly flows in spring and fall (MA27 and MA33, respectively), and higher base flows (ML17), and their drainage areas have higher elevations and slopes, and lower minimum and maximum temperatures.

Relation Between Geographic Location and Station Clusters

The distribution of station clusters across southern New England suggests that climate, geographic location, and basin characteristics are all important determinants of streamflow. The four cluster classification of stations (fig. 16B) indicates that many rivers within different regions of southern New England tend to have similar flow regimes. Stations do not cluster on the basis of geographic location alone, however, and thus lines cannot be drawn to represent geographic regions with similar streamflow characteristics. Classification of stations into nine clusters (fig. 18B) indicates that stations in adjacent basins and even within the same drainage basin do not consistently cluster together.

Basin characteristics were compared between stations and station groups that were the most similar (connected by very short branches on a dendrogram). At 95-percent information remaining, stations that cluster together are generally close to one another and share similar drainage areas and basin characteristics. About half of the stations that cluster together at this level are smaller tributary basins in the same major basin, adjacent basins, or close geographic proximity. Many, but not all stations that are close to one another share similar basin characteristics. Adjacent basins that cluster together include Hop Creek and Salmon River, Hubbard River and Valley Brook, Beaver and Wood Rivers, Priest and Tarbell Brooks, Green-Colrain and North Rivers, and Beard Brook and West Branch Warner River. Stations that are not in drainage areas adjacent to one another, but that cluster together strongly, also tend to have similar drainage areas and basin characteristics. These stations are on the Nipmuc and Ponaganset Rivers, Adamsville and Pendleton Hill Brooks, Beaver and Nooseneck Rivers, Blackwell Brook and Mount Hope River, the Contoocook and Squannacook Rivers, and Green River-Williamstown and the North Branch Hoosic River. Close geographic proximity alone does not necessarily result in stations clustering together, however, if basin and land-use characteristics differ. In particular, the flow regimes of small headwater streams can differ substantially from those of downstream rivers. Common examples of this include small upland basins that are predominantly till and have relatively uniform land use, and larger downstream basins that have a heterogeneous mix of surficial geologic and land-use conditions, along with a few water withdrawals and returns. For example, the streamflows for three small headwater basins—Pendleton Hill Brook, Nipmuc River, and Sevenmile River—do not cluster with their respective downstream stations on the Pawcatuck, Branch, and Quaboag Rivers.

The effects of water withdrawals and returns, together with land-use alterations, may have caused stations with somewhat dissimilar basin characteristics to cluster together. For example, a greater proportion of impervious surface area may cause streamflows in basins with moderate amounts of sand and gravel to resemble basins that have high percentages of till. In addition, some river types, such as low-gradient eastern streams with moderate amounts of sand and gravel, may be underrepresented by the stations used in this study, forcing the CLA to group stations with somewhat dissimilar characteristics.

Stability of the Cluster Analysis

Classification of stations with CLA can depend, in part, upon the methods or algorithms used for the classification. As larger station clusters are created, increasingly dissimilar variables and groups of stations are combined. If the clusters in the original analysis are natural and not artifacts of the cluster method used, deletion of a small number of variables from the analysis should not greatly alter the cluster composition (McGarigal and others, 2000).

For this study, the uniqueness of the CLA solution was evaluated through a type of jackknife, variable-splitting procedure that measured the effects of individual indices and stations on clustering. The effect of each of the 20 hydrologic indices in the CLA was determined by iteratively removing successive indices and stations and recalculating the CLA (McGarigal and others, 2000). The compositions of the original and jackknife clusters were then compared, and the percent affinity (Novak and Bode, 1992) for each cluster was determined. This procedure of successively removing indices and recalculating the CLA was repeated for each of the 61 stations. The jackknife procedure indicated that the cluster solutions were relatively unique, and that the classification was about equally sensitive to the removal of individual hydrologic indices as it was to the removal of stations. The percent affinity for eight of the nine clusters was 95 percent or greater for the jackknife analysis of the 20 hydrologic indices and 97 percent or greater for the 61 stations. The stations that most frequently clustered with other stations in the jackknife analysis included the Green River-Williamstown and North Branch Hoosic stations, which joined with the cluster containing Basset Brook, Blackberry River, and Mill River. This result was consistent with the results of the exploratory data analysis, during which the use of different hydrologic indices and clustering algorithms in the CLA was noted to generate slightly different cluster compositions for the stations.

Bioperiods

Recent investigations have identified seasonal flow needs for several rivers in Massachusetts, Connecticut, and New Hampshire (Parasiewicz and others, 2004, 2007; Legros and Parasiewicz, 2007; Normandeau and Associates, 2007; Northeast Instream Habitat Program, 2007a, 2007b). These seasonal flows were developed to protect habitats needed during six critical periods necessary to support fish life cycles (bioperiods): fall spawning, winter survival, spring flooding, spring spawning for clupeid (herring, shad) fish communities, spring spawning for resident fish communities, and summer rearing and growth. The seasonal bioperiods were developed on the basis of analysis of the life histories and interseasonal biological needs of resident fish communities and fluvial-dependent diadromous species (Parasiewicz and others, 2004).

Median seasonal flows, normalized by drainage area, were determined for six bioperiods for the four clusters of index stations (BF, HRO, NRO, and SRO rivers). The dates for the six bioperiods were modified slightly from those used in Connecticut (Parasiewicz and others, 2004; 2007) in that October and November were designated as the fall salmonid spawning period (T. Richards, Massachusetts Division of Fisheries and Wildlife, written commun., 2007). Median seasonal flows were developed for each cluster by determining the median of the daily mean streamflows for each bioperiod, year, and station; determining a median flow for the common POR (1960–2004) for each bioperiod and station; and then determining the median flow for each bioperiod for all stations in the cluster (table 12).

Comparisons of boxplots of the seasonal median flows (fig. 20) show that seasonal flows during the fall spawning bioperiod are several tenths of a cubic foot per second per square mile lower in the streams in the northern runoff cluster (0.55 $ft^3/s/mi^2$) than in streams in the other clusters. Winter rains and melting cause seasonal streamflows during winter to be several tenths of a cubic foot per second per square mile higher in the southern rivers than in northern rivers, and even higher for rivers in the base-flow-dominated cluster (2.10 $ft^3/s/mi^2$). Streamflows in spring (March and April) are higher for rivers in the high-gradient cluster than for the other runoff-dominated clusters (SRO and NRO). For the summer rearing and growth period (July through September), median seasonal streamflows for base-flow-dominated rivers (0.59 $ft^3/s/mi^2$) are higher than for rivers in the other three (runoff-dominated) clusters (average 0.24 $ft^3/s/mi^2$) (fig. 20, table 12).

Table 12. Median seasonal streamflows for fish bioperiods for base-flow-dominated, southern runoff-dominated, northern runoff-dominated, and high-gradient runoff-dominated rivers in southern New England.

[Streamflows are in cubic feet per second per square mile. Numbers in parentheses are cluster numbers. Fish species listed in table 6.]

Months	Bioperiod	Median seasonal streamflows ($ft^3/s/mi^2$)			
		Southern runoff-dominated (41)	Northern-runoff dominated (42)	High-gradient runoff-dominated (43)	Base-flow-dominated (44)
October–November	Fall salmonid spawning	0.70	0.55	0.90	0.81
December–February	Overwintering and salmonid egg development	1.67	1.10	1.23	2.10
March–April	Spring flooding	2.58	2.91	3.05	3.12
May	Spring spawning—clupeid fish	1.61	1.61	1.89	2.15
June	Spring spawning—resident fish	0.75	0.67	0.74	1.27
July–September	Rearing and growth	0.24	0.22	0.24	0.59

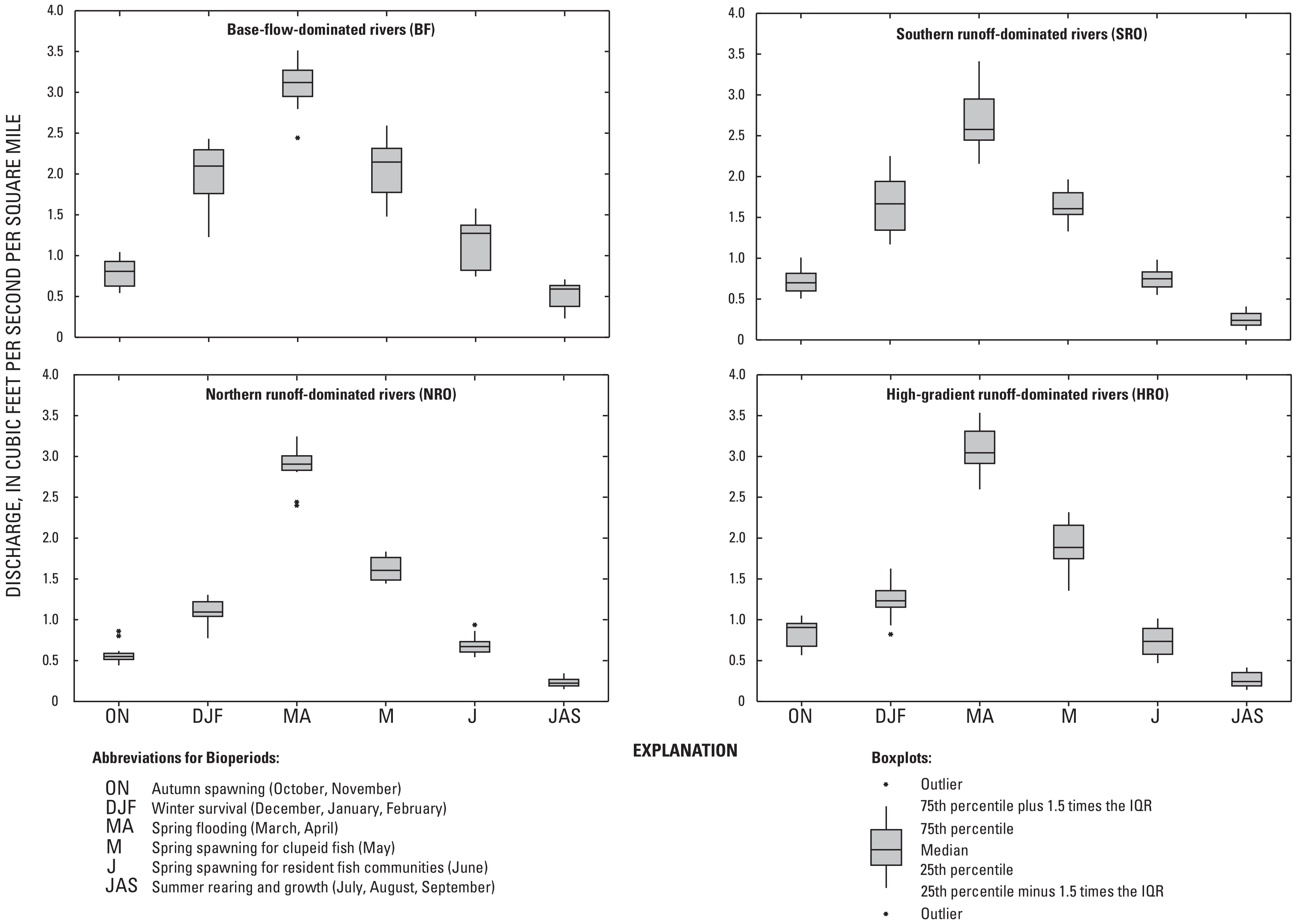


Figure 20. Median seasonal flows for six fish bioperiods for stations in the four-cluster classification of 61 streamflow-gaging stations in southern New England. IQR, interquartile range, is the difference between the 75th- and 25th-percentile values.

Suggestions for Further Study

Data collected from additional long-term streamflow-gaging stations on natural-flowing rivers could improve the definition of the natural-flow regimes of rivers for some classes of streams and in some areas of southern New England. For example, the analysis presented in this report might have shown a gradual transition between runoff-dominated streams and base-flow-dominated streams had there been more index stations available in river basins in eastern Massachusetts. For some areas where minimally altered streamflow records are unavailable because of streamflow alterations and developed land-use, simulated streamflows that account for the effects of water withdrawals, wastewater-return flows, and land-use change may be available from HSPF models (Zarriello and Ries, 2000; Barbaro and Zarriello, 2007; Barbaro, 2007).

Flow alterations from withdrawals, returns, land use, or impoundments may cause some stations to cluster differently than expected. Additional investigation would be needed to determine the relative importance of these characteristics on different streamflow statistics. A few stations were in the same cluster despite being over 50 mi apart and having different basin characteristics. For some of these stations, clustering may be influenced by flow or land-use alterations. For example, Old Swamp River and East Branch Eightmile River cluster together in the SRO cluster despite the difference in the percentages of sand and gravel in their basins (27.5 and 10.8 percent, respectively, table 3, in back of report). Runoff from impervious surfaces in the headwaters of the Old Swamp River, from residential and commercial development, the Weymouth Naval Air Station, and Route 3, may be causing streamflow patterns in the basin to be similar to the patterns for a basin with a higher percentage of till.

Further development of tools such as Target Fish Communities for each of the major river basins in Massachusetts, and a Massachusetts Index of Biotic Integrity (IBI), would be needed to improve the understanding of the relation between flow- and land-use alterations and fish-community composition. Previous studies (Armstrong and others, 2004) indicated that the proportions of fluvial fish in fish communities near index streamflow-gaging stations were similar to those of a Target Fish Community (TFC) that was developed for the Quinebaug River, Massachusetts (Bain and Meixler, 2000). The TFC method was developed to “define a fish community that is appropriate for a natural river in southern New England by specifying common members, a balance of abundances, species organization, and biological attributes” (Bain and Meixler, 2000). The method has been applied to several rivers in New England to illustrate large-scale fish community changes caused by hydrologic and other anthropogenic alterations (Bain and Meixler, 2000; Lang and others, 2001; University of New Hampshire and others, 2006; Legros and Parasiewicz, 2007; Meixler, 2006). TFCs also are being developed for many mainstem river reaches in Massachusetts (T.A. Richards and M. Kashiwagi, Massachusetts Division of Fisheries and Wildlife, written commun., 2006).

Although application of the TFC method can indicate general habitat condition in mid- to large mainstem rivers, it does not quantify the relative effects of various stresses (for example, how much of the change in stream fish communities is caused by flow alterations as compared to changes in habitat, water quality, or temperature) and is not intended to be a site-by-site evaluation method. Fish-community structure and the ecological integrity of rivers are determined by many factors, including flow. Hydrology is but one of five riverine components that determine the structure and function of riverine systems (Annear and others, 2004). The other components include water quality, connectivity, geomorphology, and biology. Comparisons of fish communities to a TFC should be made only if the rivers and drainage basins have similar characteristics to those for which the TFC was developed. Although changes in flow and habitat quality can lead to reductions in the proportions of fluvial fish and increases in habitat generalist species (Bain and others, 1988; Armstrong and others, 2001; Freeman and Marcinek, 2006), other more subtle changes to habitat, flow, or water quality also can lead to shifts in the fish-community composition. Examples include shifts from coldwater to warmwater fish species or from intolerant to more tolerant fish species. Several factors working synergistically can affect the suitability of some instream habitats for fish; in addition, determination of the relative effect of each stressor on the fish community can be difficult unless one stressor is overwhelming. Although many rivers in eastern Massachusetts and their respective fish communities are affected by alterations to flows, physical habitat and water quality, further investigation would be needed to fully understand the effects of restoration efforts on incremental improvements in aquatic community structure.

Consequently, fish communities near stations used in this study should be compared with TFCs for illustrative purposes only. Although the examination of fish communities near streamflow-gaging stations may assist in directing further study, it does not provide a categorical determination of ecological integrity at the stations. Tools such as the Index of Biotic Integrity (IBI) could quantify the relative effects of various stresses if applied on a site-by-site basis. Developed by Karr (1987), the IBI evaluates species composition, trophic composition, fish abundance and condition, biomass, and other fish community attributes by application of a set of multimetric indicators to specific sites. The MDFW is working toward development of an IBI to assess the degree of anthropogenic stress in Massachusetts rivers by assessing fish communities and quantifying hydrologic and physical basin characteristics.

Summary and Conclusions

Information about natural streamflow regimes and natural streamflow variability is needed to facilitate management of water resources in Massachusetts. The Massachusetts Department of Conservation and Recreation (MDCR) and the Massachusetts Water Resources Commission are beginning the process of developing a statewide streamflow policy (L. Hutchins, Massachusetts Department of Conservation and Recreation, written commun., April 2006). A previous analysis by the U.S. Geological Survey (Armstrong and others, 2004) evaluated median monthly flows at 23 active index stations in southern New England and indicated regional differences in median monthly flows; these differences were attributed to climate characteristics during high flow months (November through May) and basin characteristics during low-flow months (June through October). The MDCR was interested in expanding this analysis by using streamflow information from additional active and discontinued index stations in southern New England to determine whether distinct geographic regions with similar streamflow characteristics could be identified. Furthermore, because of a high population density and several centuries of settlement in the region, few unmodified basins remain that can be considered to generate natural flows. Consequently, the records of only a limited number of streamflow-gaging stations in Massachusetts reflect minimally altered flows and also have record lengths sufficient to determine long-term streamflow statistics. To address these concerns, the U.S. Geological Survey (USGS) carried out this study from 2005 through 2007, in cooperation with the MDCR, the Massachusetts Department of Fish and Game Riverways Program (Riverways), and the Division of Fisheries and Wildlife (MDFW), to evaluate flow characteristics of least altered rivers in southern New England.

Monthly flow-duration curves were developed for each month from daily mean discharges for the period of record at 85 selected stations (40 active and 45 discontinued). Annual hydrographs of the normalized median monthly flow at each station indicate distinct differences in magnitude and shape among stations across southern New England. The shapes of the winter and spring portions of the hydrographs reflect differences in winter climate conditions, and in summer, the shapes reflect differences in basin characteristics at the stations. To the north and west, in western and north-central Massachusetts, southern Vermont, and southwestern New Hampshire, winter snowpack causes median monthly streamflows to decline in January and February, and snowmelt causes median monthly streamflows to peak in April. To the south and east, in eastern and south-central Massachusetts, Rhode Island, and Connecticut, warmer winter conditions create higher median monthly streamflows in winter and earlier spring peaks in March. Median monthly streamflows in summer also depend upon the amount of sand and gravel aquifer in a given basin. To the south and east, in eastern and south-central Massachusetts, Rhode Island, and Connecticut, the percentage of sand and gravel aquifer in the contributing areas for some stations and the magnitude of median monthly streamflow in summer tend to be higher than for many stations to the north and west. Differences were gradational across the region, however, and distinct boundaries between station groups were not detected.

Daily streamflow records were statistically analyzed for a subset of 61 of the 85 stations in southern New England. L-moment ratios for the records indicated a division of the rivers into two distinct groups, described in this report as base-flow-dominated and runoff-dominated rivers. The gradation of L-moments between stations indicated that runoff-dominated rivers in southern New England could potentially be classified as a single hydrologic region.

Daily streamflows were estimated by using MOVE.3 record-extension techniques to develop a concurrent 45-year period of record from water years 1960 through 2004 for the 61 streamflow-gaging stations. A suite of 224 hydrologic indices describing various streamflow characteristics was compiled for these stations by use of the Indicators of Hydrologic Alteration (IHA) and Hydrologic Index Tool (HIT) programs. The IHA and HIT statistics were used in a Principal-Components Analysis (PCA) to identify 20 nonredundant indices that statistically summarize streamflow characteristics. A hierarchical cluster analysis used Euclidian distance and Ward's method to group stations into clusters with similar hydrologic regimes. The Kruskal-Wallis test, a nonparametric analysis of variance, was used to test for significant differences between cluster medians for both hydrologic indices and basin characteristics.

The cluster analysis and L-moment analysis both indicated that rivers in southern New England can be classified into two broad groups: (1) base-flow-dominated rivers, whose statistical properties indicated less flow variability and high magnitudes of low flow, and (2) runoff-dominated rivers, whose statistical properties indicated greater flow variability and lower magnitudes of low flows. A four-cluster classification indicated that the runoff-dominated rivers could be further classified into three groups, referred to in this report as high-gradient runoff-dominated rivers, northern runoff-dominated rivers, and southern runoff-dominated rivers. High-gradient runoff-dominated rivers have low winter flows and high spring flows that are a result of northern winters (characterized by winter snowpack, and snowmelt runoff in April) in combination with high elevations and slopes. Northern runoff-dominated rivers have streamflow characteristics similar to those of the high-gradient runoff-dominated rivers, but with lower spring peaks and mean annual flows, and more moderate elevations and slopes. Southern runoff-dominated rivers have high winter and earlier spring flows that are a result of southern winters (characterized by winter rains and less snowpack, and snowmelt runoff in March and April) in combination with moderate elevations and slopes. A nine-cluster classification includes two clusters of small basins (less than 10 mi^2), indicating that streamflow characteristics also vary by basin size. A comparison of the distribution of river basins that were classified together at different levels of clustering indicated that rivers do not cluster on the basis of geographic region alone. River basins with similar streamflow characteristics tended to be adjacent or in close proximity, but stations with dissimilar basin and climate characteristics did not cluster together, even if they were upstream or downstream within the same basin.

Acknowledgments

The authors are grateful to the Massachusetts Department of Conservation and Recreation, Riverways, Massachusetts Division of Fisheries and Wildlife, and other public agencies, private organizations, and individuals who provided assistance, guidance, and information during the study. In particular, the authors thank Linda Hutchins, Anne Monnolly, and Bruce Hansen of the Massachusetts Department of Conservation and Recreation; Margaret Kearns of Riverways; and Thomas Lamonte, Kari Winfield, and Warren Kimball of the Massachusetts Department of Environmental Protection who encouraged this study and reviewed the report. The technical assistance and guidance of Jonathan Kennen, James Henriksen, Stacey Archfield, and James Coles of the USGS, and of Richard Vogel of Tufts University is greatly appreciated. The authors are thankful for the assistance of Leanda Fontaine, Michael Kashiwagi, and Alicia Norris of the Massachusetts Division of Fisheries and Wildlife; Gabrielle Stebbins, Riverways, for analysis of MDFW fish data; and Sara Brandt of Tufts University and the USGS for assistance with analysis of L-moments. The authors also thank the many USGS colleagues who provided professional expertise, including Lance Ostiguy and Pete Steeves for GIS assistance; Mary Ashman, Ruth Larkins, Dorothy Tepper, Ann Marie Squillacci, Kim Otto, and Mark Bonito, for editorial review, layout, and publication; and Jonathan Kennen, Valerie Kelley, and Phillip Zarriello for technical reviews.

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