Estimation of Low-Flow Duration Discharges in Massachusetts

United States Geological Survey Water-Supply Paper 2418

Prepared in cooperation with the Massachusetts Department of Environmental Management Office of Water Resources

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Estimation of Low-Flow Duration Discharges in Massachusetts

By KERNELL G. RIES III

Prepared in cooperation with the Massachusetts Department of
Environmental Management Office of Water Resources

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2418

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, Secretary

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
cubic foot (ft^3)	0.02832	cubic meter
cubic feet per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
inch (in)	25.4	millimeter
mile (mi)	1.609	kilometer
million gallons per day (Mgal/d)	0.04381	cubic meter per second
square mile (mi^2)	2.590	square kilometer

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

$$°C = 5/9 \times (°F) - 32.$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

ABBREVIATIONS

Organizations

MDWS	Massachusetts Department of Environmental Protection, Division of Water Supply
MOWR	Massachusetts Department of Environmental Management, Division of Resource Conservation, Office of Water Resources (formerly MDWR)
MWRA	Massachusetts Water Resources Authority
MWRC	Massachusetts Water Resources Commission
USGS	U.S. Geological Survey

Basin Characteristics

DAREA	Drainage area, in square miles
DAxELEV	DAREA times ELEV
DAxREL	DAREA times RELIEF
DENS	Drainage density—TSTREAM divided by DAREA
DRIFT	Area of stratified-drift deposits, in square miles
DRT/TST	Area of stratified drift per unit stream length—DRIFT divided by TSTREAM
GWHEAD	Surrogate for head in the stratified-drift aquifer—MELEV minus LELEV
HELEV	Highest basin elevation, in feet
LAT	Latitude
LELEV	Lowest basin elevation, in feet
LSTREAM	Length of longest stream, in miles
MELEV	Mean basin elevation, in feet
%DRIFT	Areal percentage of stratified drift
%WATER	Areal percentage of water bodies
RELIEF	HELEV minus LELEV
SLOPE	RELIEF divided by LSTREAM
TSTREAM	Total length of streams, in miles
WATER	Area of water bodies including lakes, ponds, reservoirs, in square miles
WET	Area of wetlands, in square miles

Miscellaneous

BREG	All-possible-subsets regression analysis algorithm
CDF	Cumulative distribution function
GIS	Geographic information system computer software
MOVE.1	Maintenance of variance extension method, type 1
MST	Minimum streamflow threshold
OLS	Ordinary-least-squares regression analysis
WLS	Weighted-least-squares regression analysis
STEP	Stepwise regression algorithm

Estimation of Low-Flow Duration Discharges in Massachusetts

By Kernell G. Ries III

Abstract

Physically based mathematical models were developed to estimate the natural yields of basins in Massachusetts during times of low flow. Streamflow statistics used in the models to express basin yields are the discharges that were equaled or exceeded 95, 98, and 99 percent of the time during a base period of 25 years (October 1, 1962, through September 30, 1987; water years 1963–87). These duration discharges for 41 sites were related to the physical characteristics of the sites by use of weighted-least-squares multiple-regression analyses. All physical characteristics were measured by use of a computerized geographic information system. Record-extension techniques were used to adjust duration discharges for sites with incomplete records to the base-period conditions. Weights were determined by use of a function that corrects for length of record at each site and for nonconstant variance of the regression residuals. Basin characteristics used in the models included drainage area, the amount of stratified drift per unit length of streams in the basin, and a surrogate measure of the effective head of the aquifer in stratified-drift deposits. Standard errors of estimation were 34.1 percent, 41.4 percent, and 37.9 percent, and standard errors of prediction were 39.3 percent, 47.5 percent, and 44.4 percent, for the equations predicting the 95-, 98-, and 99-percent duration discharges, respectively.

The models were used to predict duration discharges for the base period for 72 selected sites in the Boston Harbor Basin and in the Blackstone, Charles, and Taunton River Basins in eastern Massachusetts. Ninety-percent prediction intervals were computed for the estimates at each site. Estimates of the duration discharges during water years 1980–81, the most recent drought in Massachusetts, were obtained by multiplying the estimates from the regression equations by averaged ratios of duration discharges for water years 1980–81 to those for the 25-year base period for streamflow-gaging stations in or near the study basins.

INTRODUCTION

Supplies of water in most of Massachusetts are adequate to meet demands during periods of normal hydrologic conditions. The distributions of water and population are not coincident, however, and several areas experience severe water shortages during droughts. The eastern one-third of the State, where about 75 percent of the population resides, is particularly vulnerable to water-supply shortages during droughts. With expected continued population growth and industrial expansion, adequate planning and management of water resources, including water conservation, will be required to ensure that water-supply shortages and unreasonably low streamflows do not become more severe in the future.

The most recent significant drought in Massachusetts occurred during 1980–81. This drought, with recurrence intervals[1] ranging from 30 years in eastern Massachusetts to 10 years in western parts of the State, caused serious minimum streamflow and water-supply problems for many communities (U.S.

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[1]A drought having a recurrence interval of 30 years will occur, on average, once in 30 years.

Geological Survey, 1991). The drought contributed to increased public concern for responsible management and development of water resources. Responding to this concern, the Massachusetts legislature passed the Interbasin Transfer Act and the Water Resources Management Act into law in 1983 and 1985, respectively. The Interbasin Transfer Act required that significant new or increased transfers of water between basins be approved by the Massachusetts Water Resources Commission (MWRC) and that reasonable instream flow be maintained in the source basin. The Water Resources Management Act directed the MWRC to prepare and approve management plans for each of the State's 27 major river basins. The Massachusetts Office of Water Resources (MOWR, formerly the Division of Water Resources), of the Division of Resource Conservation, Department of Environmental Management, provides technical staff support to the commission and has been directed to prepare the basin management plans (Massachusetts Office of Water Resources, written commun., 1990).

The river-basin planning process consists of five steps: (1) development of an inventory of the basin's water supply and demand, (2) analysis of streamflow and water-use data and identification of the future water needs of the basin, (3) development and analysis of alternatives to meet projected water needs, (4) preparation of a water resources management plan, and (5) adoption of the plan by the MWRC. In preparing the plans, the MOWR attempts to develop and recommend ways to meet projected water demands for the year 2020 under drought conditions similar to those of 1980–81. The plans incorporate requirements for water conservation and protection of instream flows, provide a basis for community and regional water-resource management, and allow the Massachusetts Department of Environmental Protection, Division of Water Supply (MDWS) to make informed decisions for permitting new withdrawals and interbasin transfers.

Inherent in the planning process is the establishment of minimum streamflow thresholds (MST's) within each planning basin. The MST is recommended by MOWR and must be approved by the commission. It is developed by an interactive process that attempts to balance the water needs of users with available streamflow. The MST goal is to meet water demand while preserving or enhancing the habitat of fisheries, recreation, wetlands, agriculture, and wildlife. Part of the information needed by the MOWR to determine the MST for a basin is an estimate of the natural yield of the basin under low-flow conditions. To aid in determining MST's, the U.S. Geological Survey (USGS) began a series of studies in cooperation with the MOWR to provide yield estimates for sites within each of Massachusetts' 27 major river basins (fig. 1). Estimates of the 95-, 98-, and 99-percent duration discharges were chosen by the MOWR to express basin yields at the sites. The estimates will be used by the MOWR, along with known and predicted water use information, to determine MST's for streams within each basin. After approval by the commission, the MST's will be used by the MDWS to aid in deciding whether to license new water-use applicants.

For this first of a planned series of 3-year studies to estimate basin yields for the MOWR, the USGS produced low-flow estimates for sites in four basins in eastern Massachusetts (fig. 1). The estimates were produced primarily from physically based models developed by use of weighted-least-squares regression analyses. A computerized geographic information system (GIS) was used to measure all of the physical features that were used as the independent variables in the regression models. The physical features were obtained in digital form and were either available on a national scale from various sources, or developed on a statewide basis for this and other studies.

Purpose and Scope

The purpose of this report is to (1) document physically based regional regression models that can be used to estimate natural basin yields in Massachusetts, in the form of the 95-, 98-, and 99-percent duration discharges for a base time period of sufficient length to represent long-term flow conditions, (2) provide estimates of natural basin yields for selected sites along streams located in the Blackstone, Charles, and Taunton River Basins and the Boston Harbor Basin, and (3) provide basin yield estimates for water years 1980–81[2] (October 1, 1979, through September 30, 1981) by adjusting the base-period estimates for local conditions during 1980–81.

This report describes (1) the physical, climatological, and hydrological characteristics of Massachusetts in general and of the study basins in

[2]A water year begins October 1 of the previous calendar year and ends September 30 of the year specified.

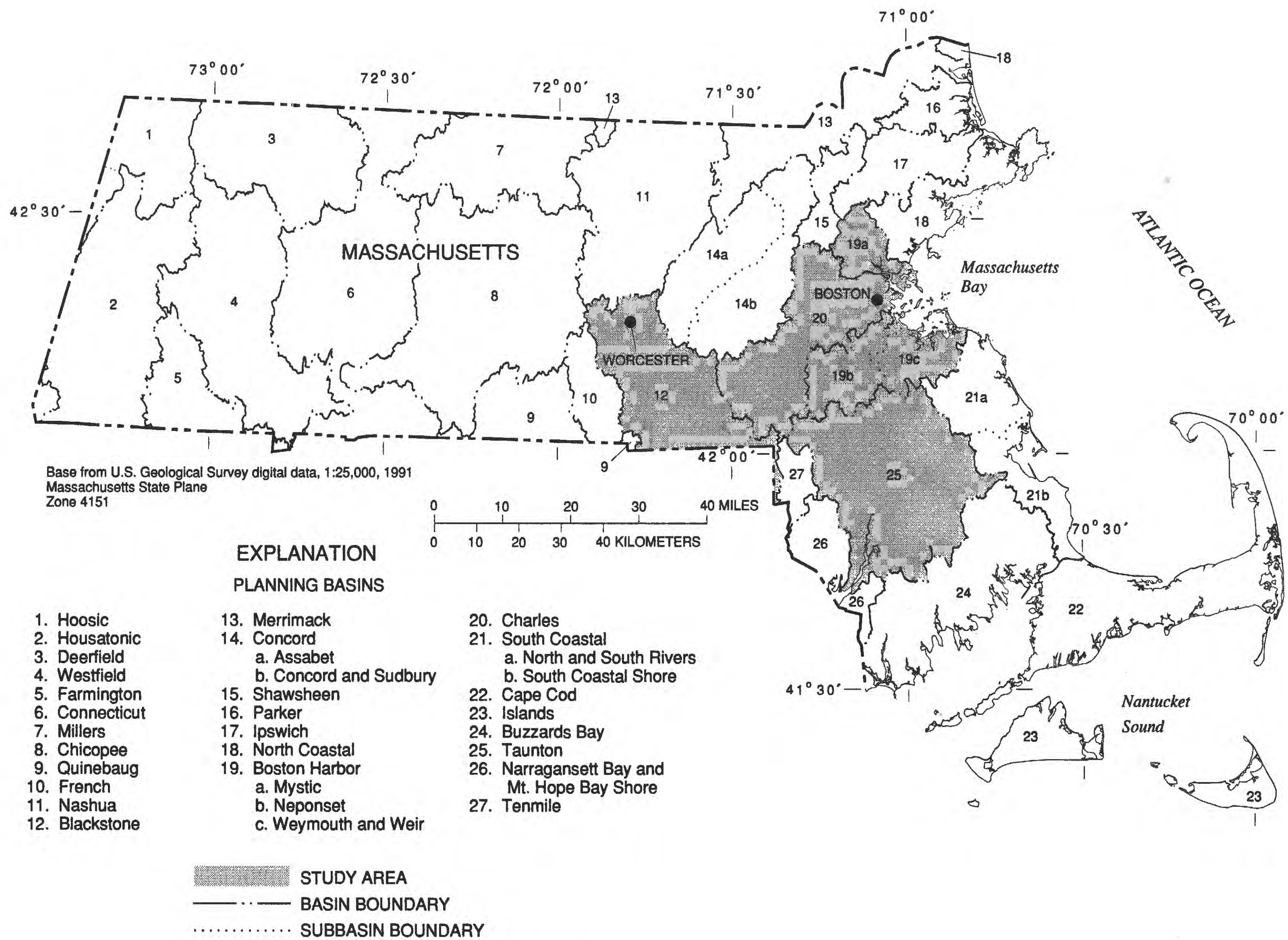


Figure 1. Locations of the 27 major river basins in Massachusetts.

particular, (2) the development and computation of low-flow statistics used as the dependent variables in the regression analyses, (3) the GIS computer data bases and procedures employed to measure basin characteristics used as the independent variables for the models, (4) development of regression models used to predict natural basin yields during the base period for sites located in most areas of Massachusetts, (5) application and assessment of the models, and (6) adjustment of the base period estimates to determine natural basin yields for the selected sites during water years 1980-81.

Previous Investigations

Low-flow statistics for most Massachusetts streamflow-gaging stations, where streamflow data are collected continuously, and many low-flow partial-record stations, where low streamflow data are collected intermittently, have been published previously by the USGS, primarily in a series of gazetteers that were published as Water Resources Investigations reports and in a series of hydrologic and water resources map reports that were published as Hydrologic Investigations Atlases. Refer to U.S. Geological Survey (1987) for a complete listing. Additional low-flow statistics are provided in a series of ground water assessment reports produced cooperatively with the MOWR under Chapter 800 of Massachusetts legislation (Lapham, 1988; Myette and Simcox, 1989).

Several studies have attempted to regionalize low-flow statistics in the northeastern United States. Low-flow frequency statistics, such as the 7-day 10-year low flow ($Q_{7,10}$), have most often been regionalized; however, some studies have attempted to regionalize flow-duration statistics. The $Q_{7,10}$ low flow is the annual minimum 7-day mean low flow that occurs, on average, once in 10 years or, equivalently, that has a 10 percent chance of occurrence in any year. Studies by Cervione (1982, p. 16) and Fennessey and Vogel (1990, p. 545) have indicated that the $Q_{7,10}$ is approximately equal to the 99-percent duration streamflow in Connecticut and Massachusetts.

Regionalization studies for Connecticut include those by Thomas (1966), in which the percentage area of coarse-grained stratified-drift deposits in a basin was used to estimate streamflow durations, and Cervione and others (1982), in which the area of coarse-grained stratified drift and the area of till were used as explanatory variables to estimate the $Q_{7,10}$. Ku and others (1975) used the percentage area of coarse-grained stratified drift in the basin and mean annual runoff to estimate low-flow frequencies in the Susquehanna River Basin of New York. Johnson (1970) estimated low-flow frequencies for sites in Massachusetts, New Hampshire, Rhode Island, and Vermont by use of drainage area, mean annual precipitation, and minimum January temperature as independent variables. Tasker (1972) found that low streamflows in southeastern Massachusetts were significantly related to drainage area and a "ground water factor," which indicates the average water availability from wells in the basin. The ground water factor, which is roughly proportional to the average transmissivity in the basin, was computed by subdividing the area of coarse-grained stratified drift by potential well yield as indicated on maps (Williams and others, 1973; Williams and Tasker, 1974a, 1974b). Male and Ogawa (1982) used a similar ground water factor—along with drainage area, mean annual precipitation, swamp and lake area, and other variables—to estimate low streamflows in Massachusetts. Dingman (1978) used drainage areas and mean basin elevations to synthesize flow-duration curves for New Hampshire. Vogel and Kroll (1990) used drainage area and basin relief to regionalize low-flow frequencies, and Fennessey and Vogel (1990) used the same variables to regionalize the lower one-half of flow-duration curves (estimated flows below the median and their corresponding durations) for streams in Massachusetts.

Acknowledgments

I thank Peter Phippen, Steve Asen, William Bowens, and Jonathan Yeo of the MOWR for their assistance in selecting sites for which low flows were to be estimated and for collecting concurrent water use data for the sites at times when streamflow measurements were obtained. I also appreciate the work of everyone involved in digitizing, preparing, and retrieving data from the GIS data bases used for this study, especially the contribution of Peter Steeves in developing programs to automate the measurement of basin characteristics used in this study.

PHYSICAL SETTING

Physical setting determines the yield of streamflow from drainage basins. The following sections

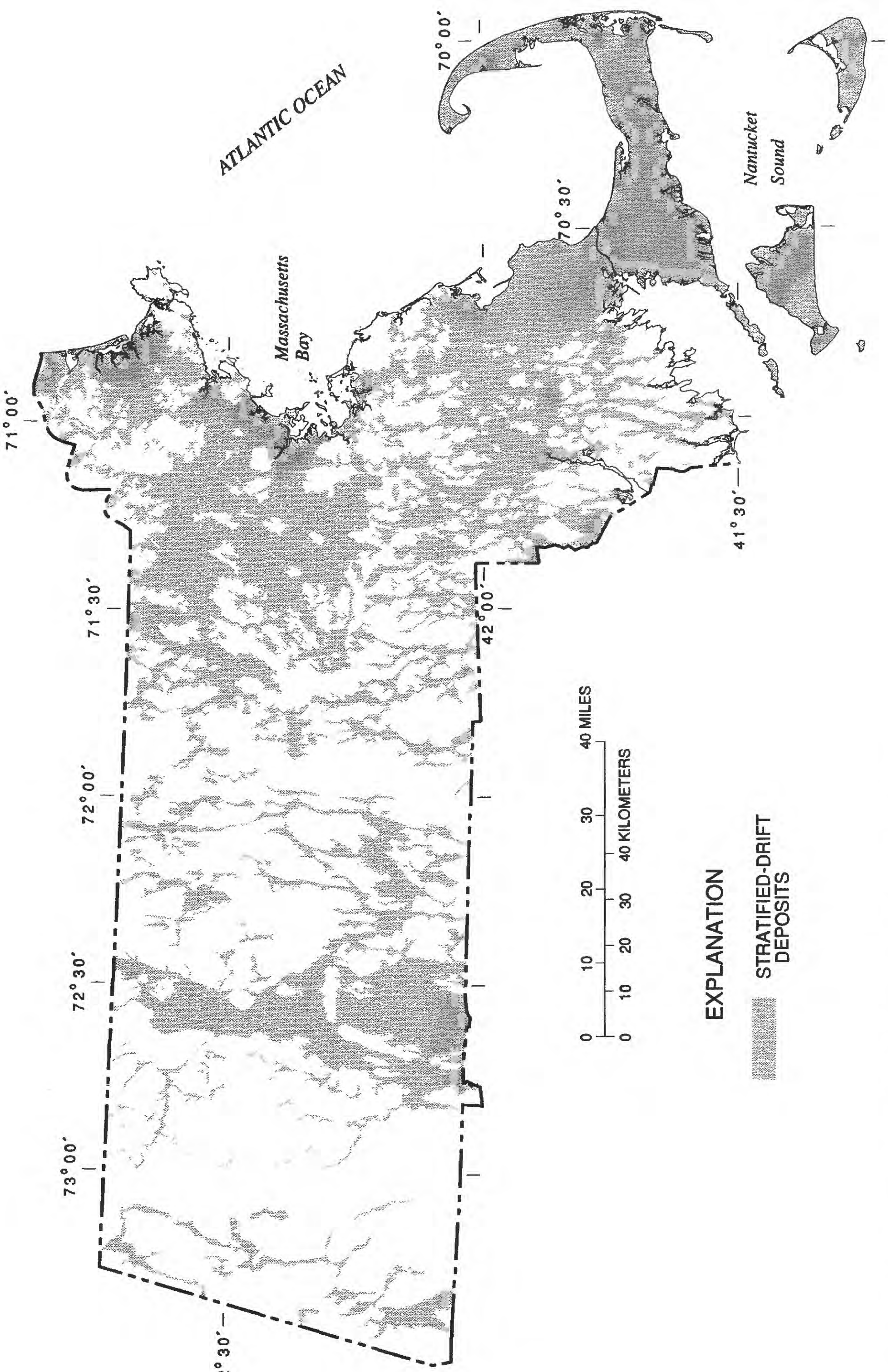


Figure 2. Distribution of stratified-drift deposits in Massachusetts.

describe the climate, geography and surficial geology of Massachusetts and the study basins, and briefly discuss how these physical characteristics affect streamflows.

Characteristics of Massachusetts

Massachusetts encompasses 8,093 mi^2 of the northeastern United States. The climate is humid, and precipitation, which is fairly evenly distributed throughout the year, averages about 45 in. throughout the State. Average temperatures range from 45°F in the western mountains to 50°F in coastal areas. Average monthly temperatures in western Massachusetts range from about 20°F in January to about 68°F in July, whereas average monthly temperatures in coastal areas range from about 30°F in February to about 71°F in July. Average annual snowfall is about 41 in. at Boston and about 68 in. at Worcester (National Oceanic and Atmospheric Administration, 1989).

Mean elevation and topographic relief tend to increase from low-lying coastal areas in eastern Massachusetts to moderate foothills in central areas, where maximum elevations reach about 2,000 ft above sea level. Elevations and relief decrease farther west in the Connecticut River valley, where the minimum elevation is about 40 ft. Elevation and relief increase to their maximums in the mountains of western Massachusetts, where the maximum elevation is almost 3,500 ft.

Surficial geology in Massachusetts is characterized by sediments deposited by glaciers at the end of the last ice age. These sediments can be further characterized as till (which may include bedrock outcrops) or stratified-drift deposits. Till is an unstratified and unsorted deposit of material ranging in size from clay particles to boulders. Stratified-drift deposits generally consist of fine sand, silt, or clay deposited in temporary lakes that formed during glacial retreat, or medium- to coarse-grained sand and gravel deposited by glacial streams. Till is found primarily in upland areas, whereas stratified drift is usually found in valleys and coastal regions. Till and fine-grained stratified drift deposits generally have smaller infiltration capacities than coarse-grained stratified drift deposits. Rainfall on till and fine-grained stratified drift deposits runs off quickly, contributing to larger peak discharges from areas overlain by these deposits than from areas overlain by coarse-grained stratified drift. Rainfall on coarse-grained stratified drift infiltrates rapidly and is stored in aquifers for later release to streams. Ground water released from aquifers is the primary source of streamflow during dry periods in most Massachusetts streams.

Southeastern Massachusetts, including Cape Cod, the southern half of the South Coastal Basin, the eastern half of the Buzzards Bay Basin, and the islands of Martha's Vineyard and Nantucket, is almost completely overlain by water-bearing coarse-grained stratified drift (sand and gravel). The extent of coarse-grained stratified drift, as a proportion of total basin area, generally decreases from east to west in Massachusetts (fig. 2). Stratified-drift deposits are mostly confined to narrow river valleys in the western half of the State, although extensive stratified drift deposits are present in the Connecticut River valley. The Connecticut River valley drift deposits consist primarily of glacial-lake sediments, and they are generally of finer texture than the large drift deposits in southeastern Massachusetts.

Lakes, ponds, and wetlands provide temporary storage for excess runoff during rain storms, and the water held in storage is gradually released from these areas. This effect tends to reduce peak streamflows in river basins where storage areas are a large proportion of the total basin areas. Areas of storage can also contribute to increased evapotranspiration, and can thereby reduce streamflows during dry periods. As with stratified-drift deposits, the extent of natural storage areas as a proportion of total basin area generally decreases from east to west in Massachusetts.

Characteristics of the Study Basins

The four basins studied in this report are the Blackstone, Charles, and Taunton River Basins and the Boston Harbor Basin. Each of the study basins is in eastern Massachusetts, as indicated by the shaded areas in figure 1. The basins are densely populated and include the two largest cities in the State, Boston and Worcester. Streamflow-gaging stations in each of the study basins are listed in table 1. Additional descriptions of each basin follow.

Blackstone River Basin

The Blackstone River Basin is part of the Narragansett Bay Basin. It has a drainage area of 472 mi^2,

Table 1. Active and discontinued streamflow-gaging stations in the study area

[Distances are in feet (ft), and in miles (mi); areas are in square miles (mi^2)]

Station number	Station name	Location	Period of record	Drainage area	Latitude	Longitude	Remarks
			Blackstone River Basin				
01109500	Kettle Brook at Worcester	75 ft downstream from Webster Street bridge	1923-78	31.2	42°13′55″	71°50′07″	Regulations by reservoirs and diversions for public supply of Worcester upstream.
01110000	Quinsigamond River at North Grafton	800 ft downstream from outlet of Hovey Pond	1939 to present	25.5	42°13′49″	71°42′41″	Regulations by Lake Quinsigamond and other ponds upstream.
01110500	Blackstone River at Northbridge	100 ft downstream from Sutton Street bridge	1939-77	139	42°09′13″	71°39′09″	Several regulations by ponds and diversions for public water supplies upstream.
01111050	Mumford River at East Douglas	100 ft upstream from Manchaug Road bridge	1939-51	27.8	42°04′24″	71°42′58″	Regulated by several ponds upstream.
01111200	West River below West Hill Dam, near Uxbridge	250 ft downstream from West Hill Dam	1962 to present	27.9	42°06′17″	71°36′28″	Peak flows regulated by West Hill Dam.
01111300	Nipmuc River near Harrisville, R.I.	1.0 mi upstream from mouth	1964 to present	16.0	41°58′52″	71°41′11″	No known regulations or diversions. Only part of basin in study area.
			Boston Harbor Basin (Mystic River Subbasin)				
01102500	Aberjona River at Winchester	0.5 mi upstream from head of Mystic Lakes	1939 to present	24.1	42°26′50″	71°08′22″	Flow affected by diversions for industrial use and municipal supply of Woburn and Winchester, and by wastage and leakage from Winchester North Reservoir. Some regulation by Winchester at dam 1,800 ft upstream.
			Boston Harbor Basin (Neponset River Subbasin)				
01104850	Mine Brook at Walpole	0.75 northwest of Walpole at inlet to Turner Road	1967-68	5.98	42°09′14″	71°16′52″	Diversions upstream along railroad line for supplies of Medfield and Walpole.
01105000	Neponset River at Norwood	200 ft upstream from Pleasant Street bridge	1939 to present	34.7	42°10′39″	71°12′05″	Several diversions upstream for municipal and industrial supplies.
01105500	East Branch Neponset River at Canton	100 ft downstream from Washington Street bridge	1952 to present	27.2	42°09′16″	71°08′47″	Regulated by several ponds upstream, and diversions for municipal supplies of Canton and Stoughton.
			Boston Harbor Basin (Weymouth-Weir Subbasin)				
01105557	Furnace Brook at Quincy	20 ft upstream from bridge on Hancock Street	1972-80	3.81	42°15′28″	71°00′33″	Occasional regulation at low flow.
01105585	Town Brook at Quincy	200 ft downstream from Miller Stile Road	1972-86	4.22	42°14′52″	70°59′52″	Regulation by Old Quincy Reservoir.
01105600	Old Swamp River near South Weymouth	Between divided lanes of State Route 3, 1.2 mi north of South Weymouth	1966 to present	4.50	42°11′25″	70°56′43″	No known regulations or diversions.

Table 1. Active and discontinued streamflow-gaging stations in the study area—**Continued**

Station number	Station name	Location	Period of record	Drainage area	Latitude	Longitude	Remarks
			Charles River Basin				
01103305	Charles River near Millis	150 ft upstream from Myrtle Street bridge	1974-80	84.0	42°07′59″	71°21′46″	Flow affected by diversions to and from the basin for municipal suplies.
01103500	Charles River at Dover	On Mill Street, 0.25 mi from Dedham Street	1937 to present	183	42°15′22″	71°15′38″	Flow affected by diversions to and from the basin for municipal supplies.
01104000	Mother Brook at Dedham	100 ft upstream from Washington Street bridge	1931 to present	--	41°15′18″	71°09′53″	Mother Brook is a diversion from the Charles River to the Neponset River.
01104200	Charles River at Wellesley	50 ft upstream from bridge on State Route 9	1959 to present	211	42°18′59″	71°13′42″	Diversion upstream to Mother Brook and to and from basin for municipal supplies.
01104500	Charles River at Waltham	800 ft downstream from Moody Street bridge	1931 to present	227	42°22′20″	71°14′03″	Same as above, and at times affected by releases from Stony Brook Reservoir.
			Taunton River Basin				
01106500	Matfield River at Elmwood	20 ft upstream from bridge State Route 18	1958-60	40.5	42°00′55″	70°57′42″	Regulation by ponds upstream, and diversion to basin for water supply of several towns supplied by Brockton.
01106900	Poor Meadow Brook at South Hanson	20 ft downstream from bridge on State Route 27	1958-60	14.6	42°02′32″	70°53′56″	Small diversion to basin for supply of town of Whitman.
01107000	Dorchester Brook near Brockton	20 ft upstream from bridge on Pearl Street	1962-74	4.71	42°03′41″	71°03′59″	No known regulations or diversions.
01107200	Taunton River at Titicut, near Bridgewater	At Summer Street bridge, 0.9 mi upstream from Nemasket River confluence	1920-25	182	41°56′50″	70°56′13″	Diversions upstream for supplies of New Bedford and other towns.
01107400	Fall Brook near Middleboro	0.4 mi upstream from mouth 2 mi south of Middleboro	1966-67	9.32	41°51′55″	70°54′32″	No known regulations or diversions.
01108000	Taunton River near Bridgewater	0.1 mi upstream from bridge on Titicut Road	1929-76 1985-88	258	41°56′05″	70°17′18″	Several regulations by dams and diversions upstream for municipal supplies.
01108500	Wading River at West Mansfield	200 ft downstream from Balcolm Street bridge	1953-86	19.5	42°00′00″	71°15′38″	Several regulations by dams and diversions upstream for municipal supplies.
01109000	Wading River near Norton	200 ft downstream from bridge on State Route 140	1925 to present	43.3	41 °56′51″	71°10′38″	Several regulations by dams and diversions upstream for municipal supplies.
01109060	Threemile River at North Dighton	800 ft downstream from Warner Boulevard	1966 to present	84.3	41°51′58″	71°07′24″	Several regulations by dams and diversions upstream for municipal supplies.
01109070	Segreganset River near Dighton	50 ft upstream from culverts on Center Street	1966 to present	10.6	41°50′25″	71°08′36″	Occasional regulation by ponds, and diversions for Dighton Water District.

of which 335 mi^2 is in Massachusetts. About 27 percent of the basin area in Massachusetts is underlain by stratified-drift deposits. The basin is bounded to the west by the French and Quinebaug River Basins, to the northwest by the Chicopee River Basin, to the north by the Nashua River Basin, to the northeast by the Concord River Basin, to the east by the Charles River Basin, and to the southeast by the Tenmile River Basin. Most of the 300,000 residents of the basin live near Worcester, the only city in the basin (U.S. Geological Survey, 1988). Southern parts of the basin are relatively rural. The headwaters are in hilly terrain about 6 mi northwest of Worcester, where the maximum elevation is about 1,300 ft. The basin flattens as the Blackstone River flows southeastward toward its mouth in Rhode Island, where the elevation is about 120 ft at the State line. There are at least 151 natural and manmade lakes and ponds within the Massachusetts part of the basin. Many of the ponds were formed during the Industrial Revolution, when dams were built along the main channel and most of the larger tributaries of the Blackstone River. Water impounded behind these dams was used by mills for power generation, industrial processes, cooling, and waste disposal.

Major tributaries to the Blackstone River in Massachusetts include the Quinsigamond, West, and Mill Rivers and Abbott Run (fig. 3), each of which flows from the north. Kettle and Tatnuck Brooks and the Mumford River are major tributaries that flow from the northwest and west.

An average of about 20 ft^3/s (12.9 Mgal/d) of water is diverted from the Nashua River Basin into the Blackstone River Basin for public supply of the city of Worcester. The diverted water is about 45 percent of the city's water supply. About 50 percent of the city's supply is obtained from reservoirs within the Blackstone River Basin; the remaining 5 percent is from ground water. All other towns in the basin obtain their municipal supplies from ground water, except Mendon and Millville, which have no municipal supplies (Walker and Krejmas, 1986).

Boston Harbor Basin

The Boston Harbor Basin has a total drainage area of 283 mi^2. With a population of 954,000 in 1985, it has the second largest population of the basins in Massachusetts, and it is the most densely populated (U.S. Geological Survey, 1988). The Boston Harbor Basin consists of three major subbasins; the Mystic and Neponset River Basins and the Weymouth-Weir Basin (fig. 4). The Mystic River subbasin is separated from the Neponset River and Weymouth-Weir River subbasins by the Charles River Basin, which is considered by the State to be a separate major basin because of its large size and its significance to the Boston metropolitan area. Small coastal parts of each of the three subbasins drain directly to Boston Harbor rather than to the river for which the subbasins are named.

Mystic River Subbasin

The Mystic River Basin has a drainage area of 76 mi^2 and is bordered on the south by the Charles River Basin, on the west by the Shawsheen River Basin, on the north by the Ipswich River Basin, and on the northeast by the Saugus River subbasin of the North Coastal Basin (fig. 4). The Mystic River flows southeast to Boston, where it empties into Boston Harbor. About 49 percent of the basin is underlain by stratified drift. All or part of the cities of Boston, Cambridge, Somerville, Malden, and Medford and 13 towns are within the basin. All of these cities and towns except Burlington, Wilmington, and Reading obtain some or all of their municipal water supplies from, and discharge wastewater to, the Massachusetts Water Resources Authority (MWRA) system. Woburn, Wilmington, Reading, and Burlington obtain all or part of their water from wells within the basin. Winchester and Woburn supplement their water supplies from the MWRA system with water from reservoirs in the basin. Cambridge obtains much of its supply from reservoirs in the Charles River Basin. Burlington obtains some of its water from the Shawsheen River Basin (Gay and Delaney, 1980).

The study area within the Mystic River subbasin was limited to the areas within the basin boundaries indicated on figure 4 for the streamflow-gaging station on the Aberjona River at Winchester (site 01102500) and Mill Brook in Arlington (site 01103015). Remaining areas within the subbasin are urbanized, or have little or no potential for developing new water supplies. Maximum elevation in the Mystic River subbasin is about 375 ft at Arlington Heights, in Arlington. The river is affected by tides up to the Lower Mystic Lake, in Arlington.

Neponset River Subbasin

The Neponset River subbasin has a total drainage area of 117 mi^2, of which about 49 percent is underlain by stratified drift (fig. 4). It is bounded on the north and west by the Charles River Basin, on the east by the Weymouth-Weir subbasin, and on the south by the Taunton River Basin. Because of the extensive stratified-drift deposits, the topographic boundary with the Taunton River Basin may not correspond exactly with the ground water divide in some places.

The headwaters of the Neponset River subbasin are in the Neponset Reservoir in Foxborough. The river flows generally northeastward through rolling terrain to its mouth at Dorchester Bay, in the southern part of Boston Harbor. The maximum elevation is 630 ft in Milton. There are 65 lakes and ponds and many large wetlands within the subbasin. The lower part of the subbasin is urbanized, whereas upper parts

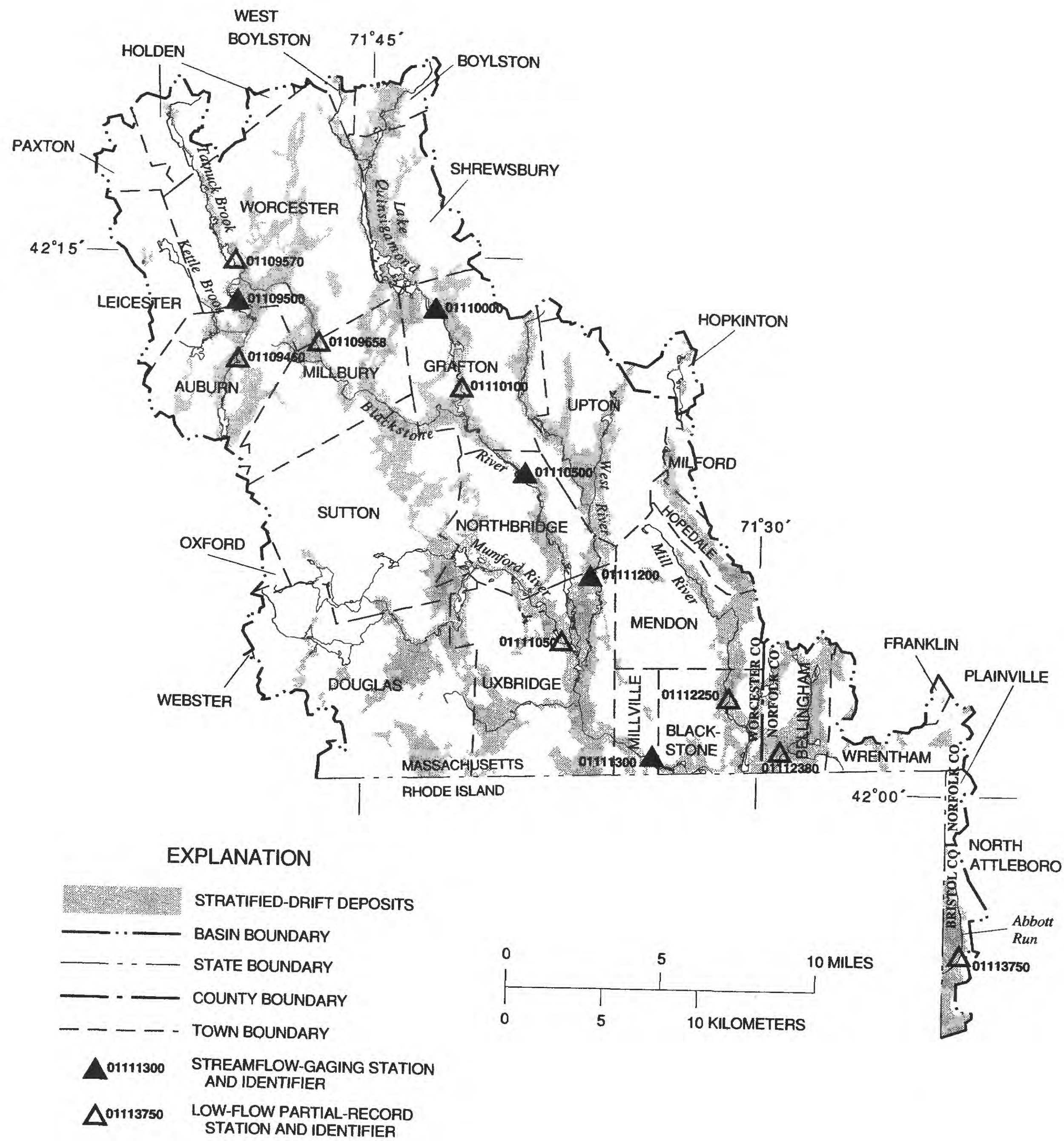


Figure 3. Drainage boundaries, areas of stratified-drift deposits, and locations of selected sites in Blackstone River Basin.

of the subbasin are more than 50 percent forested. All or part of the cities of Boston and Quincy and 12 towns are within the subbasin. Of these, Boston, Quincy, Milton and Canton receive at least part of their municipal water supplies from, and discharge wastewater to, the MWRA system. Westwood and Dedham are entitled to use MWRA water, but they currently restrict their use to sources within the subbasin. Water is diverted to or from the subbasin for public supplies and (or) wastewater disposal in parts of 10 towns in the subbasin. In addition, an average of 79 ft^3/s (51 Mgal/d) of water is diverted from the Charles River to the Neponset River through Mother Brook (Massachusetts Division of Water Resources, 1989).

Weymouth-Weir Subbasin

The Weymouth-Weir subbasin has a drainage area of 90.5 mi^2, of which about 39 percent is underlain by stratified-drift deposits (fig. 4). The subbasin consists of areas drained from east to west by the Weymouth

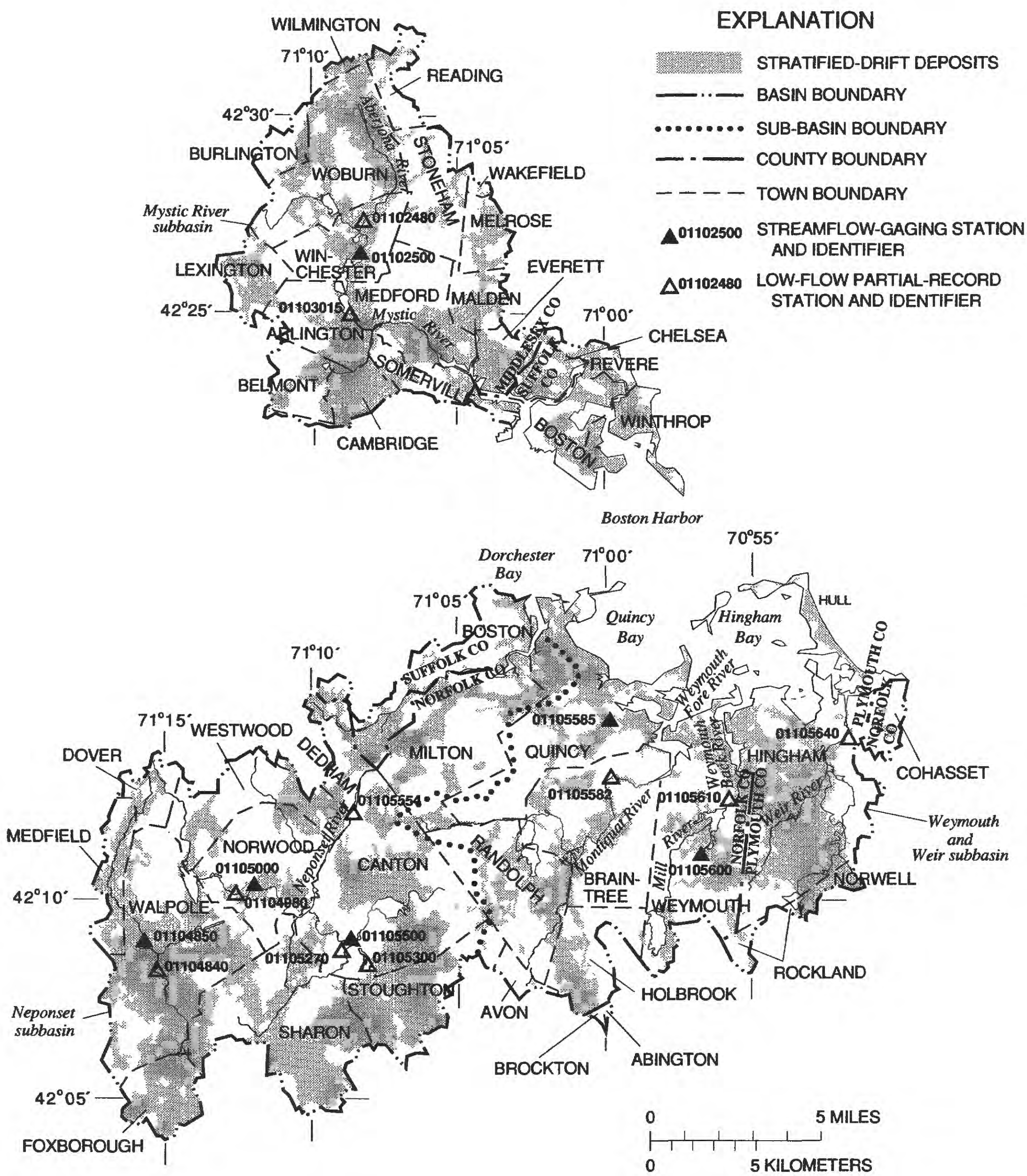


Figure 4. Drainage boundaries, areas of stratified-drift deposits, and locations of selected sites in Boston Harbor Basin.

Fore, Weymouth Back, and Weir Rivers, areas drained by smaller streams that discharge directly into Quincy and Hingham Bays (both part of Boston Harbor), and all of the Hull-Nantasket peninsula. The subbasin is bounded on the west by the Neponset River subbasin, on the south by the Taunton River Basin, and on the east and southeast by the South Coastal Basin.

Each of the three major rivers in the Weymouth-Weir subbasin flows generally in a northerly or northeasterly direction through gently rolling terrain. Relief is greatest in the western part of the subbasin, where the maximum elevation is 630 ft in Milton. There are 36 lakes and ponds and extensive wetlands within the subbasin.

Parts of the cities of Quincy and Brockton and all or part of 13 towns are within the subbasin. Quincy and Milton receive water from, and discharge wastewater to, the MWRA system. The towns of Braintree, Randolph, Weymouth, and Hingham obtain all municipal water from surface- and ground-water sources within the subbasin. Norwell obtains part of its municipal supply from within the subbasin and part from the South Coastal Basin. Holbrook has no municipal supply. The city of Brockton and the remaining towns with land inside the Weymouth-Weir subbasin obtain their municipal water supplies from sources outside the subbasin (Brackley and others, 1973; Williams and Tasker, 1974a).

Charles River Basin

The drainage area of the Charles River Basin, at 319 mi^2, is larger than the total drainage area of all other basins that drain into Boston Harbor. The basin is the most populous in the State, with 988,000 residents in 1985 (U.S. Geological Survey, 1988). All or part of the cities of Boston, Brookline, Cambridge, Somerville, Newton, and Waltham are within the basin. The basin area downstream from the streamflow gaging station at Waltham (USGS station number 01104500, drainage area of 250 mi^2, fig. 5) is highly urbanized and not suitable for development of new water supplies; thus, no sites in this area were selected by the MOWR to receive low-flow estimates.

On average, about 217 ft^3/s (140 Mgal/d) of water is supplied by the MWRA for the municipal supply of all areas of the basin below the Charles River Dam, except for the city of Cambridge. The MWRA supply is obtained from Wachusett Reservoir in the Nashua River Basin and from the Quabbin Reservoir in the Chicopee River Basin. Wastewater from the entire area below the Charles River Dam is discharged to Boston Harbor through the MWRA sewage system.

The Charles River Basin is bounded to the north by the Shawsheen River Basin and the Mystic River subbasin of the Boston Harbor Basin, to the west by the Concord River Basin, to the south by the Blackstone, Tenmile, and Taunton River Basins, and to the southeast by the Neponset River subbasin of the Boston Harbor Basin. The headwaters of the Charles River Basin are in Hopkinton, an area of gently rolling rural land. The maximum elevation of the basin is about 550 ft above sea level. From Hopkinton, the river flows southeast for about 10 mi to Franklin. Downstream from Franklin, the river meanders northeast through relatively flat terrain for the remainder of its length. There are extensive wetlands in the middle of the basin. These wetlands, in conjunction with 139 lakes and ponds upstream from the Watertown gaging station, provide a large natural storage capacity. Stratified-drift deposits underlie about 47 percent of the basin area upstream from Watertown. The largest deposits are primarily distributed along the main channel and the large tributaries of the Charles River. Major tributaries entering the main channel from the south include the Mill and Stop Rivers and Mine Brook. Major tributaries entering the main channel from the northwest include Hopping, Chicken, Bogastow, Waban, and Stony Brooks.

Water in the Charles River Basin has been extensively controlled for municipal and industrial uses. Most dams within the basin were constructed for industrial use, although about 26 ft^3/s (16.8 Mgal/d) of water from large reservoirs in the Stony Brook subbasin is diverted to the city of Cambridge, about 3.1 ft^3/s (2.0 Mgal/d) of water from Echo Lake supplies Milford, and about 0.3 ft^3/s (0.2 Mgal/d) of water from Sandy Pond supplies Lincoln (Richard Thibedeau, Massachusetts Office of Water Resources, written commun., 1986).

Water is diverted between subbasins and into and out of the Charles River Basin in several other locations. From 1980 through 1983, an average of 102 ft^3/s (66 Mgal/d) of water was used in the study area and by the city of Cambridge for municipal supplies. Of this, about 14 ft^3/s (9.0 Mgal/d) was imported from adjoining basins, and about 36 ft^3/s (23 Mgal/d) was supplied by the MWRA from sources in the Chicopee and Nashua River Basins (Richard Thibedeau, Massachusetts Office of Water Resources, written commun., 1986).

Several towns in the study area divert wastewater into the MWRA sewer system, which discharges into Boston Harbor. In 1984, about 77 ft^3/s (48 Mgal/d) of wastewater was discharged to the MWRA system from the study area, including 26 ft^3/s (17 Mgal/d) from Cambridge (from the Stony Brook subbasin) and about 42 ft^3/s (27 Mgal/d) obtained from the MWRA and other out-of-basin sources. Additionally, an average of 79 ft^3/s (51 Mgal/d) of surface water was diverted from the Charles River through Mother Brook into the Neponset River Basin (Richard Thibedeau, Massachusetts Office of Water Resources, written commun., 1986).

Taunton River Basin

The Taunton River Basin is in southeastern Massachusetts and is a subbasin of the larger Narragansett Bay Basin. In 1985, the population within the 530-mi^2 basin was 394,000. All or part of the cities of Attleboro,

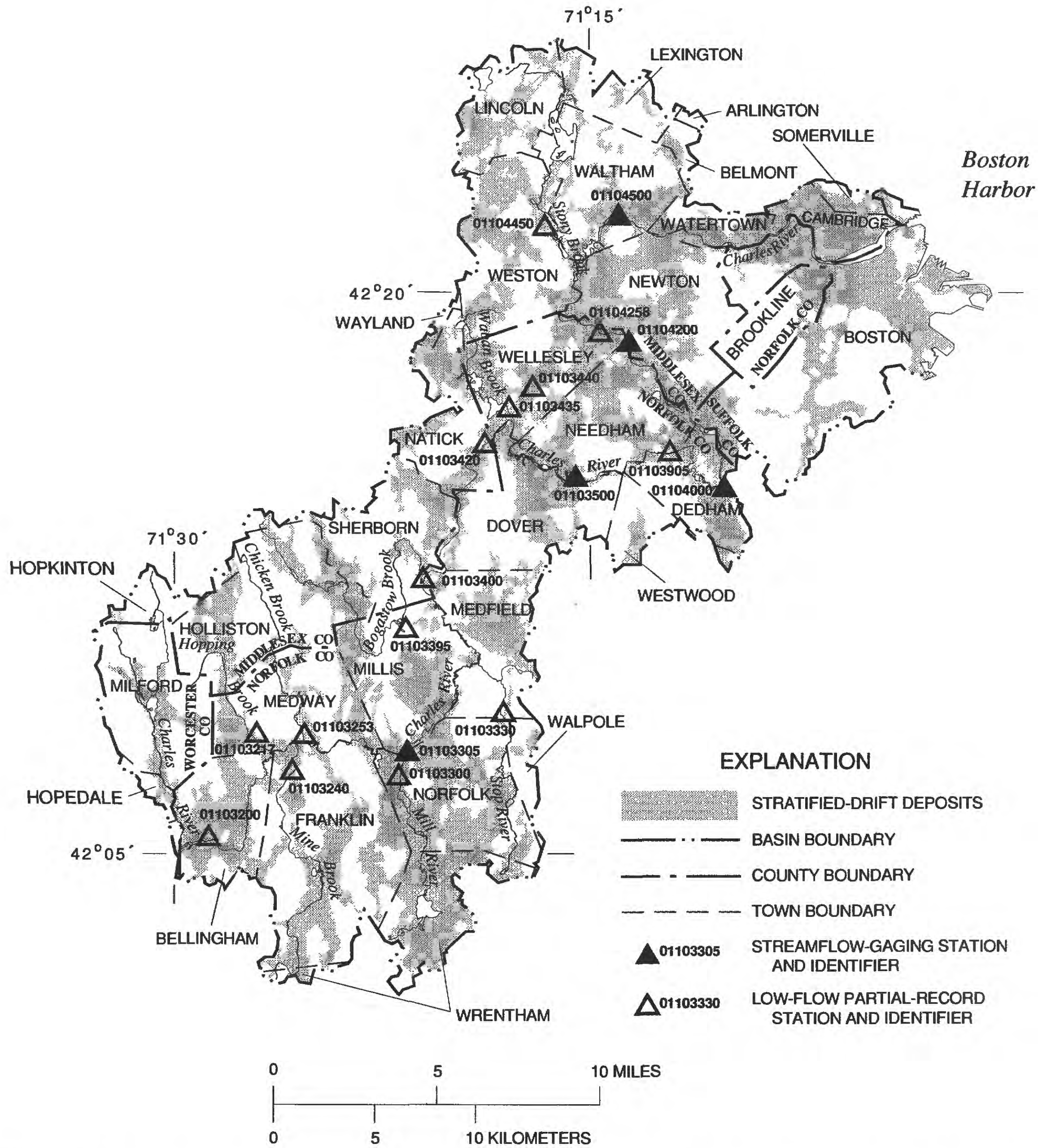


Figure 5. Drainage boundaries, areas of stratified-drift deposits, and locations of selected sites in Charles River Basin.

Brockton, Fall River, New Bedford, and Taunton and 36 towns are within the boundaries of the basin (fig. 6). The Taunton River flows generally southwest to its mouth at Fall River, where it empties into Mount Hope Bay, part of Narragansett Bay. Tides affect about 24 mi of the river, the last 8 or 9 of which are tidal estuary

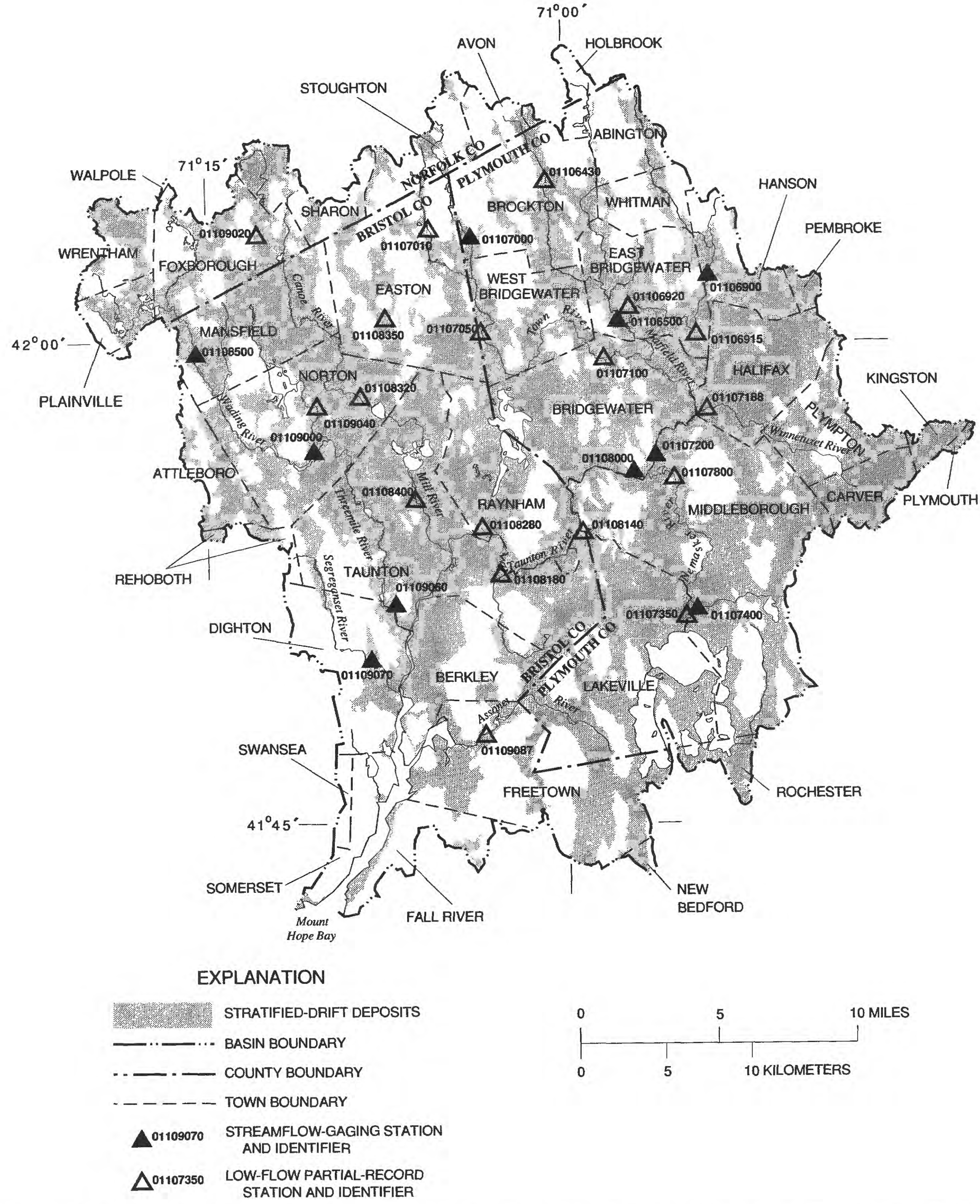


Figure 6. Drainage boundaries, areas of stratified-drift deposits, and locations of selected sites in Taunton River Basin.

(Williams and others, 1973). Major tributaries to the Taunton River include the Segreganset, Threemile, Mill, Town, and Matfield Rivers, which flow from the north into the main channel. The Assonet, Nemasket, and Winnetuxet Rivers drain southern and eastern parts of the basin. Maximum elevation in the basin is 490 ft above sea level at Bluff Hill in Sharon.

The Taunton River Basin is bounded to the west by the Tenmile River Basin and small subbasins of the Narragansett Bay Basin, to the south and southeast by the Buzzards Bay Basin, to the east by the South Coastal Basin, and to the north by the Charles River Basin and the southern part of the Boston Harbor Basin. About 48 percent of the Taunton River Basin is underlain by stratified-drift deposits. These deposits are mostly confined to narrow valleys in northern and southern sections of the basin where the topography is generally rolling. Drift deposits in these areas form small aquifers that often become depleted as a result of pumping during droughts. In central and eastern parts of the basin, which are comparatively flat, stratified drift deposits predominate. Because of the extensive drift deposits in these areas, the topographic boundaries between adjacent basins and between subbasins within the Taunton River Basin may not correspond exactly with the ground water divides in several locations.

About 200 lakes and ponds make up more than 4 percent of the surface area of the basin. Water from many of these lakes and ponds is regulated by dams and (or) has been diverted for municipal, agricultural, and (or) industrial uses. Almost 18 percent of the basin is classified as wetland. In addition to the natural wetlands, large areas are flooded annually for harvesting cranberries, the major crop in the basin.

Of the 36 communities that are at least partially within the basin, 19 depend on ground water for their sole water supply. Most of these communities are in the northern one-half of the basin (Lapham, 1988). Six municipalities depend solely on surface water for their supplies, including four of the five cities in the basin. The remaining city, Attleboro, and the towns of Somerset, Swansea, Raynham, and Abington obtain their water supplies from a combination of ground-water and surface-water sources. Significant amounts of water are diverted out of the Taunton River Basin to supply 11 cities and towns that are located at least partially in adjacent basins. Some of this water is returned as wastewater through treatment plants in the basin. Water is diverted into the basin for the supplies of Abington and Fall River. In addition, there are several diversions between subbasins within the Taunton River Basin.

PRINCIPLES OF LOW-FLOW ANALYSES

The term "basin yield" has several definitions in hydrologic literature. Generally, a basin yield refers to a quantity of streamflow that is available at a given point on a stream over a specified time interval (Ayers, 1970). Researchers in different fields of hydrology have defined specific values for the yields of basins. For instance, Freeze and Cherry (1979) defined basin yield as the maximum rate of withdrawal from water wells that can be sustained without causing unacceptable declines in the hydraulic head in an aquifer or causing unacceptable changes to any other component of the hydrologic cycle in the basin. Hydrologists and engineers interested in watershed management and the design of reservoirs often use basin yield to mean a minimum value available for use during some critical period, such as the worst drought of record (Linsley and others, 1982). The MOWR defines a basin yield as the "maximum dependable withdrawals that can be made continuously from a water source including ground or surface water during a period of years in which the probable driest period or period of greatest water deficiency is likely to occur" (Massachusetts Office of Water Resources, written commun., 1990).

The MOWR chose the drought of water years 1980–81 as the reference period to determine the MST (its expression of basin yield). The MOWR determines MST's by balancing known or estimated water use with estimates of available discharge under "natural-flow" conditions. The estimates of available streamflow that are provided in this report are expressed in terms of discharges, in cubic feet per second, that are equaled or exceeded under natural-flow conditions 99, 98, and 95 percent of the time at a specified point on a stream during a period hydrologically similar to water years 1980–81. These statistics are further explained in the section "Development of Low-Flow Statistics Used to Express Basin Yields."

In the strictest interpretation, natural-flow conditions occur only in basins where there is no effect of human activity on streamflows. According to this interpretation, almost no basins of significant size in densely populated Massachusetts could be said to have natural flow conditions. For this study, it was necessary to broaden the interpretation: Flow conditions in a basin are considered to be natural if diversions to, from, or within the basin, or regulations by dams or other manmade controls have no significant effect on the daily mean discharges of the stream during low-flow periods.

Effects of Regulations and Diversions on Low-Flow Analyses

Streamflow for most of the larger streams and rivers in the four study basins is significantly affected by dam regulations or by diversions for water supplies of municipalities and manufacturers. Regulations affect the temporal pattern of streamflows on rivers where dams are present. Flood-control dams that impound water only during times of peak flow, such as the West Hill Dam on the West River near Uxbridge, generally have little effect on low flow. Many dams operated by manufacturers, and some dams operated for hydroelectric power, have small storage capacities and are controlled on a diurnal or a more frequent cycle. Regulations of this type do not substantially affect daily mean discharges. Dams that control large reservoirs can have substantial effects on river flow. These effects often take the form of reduced peak discharges and sometimes increased low discharges, which are augmented from storage in the reservoir. Total annual discharges in a basin may be reduced because of increased evapotranspiration and seepage from the impounded water bodies.

In southeastern Massachusetts, extensive areas of bogs are flooded each fall to harvest cranberries. Low flows in these areas are usually not dramatically affected because the bogs are usually flooded after the low-flow season has ended. Irrigation of cranberries during the growing season, however, can reduce low flows because of pumping directly from the streams or adjacent aquifers, and also because of increased evapotranspiration.

Diversions by manufacturers are commonly confined to short distances along rivers. Water is generally taken from the river channel; passed through the manufacturing plant for use in processing, cooling, dilution of wastes, or other uses; and then returned to the river. In many cases, consumptive losses from diversions by manufacturers are negligible. Diversions by municipalities generally affect streamflow distribution to a greater extent than diversions by manufacturers. The consequences of diversions to the flow regime of the river are variable and depend not only on where the diversions occur, but also on the final fate of the diverted water.

Water that is diverted from a stream or adjacent aquifer for municipal supplies and is returned to the basin as effluent from individual septic systems, or from sewage treatment plants within the basin, generally causes little loss of water to the basin, but such diversion may affect the temporal pattern of streamflows. Diversions from one basin to another reduce streamflow in the donor basin and increase it in the receiving basin. Diversions between subbasins of a larger basin can dramatically affect streamflows in the subbasins, but if consumptive losses are negligible, streamflows for the larger basin may be nearly unaffected.

Development of Low-Flow Statistics Used to Express Basin Yields

Statistics used to describe low-flow characteristics of streams are generally of two categories: those based on frequency of occurrence, such as the $Q_{7,10}$, and those based on the duration of occurrence, such as the 95-percent duration discharge. Low-flow-frequency statistics for a gaged site (streamflow-gaging station) with at least 10 years of record are computed from the annual series of observed minimum discharges averaged over a specified number of days. Low-flow-frequency statistics are used to estimate the probability of future occurrences of the specified event on the basis of an assumed probability distribution. The accuracy of the computed statistics depends on the length of record at the site. Regardless of record length, however, the interpretation of low-flow frequency statistics as estimates of the likelihood of future occurrences of specified events does not change.

Flow-duration percentiles are computed from the cumulative distribution function (CDF) of the mean discharges at a site for a given time step during a specified period. A CDF is a function that gives the probability of a given value of a random variable being equaled or exceeded (Iman and Conover, 1983, p. 75). The random variable is not fit to an assumed probability distribution.

Flow-duration percentiles are usually computed with a daily time step, but weekly, monthly and annual time steps are sometimes used. A flow-duration curve is a graphical representation of the CDF. Flow-duration curves are constructed by ranking the n observed discharges, q_k, where $k = 1,2,3,...n$, such that q_1 is the largest streamflow for the specified period and q_n is the smallest. An empirical curve is constructed by plotting each ordered observation against its plotting position, p_k. The plotting position, which is an estimate of exceedence probability, is usually calculated by use of the Weibull formula

$$p_k = k/(n+1),\ k = 1,2,3,...n, \qquad (1)$$

where k is the rank of the observed value, or by use of one of several similar formulas (Loaiciga, 1989).

An example of a flow-duration curve of daily mean discharges for a site with natural flow conditions is shown in figure 7. The curve is plotted on a logarithmic-probability graph, which results in a straight line when the data are log-normally distributed. When done manually, a smooth line is usually drawn through the plotted points for the specified discharges (Searcy, 1959, p. 2); however, computer programs that have been developed to calculate and plot duration curves, such as figure 7, often connect the selected points along the curve and interpolate between them with straight lines (Lumb and others, 1990, p. 123).

Strictly interpreted, flow-duration curves represent only the period for which they are calculated. Duration discharges computed for different periods at a single site are not considered equivalent because climatic conditions and subsequent streamflows during the different periods are not the same. For example, all daily mean discharges that were less than the 95-percent duration flow for a 10-year period may have occurred during a single 6-month period. The 95-percent duration discharge for the 10-year period then is equal to the 50-percent duration discharge for the year encompassing that 6-month period. Likewise, if all daily discharges in the 6-month period were the lowest in 20 years, the same discharge may have been equaled or exceeded 97.5 percent of the time during the 20-year period. Although flow-duration statistics computed for different periods are not considered equivalent under the strict interpretation, the flow-duration curve can be

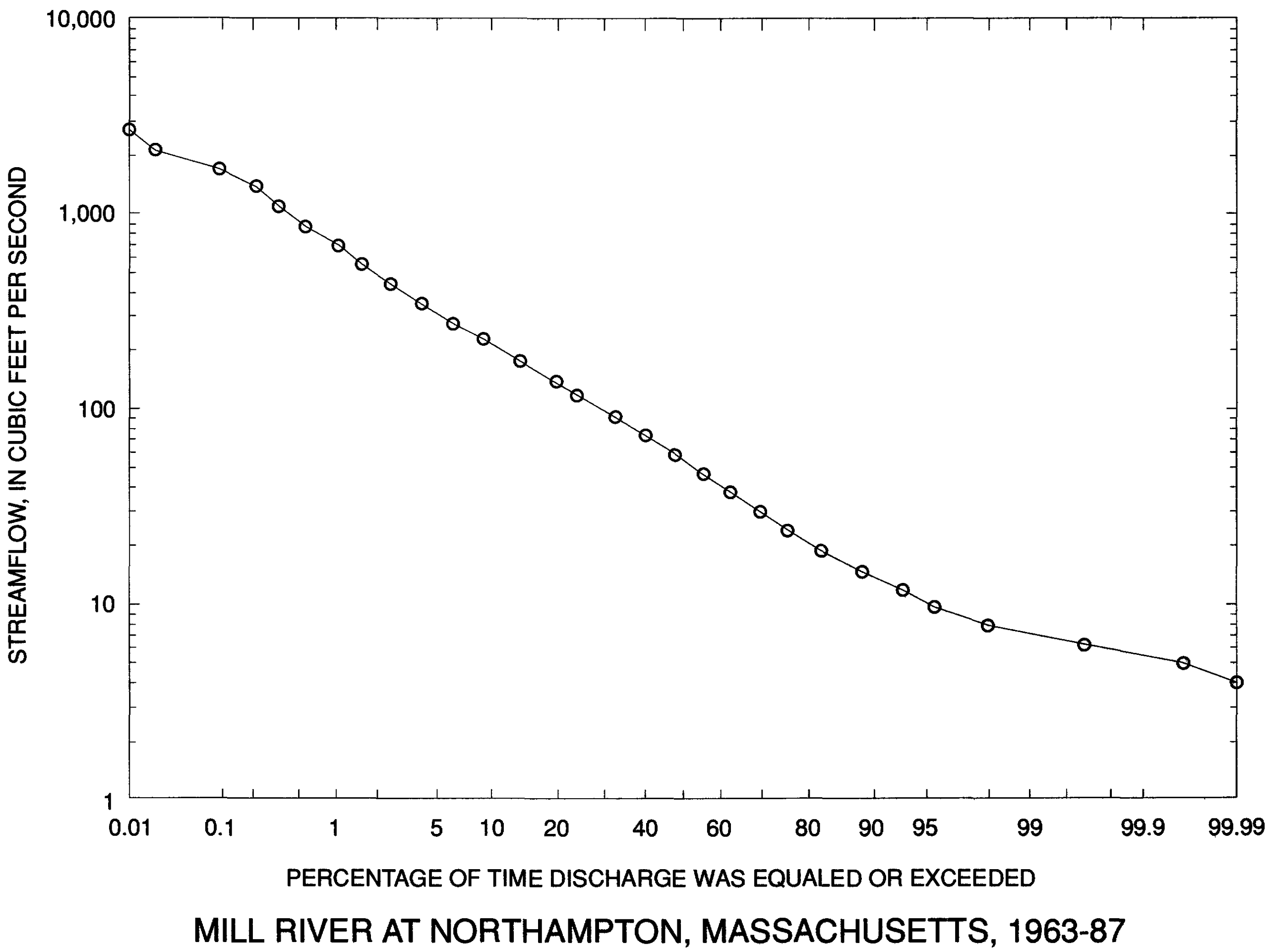


Figure 7. Example of flow-duration curve for gaged site under natural flow conditions: Mill River at Northampton, 1963–87.

used to estimate the percentages of time that future discharges will be equaled or exceeded if the period of record used to compute the flow-duration curve is sufficiently long and if discharges during that period are considered to adequately represent long-term conditions (Searcy, 1959, p. 2). When the period of record at a site is not sufficient to represent long-term conditions, record-extension procedures can be used to adjust the short-term record to a longer period. (These procedures are discussed in the "Record-Extension Techniques" section.)

Water-supply and planning agencies in Massachusetts have found that use of flow-duration curves has a distinct advantage over the more widely used low-flow-frequency statistics when assessing the effect of a proposed diversion. Water users have varying streamflow needs, requiring that the effect of diversions be assessed at different levels of flow. Because flow-duration curves can be easily adjusted up or down to account for a proposed diversion, they are more flexible than low-flow frequency statistics, which are usually computed for single extreme events, such as the $Q_{7,10}$.

METHODS USED TO ESTIMATE LOW-FLOW DURATION DISCHARGES

Streamflow-data-collection sites were selected from a data base consisting of all currently operating and discontinued streamflow-gaging stations, low-flow partial-record sites, and miscellaneous measurement sites in Massachusetts for inclusion in multiple-regression analyses to obtain equations for use in estimating the 99-, 98-, and 95-percent duration discharges. Streamflow data for each site were used to obtain the duration discharges for a selected base period. Record-extension techniques were used to estimate the selected duration discharges for sites with incomplete records during the base period; otherwise, the duration discharges were computed directly from the gaged record. Criteria were set to ensure that estimated duration discharges for sites with incomplete records during the base period were reasonably precise. Sites that did not meet these criteria were omitted from the analyses. Basin characteristics were selected for use in the analyses, and were measured for all sites included in the analyses. Weighted-least-squares (WLS) multiple-regression analyses were then performed to relate duration discharges for each site to their measured basin characteristics. Equations obtained from the WLS regression analyses were used to estimate the duration discharges for selected ungaged sites. The following subsections discuss these procedures in greater detail.

Streamflow Data Base

During the 1987 water year, the latest year for which data were available when this study began, the USGS operated 81 continuous-record streamflow-gaging stations within Massachusetts. Periods of record for these stations ranged from less than 2 years (Whetstone Brook at Depot Road at Wendell Depot) to 84 years (Connecticut River at Montague City). In addition to the 81 stations gaged during 1987, 46 additional sites were gaged continuously for at least one year, but were not active during 1987. To supplement the continuous data collected at the streamflow-gaging stations, the USGS obtained at least one discharge measurement at about 1,000 miscellaneous-measurement and low-flow partial-record sites within the State. Discharge measurements were generally obtained at these sites to provide data for specific studies, such as aquifer assessments or hydrologic atlases, or as part of networks for various low-flow investigations.

At most of these gaging stations, miscellaneous measurement sites, and low-flow partial record sites, discharges are affected by regulations or diversions and are not useful for regression analyses without concurrent knowledge of upstream water use. With few exceptions, such data are not available. Discharge data for all gaged sites, and most other sites, are stored in data bases at USGS offices in Albany, N.Y., and Reston, Va. Information regarding the availability of data and statistical analyses can be obtained from the U.S. Geological Survey, 28 Lord Road, Suite 280, Marlborough, MA 01572.

Selection of a Base Period

Climatic patterns and, consequently, patterns of streamflow are not entirely random. Recorded discharges for any given period are related to those of a previous or subsequent period because wet periods (days, months, years, and so forth) tend to be followed by wet periods, and dry periods tend to be followed by dry periods. This dependence between periods tends to diminish, but is not completely eliminated, as the time period chosen for analysis increases. Because the distribution of streamflows is not constant with time, percentile discharges obtained from flow-duration curves vary for different periods of computation.

Time-sampling errors are the differences between the observed values of a statistic computed from a sample and the true values that would be obtained if the statistic were computed from the entire population. Flow-duration statistics computed for a specified period have no time-sampling errors because the statistics are obtained from the entire population of daily mean discharges for the period; however, when those statistics are used to estimate conditions during periods different from the period for which they were computed, time-sampling errors become a factor in the quality of the estimates.

Estimates of flow-duration statistics obtained from regression analyses that include sites with different record lengths have larger time-sampling errors than estimates produced from site records of identical length. To minimize time-sampling errors, all sites used in an analysis would ideally have the same period of record, thus ensuring that differences in streamflow characteristics are due to differences in climatic or drainage-basin characteristics rather than in the periods of record (Searcy, 1959, p. 12). This ideal is rarely met.

Time-sampling errors in the estimates of flow-duration statistics for future or long-term conditions can be reduced by using data only from stations whose records are long enough to be representative of long-term conditions. This can be a problem where few stations have long record lengths. If additional sites are needed in regression analyses for such areas, streamflow statistics for sites with short periods of record can be adjusted to represent a longer period by use of record-extension techniques. When records for several sites are to be extended, it is convenient to use a base period to which all short-term records can be extended. Use of a base period also helps to reduce time-sampling errors that result from inclusion of short-term sites in the regression analyses.

A base period of 25 years (water years 1963–87, October 1, 1962, through September 30, 1987) was chosen for use in regionalizing streamflow characteristics. The base period was selected to (1) be long enough to represent long-term conditions, (2) include the 1962–66 drought, the most extreme drought of record at most long-term gaging stations in Massachusetts, and (3) include the 1980–81 drought, which is the most recent drought of significance. The MOWR uses the 1980–81 drought as its planning drought; concurrent water-use data for this drought are superior to those available during previous droughts.

Initial Site Selection

The occurrence of natural flow was the primary criterion used in selecting sites for the regression analyses. This status was determined on the basis of the absence of regulations or diversions noted in the remarks listed for each site in USGS annual data reports (U.S. Geological Survey, 1976–89). In addition to conditions that affect the natural flow, these remarks sections include an accuracy statement, a description of special methods of computation, and other pertinent information for each streamflow-gaging station (Novak, 1985, p. 61). Municipal water-supply wells, sewage-treatment plants, or dams within the basin that were not discussed in the remarks section of the annual data reports, and the appearance of the flow-duration curve, also could disqualify sites. Flow-duration curves for sites with natural flow conditions generally plot as a straight line or smooth curve on log-probability graphs (fig. 7). Flow-duration curves for sites affected by dam regulations or diversions sometimes exhibit sharp breaks or bends (fig. 8). Duration discharges computed for sites such as these may not be representative of the natural response of their drainage basins to changes in climatic conditions. Sites where streamflows are affected this way should not be used in the regionalization analyses without corrections.

Of the 127 past and presently operated streamflow-gaging stations in Massachusetts, 44 were initially selected. Of these, 29 were considered to have entirely natural streamflow conditions. The remaining 15 stations were only slightly affected by regulations.

Although the regionalization models developed for this study are intended for statewide use, accurate estimates of percentile discharges are desired primarily for the four study basins, all in eastern and southeastern Massachusetts. Of the gaged sites initially selected for possible use in the regression analyses, only 13 are within 40 mi of the coast and only 3 are within any of the study basins.

Because of the unique surficial geology of southeastern Massachusetts, and because so few of the initially selected sites were in eastern and southeastern Massachusetts, regression equations produced from data for only those sites were not expected to yield satisfactory estimates of percentile discharges in these areas. Indeed, preliminary analyses using these sites produced poor results for southeastern areas. It thus became evident that either alternative methods would be necessary to estimate low-flow durations for sites in southeastern Massachusetts or additional data from low-flow partial-record stations would be necessary to adequately represent this region in the regression analyses.

The data for all low-flow partial-record stations in southeastern Massachusetts contain eight sites that were suitable for possible inclusion in the regression analyses. Record-extension techniques, discussed in the following section, were used to estimate base-period duration discharges for these stations, and five stations yielded adequate estimates of the selected duration discharges. All partial-record stations and short-term streamflow-gaging stations used in the regression analyses are identified in the "Final Site Selection" section of this report.

Record-Extension Techniques

Thirteen of the streamflow-gaging stations used in the regression analyses were operated continuously throughout the 25-year base period. Duration discharges for the 13 stations were computed directly from the daily mean discharges recorded during the base period. Records for all other sites to be used in the regression analyses were extended to reflect conditions during the base period by use of record-extension techniques. In applying these techniques, relations were established between the available data at the short-term sites and concurrent data from nearby, hydrologically similar sites (index stations). Estimated base-period values for the short-term sites were obtained from these relations and the known

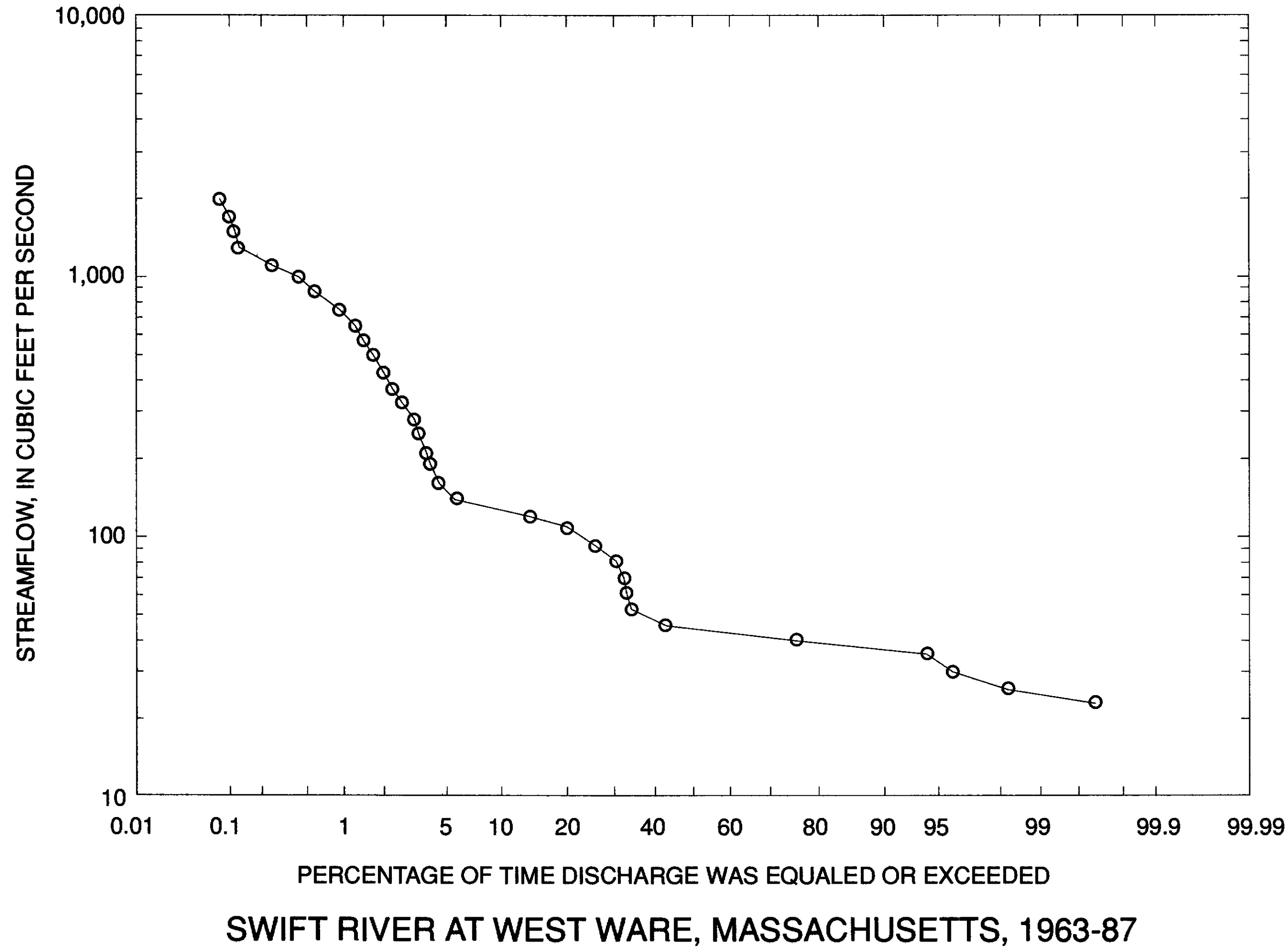


Figure 8. Example of flow-duration curve for gaged site affected by dam regulations and diversions: Swift River at West Ware, 1963–87.

base-period values for the index station. The specific technique used for record extension depended on whether the site was a streamflow-gaging station (continuous data collection) or a partial-record station (intermittent data collection).

Streamflow-Gaging Stations

Two techniques were used to extend records for streamflow-gaging stations that were not in operation throughout the base period (short-term gaged sites). These methods were the graphical-correlation method, described by Searcy (1959, p. 14) as the index-station method, and the Maintenance Of Variance Extension, Type 1 (MOVE.1) technique (Hirsch, 1982). The two extension techniques are based on the assumption that the relation between discharges at the short-term gaged site and the index station is the same for any specified period of time. Thus, a relation established for a period of concurrent record can be used to predict the duration discharges for the specified longer period at the short-term gaged site from the known duration discharges for the longer period at the index station. The methods are explained in detail in the references cited.

The initial procedures used were the same for both the graphical-correlation technique and the MOVE.1 technique and were as follows:

1. Discharges for selected durations from the lower half of the flow-duration curve (the 50-, 55-, 60-, 65-, 70-, 75-, 80-, 85-, 90-, 93-, 95-, 97-, 98-, and 99-percent duration discharges) were computed for the period of record for the short-term gaged site; only complete years of record were used.
2. Duration discharges for the concurrent period were computed for selected index stations, of which there were usually three or more.
3. The correlation coefficient was calculated between the natural logarithms of the discharges for the specified durations for the short-term site and each selected index station. Potential index stations with correlation coefficients less than 0.8 were not used for record extension.
4. Concurrent duration discharges for each pairing of short-term gaged site and index station were plotted in log-space to detect curvature in the relation between the two sites.

When curvature was detected, as was most often the case, the graphical-correlation technique was used. The technique is begun by drawing a smooth curve through the plotted points of the concurrent duration discharges. Discharges for the short-term site corresponding to the known duration discharges for the base period at the index station are then read off the graph. These values become the estimated duration discharges for the base period at the short-term site. The data were often replotted on arithmetic paper before drawing the curve of relation to reduce extreme low-end curvature and to avoid long downward extrapolations that would sometimes be necessary with plots on log-log paper.

Figure 9 and table 2 provide an example application of the graphical-correlation technique. Figure 9 is a plot of pairs of discharges at the selected durations for the concurrent period of record (water years 1964–74) for Bassett Brook near Northampton (station 01181800), the short-term site, and for Cadwell Creek near Belchertown (station 01174900), the index station. A curve of relation was drawn through the points for the concurrent discharges in figure 9. The concurrent discharges are listed in the second and third columns of table 2. Discharges for Bassett Brook corresponding to the duration discharges for the base period at Cadwell Creek (table 2, column 4) are obtained from the curve. These discharges are the estimates of the duration discharges for the base period for Bassett Brook (table 2, column 5).

When there was little or no curvature evident in the plotted curve, the MOVE.1 technique was used. The technique is begun by plotting the concurrent daily mean discharges for the short-term station and for the index station on a log-log scale to confirm that a linear relation exists between the daily values at the two sites. The correlation coefficient is also computed to confirm linearity. If a log-linear relation is indicated, the concurrent daily mean discharges for the two sites are transformed to base-10 logarithms. The means ($\overline{Y}$ and $\overline{X}$) and the standard deviations (s_y and s_x) of these logarithms are then calculated. The transformation to logarithms generally produces a bivariate normal distribution, which is a required assumption for use of the MOVE.1 technique. Estimates of the base-period discharges for the selected durations ($\hat{Y}_i$ where i = 99, 98,..., 50 percent) are obtained by entering the known logarithms of the base-period duration discharges for the index station (X_i) into the MOVE.1 formula:

$$\hat{Y}_i = \overline{Y} + \frac{s_y}{s_x}(X_i - \overline{X}) \,, \qquad (2)$$

and then retransforming the estimates by exponentiating the values of $\hat{Y}_i$ to convert the estimates into their original units of measurement—cubic feet per second.

An example of record extension done with the MOVE.1 technique (fig. 10) uses the Green River near Colrain as the short-term station and the North River at Shattuckville as the index station. The graph of concurrent daily mean discharges for the two sites (water years 1968–87) and the computed correlation coefficient in the graph confirm a linear relation between the daily values for the Green River and the North River. The means and standard deviations of the logarithms of the daily mean discharges for the two sites, listed in the top table, are inserted into their appropriate locations in the MOVE.1 formula. Log-space estimates of the selected base-period duration discharges for the Green River ($\hat{Y}_i$) are obtained by substituting the logarithms of the base-period values for the North River (listed in the second table) for the X_i in the MOVE.1 equation. The log-space estimates are exponentiated ($10^{\hat{Y}_i}$) to obtain the real-space estimates of the base-period duration discharges for the Green River (listed in the second table).

Partial-Record Stations

The graphical-correlation and MOVE.1 techniques were modified to estimate base-period duration discharges for partial-record stations. Instead of relating computed duration discharges for the concurrent period of record between a short-term gaged site and an index station, estimates for partial-record stations were obtained by relating measured discharges at the partial-record station to concurrent daily discharges recorded at the index station. These concurrent discharges were plotted and correlated in the same manner as described above. The graphical-correlation

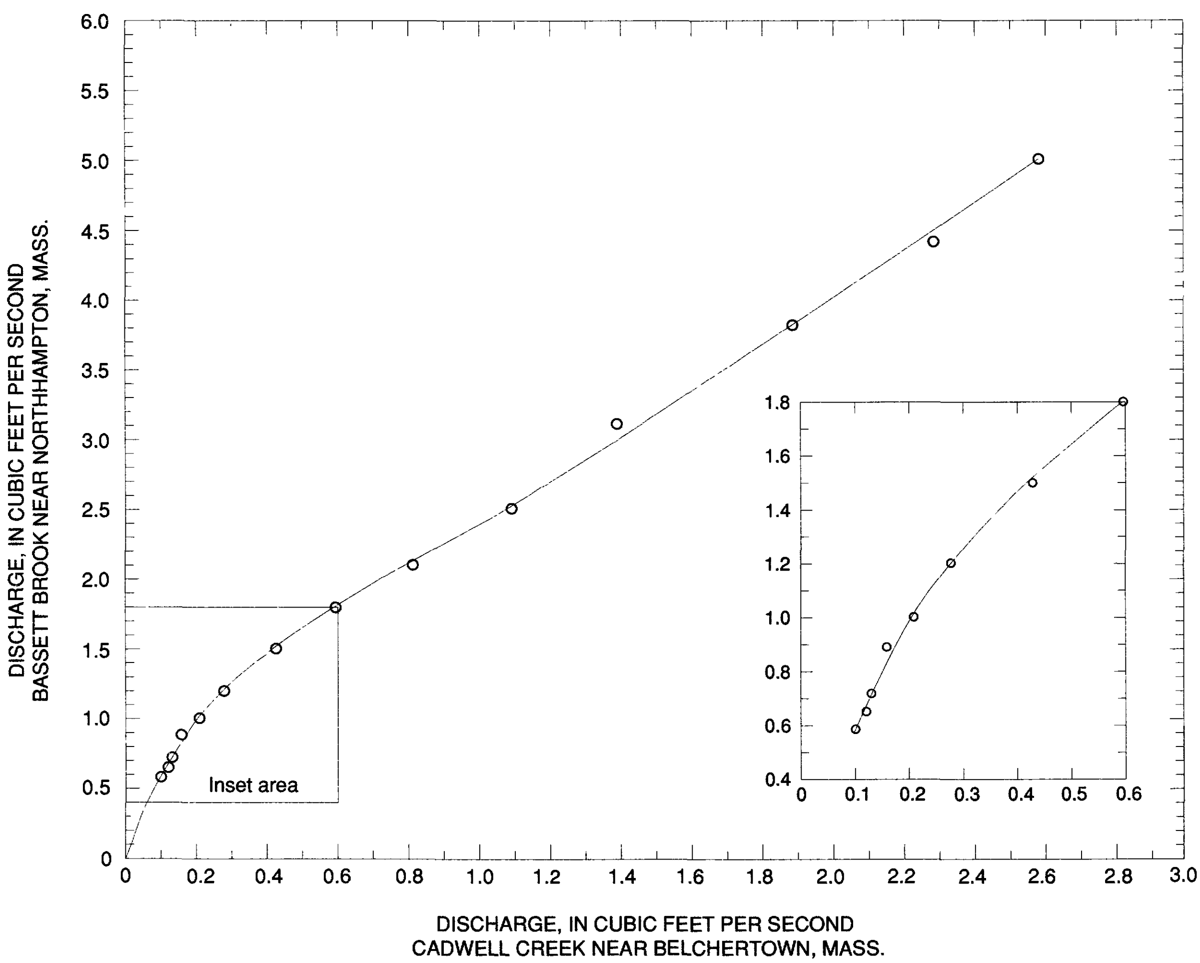


Figure 9. Graphical correlation of concurrent duration discharges for water years 1964–74 between Bassett Brook near Northampton, Mass. (short-term site), and Cadwell Creek near Belchertown, Mass. (index station).

Table 2. Concurrent-period duration discharges for Bassett Brook near Northampton, Mass. (the short-term site) and Cadwell Creek near Belchertown, Mass. (the index station), base-period duration discharges for Cadwell Creek, and base period duration discharges for Bassett Brook estimated by use of the graphical record-extension technique

[Discharges are in cubic feet per second]

Percent duration	Duration discharges			
	Concurrent period, water years 1964-74		Base period, water years 1963-87	
	Cadwell Creek	Bassett Brook	Cadwell Creek	Bassett Brook
99	0.10	0.58	0.11	0.62
98	.12	.65	.13	.71
97	.13	.72	.15	.80
95	.16	.89	.21	1.01
93	.21	1.00	.25	1.13
90	.28	1.20	.33	1.32
85	.43	1.50	.51	1.65
80	.60	1.80	.71	1.97
75	.82	2.10	.95	2.30
70	1.10	2.50	1.20	2.67
65	1.40	3.10	1.60	3.32
60	1.90	3.80	2.00	3.97
55	2.30	4.40	2.40	4.66
50	2.60	5.00	2.80	5.34

technique or the MOVE.1 technique of record extension was then selected based on the appearance of curvature in the plots.

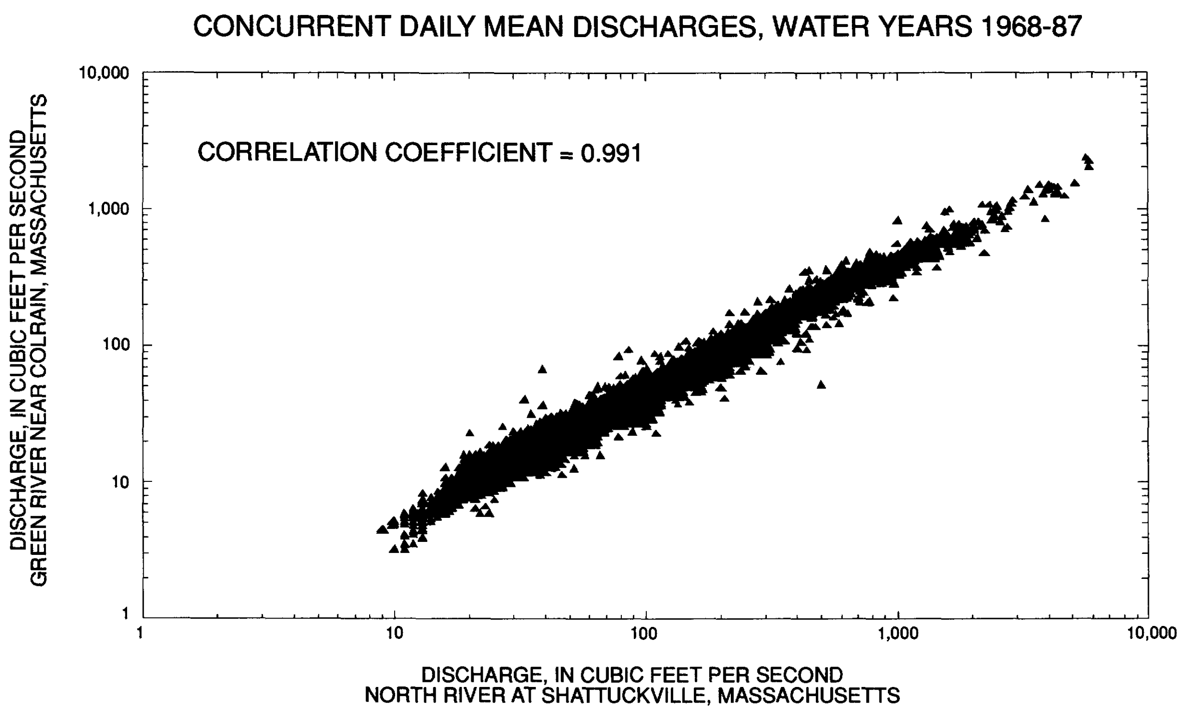
Final Site Selection

A minimum correlation coefficient of 0.80 between the natural logarithms of the concurrent duration discharges was the criterion for choosing index stations to extend the records for short-term gaging stations to base-period conditions. When one index station had a substantially higher correlation coefficient than all other potential index stations, only that station was used for record extension. For example, three gaging stations with complete records during the base period (Green River at Williamstown, North Branch Hoosic River at North Adams, and Salmon River at Lime Rock, Conn.) were potential index stations for extending the records for Town Brook at Bridge Street, Lanesborough to base-period conditions. Correlation coefficients between the selected duration discharges for Town Brook and the potential index stations were 0.977, 0.897, and 0.889 for Green River, North Branch Hoosic River, and Salmon River, respectively, so only Green River was used to extend the records for Town Brook.

This method did not always ensure the best possible estimates of the selected low-flow duration discharges for the short-term site. The correlation coefficient measures the strength of the linear relation between all of the selected pairs of duration discharges for an index site and a site for which record extension is required. The duration discharges estimated for this study, however, are at the extreme low end of the duration curves for the sites. Although the duration discharges used to test correlation between the index and short-term sites were limited to values below their median discharges, the computed correlation coefficient may not adequately reflect the degree of relation between the two sites for the extreme low flows being estimated. This is especially true when curvature is present in the relation. Using the minimum correlation coefficient of 0.8 as the criterion for choice of index sites reduced but did not eliminate this problem.

When the correlation coefficients and plots of the data for the potential index sites were similar, there was little confidence that the index site with the largest correlation coefficient would yield the best results. In these instances, which were predominant, records were extended by using all index stations having a correlation coefficient greater than 0.8. The estimates obtained from each of the index stations were then averaged to obtain single estimates of the selected duration discharges for the base period at the short-term site.

Occasionally, there were large disparities between the estimates for the short-term site from multiple index stations. This was true for short-term gaging stations and for partial-record stations. When there is little confidence in the estimated duration discharges for a short-term site, it is unlikely that use of the site in the regression analyses will improve the models. Thus, a criterion was necessary to include in the regression analyses only those short-term sites with reasonable agreement between the estimated duration discharges obtained by use of multiple index stations. The criterion used was based on the differences between individual estimates of the base-period 99-percent duration discharge, $\hat{Q}_{99_i}$ (i = 1, 2, ..., n, where n is the number of different index stations), and the mean of those estimates, $\bar{Q}_{99}$. The maximum allowable difference, D_{max}, is then defined as



Formula for the MOVE.1 technique:

$$\hat{Y}_i = \bar{Y} + \frac{s_y}{s_x}(X_i - \bar{X}) = 1.684 + \frac{0.4800}{0.4844}(X_i - 2.022)$$

where $\hat{Y}_i$ are the logarithms of the estimated duration discharges for the base period at the Green River streamflow-gaging station, and $\bar{Y}$ and $\bar{X}$ and s_y and s_x are the means and standard deviations of the logarithms of the concurrent daily mean discharges at the Green River and North River streamflow-gaging stations, respectively, and x_i are the logarithms of the duration discharges computed from the base period records for the North River stream-gaging station. These statics are listed in the tables to the right. The duration discharges in the bottom table have been retransformed from the logarithms to units of cubic feet per second.

Computed statistics for the index station (North River) and the estimation station (Green River) for the concurrent period, water years 1968-87 [Statistics are computed from the logarithms of the daily mean discharges]

Station	Mean	Standard deviation
North River	2.022	0.4844
Green River	1.684	0.4800

Duration discharges computed for the North River and estimated for the Green River for the base period, water years 1963-87 [Discharges are in units of cubic feet per second]

Percent duration	North River (computed)	Green River (estimated)
99	9.80	4.61
98	12.0	5.63
97	13.0	6.09
95	16.0	7.49
93	18.0	8.41
90	21.0	9.80
85	27.0	12.6
80	34.0	15.8
75	41.0	19.0
70	49.0	22.7
65	58.0	26.8
60	68.0	31.4
55	81.0	37.3
50	94.0	43.3

Figure 10. Example of MOVE.1 record-extension technique with Green River near Colrain as short-term site, and North River at Shattuckville as long-term site.

$$D_{max} = 100\left(\frac{\left|\hat{Q}_{99i} - \bar{Q}_{99}\right|}{\bar{Q}_{99}}\right). \quad (3)$$

Limits were set for various magnitudes of $\bar{Q}_{99}$, as follows:

1. When $\bar{Q}_{99} \geq 5.0$ ft^3/s, $D_{max} \leq 10$ percent.
2. When 5.0 ft^3/s $> \bar{Q}_{99} \geq 1.0$ ft^3/s, $D_{max} \leq 20$ percent.
3. When 1.0 ft^3/s $> \bar{Q}_{99} \geq 0.5$ ft^3/s, $D_{max} \leq 40$ percent.
4. When 0.5 ft^3/s $> \bar{Q}_{99} \geq 0.1$ ft^3/s, $D_{max} \leq 60$ percent.
5. When $\bar{Q}_{99} \leq 0.1$ ft^3/s, $D_{max} \leq 100$ percent.

The 99-percent duration discharge was used because discharge estimates for the 98th and 95th percentiles were generally in closer agreement with each other than estimates for the 99th percentile. Therefore, the criterion for inclusion of sites was based on the least precise of the estimated duration discharges.

After going through these record-extension procedures and discarding sites based on the maximum difference criterion, 41 sites were selected for use in the regression analyses. Of those, 13 were streamflow-gaging stations with complete record during the 25-year base period, 23 were streamflow-gaging stations with incomplete records during the base period, and 5 were low-flow partial-record sites. Locations of all sites used in the regression analyses are shown in figure 11. The number indicated on the map for each site is the assigned USGS station identification number. Sites used in the regression analyses, along with their respective USGS station identification numbers, station names, latitudes and longitudes, drainage areas, periods of record (for gaging stations) or number of discharge measurements (for partial-record stations), and pertinent remarks are listed in table 3. Two of the sites are in Rhode Island (sites 01106000 and 01111300), but most of their drainage basins are in Massachusetts.

Selection and Measurement of Basin Characteristics

GIS computer software was used to measure all basin characteristics used as independent variables in the regression analyses. GIS software allows the user "to capture, store, update, manipulate, and display all forms of geographically referenced data" (Environmental Systems Research Institute, 1990, p. 1–2). It can be used to measure lengths and areas and to do other spatial analyses. Physical characteristics measured by use of GIS were chosen based upon (1) the theoretical hydrologic relation between the physical characteristic and its effect on low discharges, (2) the results of previous studies in similar hydrologic environments, and (3) the availability of an adequate GIS data layer from which to measure the characteristic for each site used in the regression analyses and for each site where estimated duration discharges are needed. Procedures to measure the basin characteristics with the GIS software were automated to save time and to ensure consistency.

The characteristics measured by use of GIS software were (1) drainage-basin area, (2) longest stream length in the basin, (3) total length of all streams in the basin, (4) total area of coarse-grained stratified drift deposits, (5) total area of all water bodies, including lakes, ponds, reservoirs, and large streams, (6) total area of wetlands, (7) mean basin elevation, (8) highest basin elevation, and (9) lowest basin elevation.

The basin characteristics were measured for this study by use of ARC/INFO GIS software (Environmental Systems Research Institute, Inc., 1987). Data bases and procedures used were as follows:

Drainage area (DAREA).—Approximately 1,800 subbasin boundaries within the 27 major river basins in Massachusetts, and areas in adjacent states that drain into Massachusetts, were previously delineated by the USGS on 1:24,000-scale USGS topographic quadrangle maps published as a series of open-file reports (Brackley and Wandle, 1982, 1983; Gadoury and Wandle, 1982a, 1982b; Krejmas, 1982; Krejmas and Wandle, 1982a, 1982b; Wandle, 1982; Wandle and Frimpter, 1982) that are available for inspection in the USGS Massachusetts office. Drainage boundaries delineated on the maps were digitized into a GIS coverage by USGS Massachusetts office personnel and employees of MassGIS (the GIS section of the Massachusetts Executive Office of Environmental Affairs). The coverage contains boundaries for virtually all surface-water and water-quality data-collection sites within the State that were active or discontinued at the time the maps were prepared. In addition to boundaries for data-collection sites, the coverage also includes boundaries for the mouths of most rivers and any other locations along streams that were considered to be important for political, geographic, or other reasons.

Several of the sites included in the regression analyses have basin areas that are not

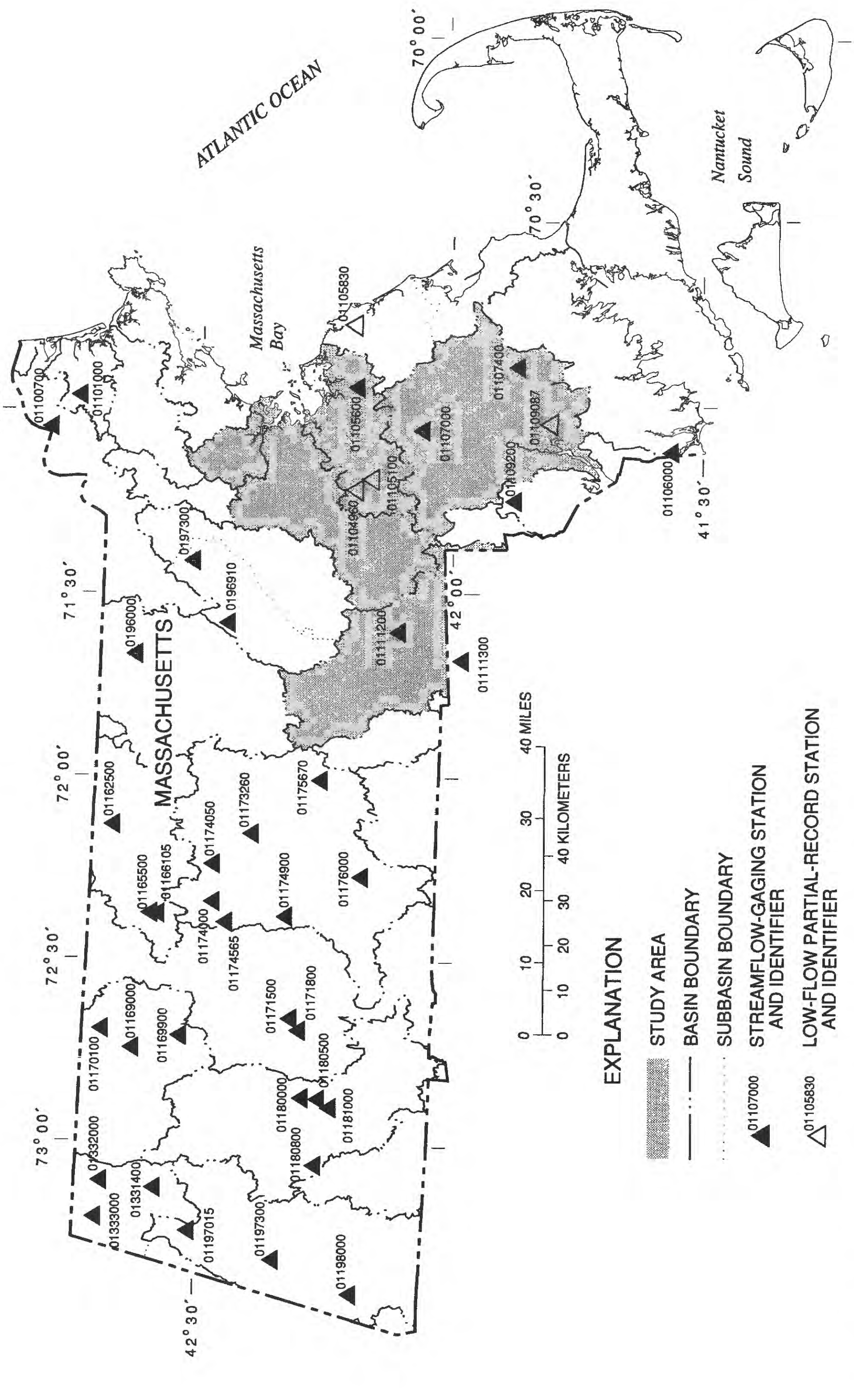


Figure 11. Locations of sites used in regression analyses.

Table 3. Descriptions of streamflow-gaging stations and low-flow partial-record stations used in the regression analyses

[Drainage areas were measured by use of geographic information systems technology. Measurements differ slightly from, and do not supersede, previously published figures]

Station	Latitude	Longitude	Station name measurements	Period of record or number of (square miles)	Drainage area	Remarks
01096000	42°38′03″	71°39′30″	Squannacook River near West Groton, Mass.	1950-present	63.6	Occasional regulation by mill
01096910	42°27′04″	71°34′39″	Boulder Brook at East Bolton, Mass.	1972-83	1.61	- -
01097300	42°31′19″	71°24′15″	Nashoba Brook near Acton, Mass.	1964-present	12.6	- -
01100700	42°48′41″	71°01′59″	East Meadow River near Haverhill, Mass.	1962-74	5.48	- -
01101000	42°45′10″	70°56′46″	Parker River at Byfield, Mass.	1946-present	21.4	Occasional regulation by mill and ponds
01104960	42°11′04″	71°13′29″	Germany Brook near Norwood, Mass.	16	2.37	Partial-record site
01105100	42°09′36″	71°11′47″	Traphole Brook near Norwood, Mass.	22	3.40	Partial-record site
01105600	42°11′25″	70°56′43″	Old Swamp River near South Weymouth, Mass.	1966-present	4.47	- -
01105830	42°11′30″	70°46′49″	First Herring Brook near Scituate Center, Mass.	16	1.72	Partial-record site
01106000	41°33′30″	71°07′47″	Adamsville Brook at Adamsville, R.I.	1941-78	7.99	- -
01107000	42°03′41″	71°03′59″	Dorchester Brook near Brockton, Mass.	1962-74	4.71	- -
01107400	41°51′55″	70°54′32″	Fall Brook near Middleboro, Mass.	36	9.30	Partial-record site
01109087	41°55′23″	71°03′37″	Assonet River at Assonet, Mass.	16	20.7	Partial-record site
01109200	41°52′46″	71°15′18″	West Branch Palmer River near Rehoboth, Mass.	1962-74	4.33	- -
01111200	42°06′17″	71°36′28″	West River at West Hill Dam near Uxbridge, Mass.	1962-90	27.8	Flood-control dam upstream
01111300	41°58′52″	71°11′41″	Nipmuc River near Harrisville, R.I.	1965-91	15.9	- -
01162500	42°40′57″	72°06′56″	Priest Brook near Winchendon, Mass.	1917-present	19.2	- -
01165500	42°36′10″	72°21′36″	Moss Brook at Wendell Depot, Mass.	1909-82	12.1	- -
01166105	42°35′39″	72°21′41″	Whetstone Brook at Depot Road, Wendell Depot, Mass.	1986-present	5.24	- -
01169000	42°38′18″	72°43′32″	North River at Shattuckville, Mass.	1939-present	88.9	Occasional small diurnal fluctuation
01169900	42°32′31″	72°41′39″	South River near Conway, Mass.	1966-present	24.1	Small diurnal fluctuation since 1982
01171500	42°19′05″	72°39′21″	Mill River at Northampton, Mass.	1940-present	54.0	- -
01171800	42°18′09″	72°41′16″	Bassett Brook near Northampton, Mass.	1963-74	5.56	- -
01173260	42°23′52″	72°08′51″	Moose Brook near Barre, Mass.	1962-74	4.61	- -
01174000	42°28′42″	72°20′05″	Hop Brook near New Salem, Mass.	1947-82	3.39	- -
01174050	42°28′49″	72°13′27″	East Branch Fever River near Petersham, Mass.	1984-85	5.11	- -
01174565	42°27′19″	72°22′56″	West Branch Swift River at Shutesbury, Mass.	1984-85	12.6	- -
01174900	42°20′08″	72°22′12″	Cadwell Creek near Belchertown, Mass.	1962-present	2.59	- -
01175670	42°15′54″	72°00′19″	Sevenmile River near Spencer, Mass.	1961-present	8.69	Occasional regulation by ponds
01176000	42°10′56″	72°15′51″	Quaboag River at West Brimfield, Mass.	1913-present	150	Flood-retarding reservoirs upstream
01180000	42°17′27″	72°52′15″	Sykes Brook at Knightville, Mass.	1946-73	1.74	- -

Table 3. Descriptions of streamflow-gaging stations and low-flow partial-record stations used in the regression analyses—**Continued**

Station	Latitude	Longitude	Station name measurements	Period of record or number of (square miles)	Drainage area	Remarks
01180500	42°15'31"	72°52'23"	Middle Branch Westfield River at Goss Heights, Mass.	1910-present	52.8	Flood-control dam upstream
01180800	42°15'49"	73°02'48"	Walker Brook near Becket Center, Mass.	1963-77	2.95	- -
01181000	42°14'14"	72°53'46"	West Branch Westfield River at Huntington, Mass.	1908-present	93.6	- -
01197015	42°31'12"	73°13'48"	Town Brook at Bridge Street, Lanesborough, Mass.	1981-84	10.6	- -
01197300	42°20'59"	73°17'56"	Marsh Brook at Lenox, Mass.	1962-74	2.18	- -
01198000	42°11'31"	73°23'28"	Green River near Great Barrington, Mass.	1952-71	51.0	- -
01331400	42°35'20"	73°06'48"	Dry Brook near Adams, Mass.	1963-74	7.68	- -
01332000	42°42'08"	73°05'37"	North Branch Hoosic River at North Adams, Mass.	1927-90	41.0	Infrequent small diurnal fluctuation
01333000	42°42'32"	73°11'50"	Green River at Williamstown, Mass.	1948-present	42.6	Infrequent small diurnal fluctuation

entirely within Massachusetts. In most cases, these basin boundaries were already included in the statewide GIS coverage. The remaining boundaries, and boundaries for sites within Massachusetts that were established after preparation of the coverage, were delineated, checked, and then digitized and added to the coverage by USGS personnel. The GIS basin-boundary coverage was used to compute drainage areas, in square miles, for each site included in the regression analyses, and for each site where low-flow estimates were desired by the MOWR. This coverage was then intersected with each of the coverages discussed below to measure the remaining basin characteristics for all sites of interest for this study.

Drainage areas for all subbasins included in the original coverage were computed previously, in square miles, by use of an electronic digitizing tablet (U.S. Geological Survey, Office of Water Data Coordination, 1977, ch. 7, p. 9–10). Comparisons between the older computations and the drainage areas computed from the GIS coverage indicated excellent agreement between the two methods, with nearly all measured areas in agreement within 1 percent. Digitized boundaries for basins where measured differences exceeded 2 percent were checked for differences against the boundaries drawn on the original topographic maps, and were corrected if necessary. For consistency, all drainage areas used were computed with the GIS software.

Longest stream length (LSTREAM).—The longest stream length, in miles, was computed for each site by use of the Survey's 1:100,000-scale Digital Line Graph (DLG) coverage (U.S. Geological Survey, National Cartographic Information Center, 1985). The longest stream was identified for each site from plots of the intersected drainage area and DLG coverages. Longest lengths were then computed by use of the GIS software to measure the distance from each site upstream to the end of the longest stream segment. Lengths through ponds, swamps, and artificial conveyances that were not already included in the DLG coverage were added before this step.

Total stream length (TSTREAM).—After measuring longest stream lengths for all sites used in this study, a statewide enhancement of the 1:100,000-scale DLG stream coverage was completed by personnel of MassGIS and the USGS Massachusetts office. The initial step in the enhancement was to produce 1:25,000-scale plots of all stream lengths and water bodies included in the 1:100,000-scale DLG coverage on transparent Mylar. Plots were produced for each 1:25,000-scale topographic quadrangle map for Massachusetts and for areas in adjacent states that drain into Massachusetts. Each plot was laid over the most current corresponding topographic map. Stream lengths and water bodies appearing on the maps, but not on the Mylar plot, were drawn onto the plot and then digitized. In addition, stream lines for flow through ponds, swamps, culverts, and other known artificial conveyances not appearing on either the plot or the map were estimated and digitized. The newly digitized streams and ponds were merged with the original DLG coverage to form a single coverage. This coverage was checked to ensure proper connections of streams across quadrangle boundaries. Connections of streams across basin boundaries were also checked and were eliminated where necessary. When checking was complete, the lengths of all stream segments were computed for each study site and then summed to determine the total length of all streams upstream from each site.

Stratified drift deposits (DRIFT).—Areas, in square miles, of stratified-drift deposits for each site were computed by intersecting the basin boundary data layer with a statewide surficial geology data layer. This data layer was digitized by the USGS from a set of three 1:125,000-scale maps drawn on stable-based film that together cover the entire State (Byron Stone, written commun., 1988). Drift boundaries on the three maps were compiled from a set of 1:24,000-scale geologic quadrangle maps and other maps of various types (bibliographic citations compiled by McIntosh and others, 1982). Areas of stratified drift for parts of some basins not within Massachusetts were measured from unpublished reconnaissance maps of field geology in the USGS Massachusetts office.

Water bodies (WATER).—Areas, in square miles, of all water bodies were measured for the basin corresponding to each site from a statewide land-use coverage developed by the Resource Mapping Project at the University of Massachusetts. The data layer incorporates 21 land-use categories, which are listed in table 4 (MassGIS, 1990). Areas with a land-use code of 20 (table 4) were summed. The data were interpreted from 1:25,000-scale color infrared aerial photographs obtained mostly during the summer of 1985. Aerial photographs for southeastern areas were obtained during September 1984. Several plots of the water bodies obtained from the statewide data layer were drawn on transparent Mylar and checked for consistency with water bodies on 1:25,000-scale topographic quadrangle maps. All checks indicated that the digitized water bodies were satisfactory for use in the regression analyses. Pond areas for parts of basins not in Massachusetts were delineated on 1:24,000-scale topographic maps and then digitized and measured by use of GIS technology.

Wetlands (WET).—Wetland areas were also measured as a separate variable by use of the statewide land-use data layer (codes 4 and 14 in table 4); however, the data layer includes only nonforested wetlands because the aerial photographs were taken when foliage obscured forested wetlands. Comparisons of check plots of the digitized wetland data to wetlands found on the topographic quadrangle maps indicated that the digitized wetlands were of insufficient accuracy for use in the regression analyses. Plots were also made of wetland data retrieved from the USGS DLG national land-use data layer (U.S. Geological Survey, National Cartographic Information Center, 1986). Comparisons with the topographic quadrangle maps indicated that these data were also of insufficient accuracy for use in the regression analyses.

Mean (MELEV), highest (HELEV), and lowest (LELEV) basin elevations.—Elevations were obtained from the Survey's 1:250,000-scale Digital Elevation Model (DEM) data layer. DEM data at this scale, which are available for most of the United States, consist of elevations interpolated from 1:250,000-scale topographic maps for every 3 arc-seconds in latitude (about every 295 ft) and longitude (ranging from about 295 ft at the equator to about 197 ft at 50 degrees latitude) (Elassal and Caruso, 1983). Mean basin elevations for each basin were computed by intersecting the basin boundary coverage with the DEM coverage and averaging all points that fell within the basin boundaries.

Table 4. Land-use categories and definitions for the data layer used to measure areas of wetlands and water bodies

[From MassGIS, 1990. Measured categories in bold type]

Code	Abbre-viation	Category	Definition
1	AC	Cropland	Intensive agriculture
2	AP	Pasture	Extensive agriculture
3	F	Forest	Forest
4	**FW**	**Wetland**	**Nonforested freshwater wetland**
5	M	Mining	Sand, gravel, and rock mining
6	O	Open land	Abandoned agriculture, power lines, area of vegetation.
7	RP	Participation recreation	Golf, tennis, playgrounds, skiing
8	RS	Spectator recreation	Stadiums, racetracks, fairgrounds, drive-ins
9	RW	Water-based recreation	Beaches, marinas swimming pools
10	R0	Residential	Multifamily
11	R1	Residential	Smaller than 1/4 acre lots
12	R2	Residential	1/4 to 1/2 acre lots
13	R3	Residential	Larger than 1/2 acre lots
14	**SW**	**Salt wetland**	**Salt marsh**
15	UC	Commercial	General urban, shopping center
16	UI	Industrial	Light and heavy industry
17	UO	Urban open	Parks, cemeteries, public and institutional greenspace, also vacant and undeveloped land
18	UT	Transportation	Airports, docks, divided highways, freight storage, railroads
19	UW	Waste disposal	Landfills, sewage lagoons
20	**W**	**Water**	**Fresh water, coastal embayments**
21	WP	Woody perennial	Orchard, nursery, cranberry bog

Highest and lowest elevations were also obtained from the intersected coverages.

From the original nine basin characteristics measured using GIS software, several additional characteristics were computed for possible use as independent variables in the regression analyses. These included:

Relief (RELIEF)—Computed by subtracting LELEV from HELEV;

Slope (SLOPE)—Computed by dividing RELIEF by LSTREAM;

Drainage density (DENS)—Computed by dividing TSTREAM by DAREA;

Drift per unit of total stream length (DRT/TST)—Computed by dividing DRIFT by TSTREAM);

Percentage of stratified-drift (%DRIFT), percentage of water bodies (%WATER)—Computed by dividing the original variables by DAREA;

GWHEAD—A surrogate for the head in the stratified drift aquifer computed by subtracting LELEV from MELEV, and

Several interactive terms, such as: **DA×REL** (DAREA times RELIEF), **DR×ELEV** (DRIFT times ELEV), and so forth.

Some basins contain no stratified-drift deposits. Because all independent variables were transformed into natural logarithms for the regression analyses and computation of the natural logarithm of zero is impossible, it was necessary to add a constant to the value of stratified-drift for each site before doing the regression analyses. A constant of 0.1 was selected because it is relatively small in comparison to the areas of stratified-drift deposits measured for most sites. For consistency, the same constant of 0.1 was also added to eliminate zeros in the values of DRT/TST and %DRIFT for each site. The 0.1 constant is a larger proportion of the total variation in DRT/TST and %DRIFT than in DRIFT, but tests done with various constants ranging from 0.001 to 1.0 indicated only small variations in the regression results.

In addition to the basin characteristics computed from the various GIS data layers, latitude (**LAT**) and longitude (**LONG**) were also tested as independent variables in the regression analyses. These were measured from 1:24,000-scale USGS topographic maps and were decimalized by converting minutes and seconds to fractions of a degree. These variables were particularly useful for plotting against the residuals from trial regression analyses to see if there was any systematic variation in the distribution of estimation errors (residuals) with respect to geographic location.

Table 5 lists the computed discharges for the selected durations, years of record, and basin characteristics measured by use of GIS software for each station in the regression analyses. The years of record for the streamflow-gaging stations equals the number of complete water years of record during the base period for each station. The years of record for partial-record sites were assigned somewhat subjectively. The partial-record site on the Fall River near Middleboro was assigned 2 years of record because of the comparatively large number of discharge measurements (36, indicated in table 3) obtained at the site. All other partial-record sites were assigned the minimum of 1 year of record for the regression analyses. The maximum record length assigned for the partial-record sites (2 years) was therefore set equivalent to the minimum record length for the streamflow-gaging stations used in the analyses.

Table 5. Duration discharges and basin characteristics for streamflow-gaging stations used in the regression analyses

USGS number	99-percent duration streamflow	98-percent duration streamflow	95-percent duration streamflow	Years of record for analysis	Drainage area	Area of drift	Longest stream	Total streams	Highest elevation	Lowest elevation	Mean elevation	Total relief	GWHEAD
01096000	6.40	7.60	11.0	25	63.6	17.2	15.4	144	1,450	249	615	1,200	366
01096910	.033	.045	.076	13	1.61	.182	1.61	3.28	548	299	433	249	134
01097300	.210	.270	.620	24	12.6	7.44	4.82	31.6	463	157	237	306	80
01100700	.220	.320	.480	11	5.48	2.75	3.09	7.92	266	59	133	207	74
01101000	.300	.390	.810	25	21.4	9.46	11.3	34.6	351	49	121	302	72
01104960	.136	.156	.219	1	2.37	.670	1.79	3.65	282	141	198	141	57
01105100	.941	1.01	1.22	1	3.40	1.96	6.06	3.65	530	75	225	455	150
01105600	.154	.191	.370	21	4.47	1.19	4.58	9.18	197	98	146	99	48
01105830	.015	.020	.037	1	1.72	.080	1.86	1.28	200	65	103	135	38
01106000	.082	.092	.170	17	7.99	.740	5.50	14.6	203	16	138	187	122
01107000	.031	.054	.131	10	4.71	.774	5.52	10.7	299	98	189	201	91
01107400	1.54	1.76	2.44	2	9.30	7.18	2.88	11.3	190	56	105	134	49
01109087	.880	1.02	1.91	1	20.7	8.88	8.20	28.0	200	23	113	177	90
01109200	.017	.034	.091	12	4.33	2.78	2.57	12.7	266	102	120	164	18
01111200	2.10	2.40	3.00	25	27.8	8.42	11.8	44.1	630	240	405	390	165
01111300	.500	.660	.960	25	15.9	4.15	7.09	30.3	758	361	532	397	171
01162500	.460	.600	1.10	25	19.2	1.55	9.97	88.8	1,800	899	1,100	899	202
01165500	.629	.733	1.07	20	12.1	1.86	5.28	23.2	1,520	594	862	925	268
01166105	.880	.910	1.02	3	5.24	1.24	4.51	14.2	1,300	499	934	800	435
01169000	9.80	12.0	16.0	25	88.9	3.71	19.8	190	2,200	498	1,410	1,710	916
01169900	2.92	3.40	4.48	22	24.1	3.18	11.4	52.9	1,800	498	1,120	1,300	625
01170100	4.40	5.40	7.20	21	41.2	1.86	22.3	84.5	2,400	498	1,370	1,900	873
01171500	6.87	7.78	8.70	25	54.0	9.36	16.2	107	1,600	197	847	1,400	650
01171800	.630	.720	.990	12	5.56	2.04	4.34	9.02	797	272	424	525	152
01173260	.010	.025	.103	12	4.61	.000	3.66	4.25	1,180	932	1,030	246	101
01174000	.023	.052	.161	20	3.39	.074	2.83	7.96	1,200	794	1,030	404	236
01174050	.110	.127	.220	2	5.11	.716	3.49	5.76	1,200	699	872	499	173
01174565	.580	.680	1.04	2	12.6	2.05	5.36	30.4	1,300	568	951	731	383
01174900	.110	.130	.210	25	2.59	.018	3.12	5.02	1,100	594	934	505	340
01175670	.280	.330	.550	25	8.69	1.09	6.34	21.5	1,050	637	873	413	236
01176000	14.3	17.6	26.0	25	150	31.8	30.8	317	1,200	397	806	801	409
01180000	.088	.106	.147	11	1.74	.000	2.54	2.17	1,300	699	1,090	600	389
01180500	2.70	3.15	4.65	22	52.8	1.50	19.2	98.2	2,200	495	1,380	1,700	881
01180800	.270	.302	.418	14	2.95	.121	3.38	6.75	1,810	1,300	1,560	515	258
01181000	7.40	9.30	12.0	25	93.6	3.90	20.0	152	2,160	397	1,410	1,760	1,010
01197015	.747	.850	1.25	4	10.6	.523	5.74	18.9	2,600	1,120	1,560	1,480	446
01197300	.018	.039	.141	12	2.18	.012	2.00	2.72	1,800	997	1,220	801	227
01198000	3.56	4.18	5.47	9	51.0	5.32	17.1	78.2	2,000	699	1,170	1,300	475
01331400	.270	.420	.870	13	7.68	.212	4.02	9.13	2,150	1,200	1,760	954	564
01332000	5.50	6.20	8.20	25	41.0	4.73	10.2	58.8	3,040	899	1,840	2,150	946
01333000	4.90	5.50	7.80	25	42.6	4.85	12.2	70.0	3,400	659	1,560	2,740	897

Multiple-Regression Analyses

Multiple-regression analyses were used to relate the 99-, 98-, and 95-percent duration discharges (the dependent variables) at 41 sites to the basin characteristics (the independent variables) described in the previous section. The regression analyses produce mathematical models with which the mean response of the flow-duration statistics for ungaged sites can be estimated on the basis of the selected basin characteristics that appear in the models.

All measured streamflow and basin characteristics were transformed to natural logarithms (ln). This was done to eliminate skew in the sample distributions of the variables prior to performing the regression analyses and to fulfill the requirement that the residual errors be normally distributed. Mathematical models produced from the multiple-regression analyses on log-transformed data take the form of linear equations in the logarithms, such as

$$\ln(Y) = \ln(\alpha)+\beta_1\ln(\chi_1)+ \beta_2\ln(\chi_2)+ \ldots +\beta_n\ln(\chi_n)+\varepsilon_i \qquad (4)$$

or, retransforming by exponentiation to obtain the algebraically equivalent form,

$$Y = \alpha\chi_1^{\beta_1}\chi_2^{\beta_2}\ldots\chi_n^{\beta_n}\exp(\varepsilon_i)\ , \qquad (5)$$

where

- Y is the dependent variable (the 99-, 98-, or 95-percent duration streamflow),
- χ_1 to χ_n are the n independent variables (basin characteristics),
- β_1 to β_n are the n regression model coefficients,
- α is the regression constant, and
- ε_i is the residual error, i = 1, 2, ..., N, and N is the number of sites used in the regression.

Because the log-space residual errors are normally distributed, the expected error value for each estimate of the mean response of the dependent variable is zero. The mean and median responses of the dependent variable to the measured values of the independent variables for a site are the same in log space. When retransformed to the original units of measurement, the regression equations produce estimates of the median response of the dependent variable rather than the mean response. The resulting estimates are somewhat biased because the expected error value for the estimates is no longer zero. Duan (1983) provided a method of estimating the mean residual error of the model in order to approximately correct for the bias in the estimates. Adjusting equation 3 by use of Duan's "smearing estimate" yields

$$Y = \left(\alpha\chi_1^{\beta_1}\chi_2^{\beta_2}\ldots\chi_n^{\beta_n}\right)\left(\sum_{i=1}^{N}[\exp(\varepsilon_i)]/N\right) \qquad (6)$$

Duan's smearing estimate is determined by summing the exponentiated natural log-space residuals, $\exp(\varepsilon_i)$, and dividing by the number of sites used in the regression, N. Multiplying the regression estimate by Duan's smearing estimate yields approximately unbiased estimates of the mean response of the dependent variable. Other bias correction estimates have been developed (Cohn and others, 1989; Gilroy and others, 1990), but Duan's smearing estimator was chosen because it has been shown to have less error than some other estimators, and it is relatively easy to determine.

All-possible-subsets (BREG) and stepwise (STEP) regression algorithms aided in the selection of subsets of independent variables included in the final regression models (Ryan and others, 1985). Further testing by use of ordinary-least-squares regression (OLS) was done on the four 3-variable and 4-variable combinations of independent variables that were selected by the BREG algorithm as providing the best estimates for each of the dependent variables. The model selected by the STEP algorithm also received further testing by use of OLS regression. The final regression models were selected on the basis of the following statistical parameters: (1) standard errors of estimate; (2) R_{adj}, the percentage of the variation in the dependent variable that is explained by the regression equation, adjusted for the number of stations, and the number of independent variables used in the regression; (3) Mallows' C_p statistic; (4) the PRESS statistic, an estimate of the prediction error sum of squares; and (5) VIF, variance inflation factor, a test for multicollinearity (Montgomery and Peck, 1982, p. 299). In addition to statistical considerations, the selected independent variables, and the signs and magnitudes of their coefficients, must make sense hydrologically. The independent variables were required to be statistically significant at the 95-percent confidence level.

Diagnostic checks were performed to test for model adequacy, for violations of assumptions for regression analysis, and for outliers. These checks indicated that, for all of the candidate models selected by use of the BREG and STEP algorithms, all assumptions for regression analysis were satisfied except that heteroscedasticity (nonconstant variance of the regression residuals, a violation of the assumptions for regression) was always present. The variance of the residuals decreased significantly with increasing values of the independent variables, particularly with drainage area, and with increasing values of the duration discharges estimated by use of the regression equations. Some of the heteroscedasticity can be attributed to differences in time-sampling errors among the sites used in the analyses. Duration discharges for gaging stations with complete records during the base period were computed with no time-sampling errors. Time-sampling errors for sites where the duration discharges were estimated by use of record-extension techniques should, in theory, decrease with increasing record length. Gaging stations on large rivers in Massachusetts tend to have longer periods of record than gaging stations on small rivers. Therefore, the gaging stations on small rivers generally have larger time-sampling errors associated with their flow-duration statistics than do large rivers. Of the 41 sites used in the regression analyses, only 1 of 10 sites (10.0 percent) with drainage areas equal to or greater than 40 mi^2 had less than 20 years of record, 2 of 16 sites (12.5 percent) with drainage areas equal to or greater than 15 mi^2 had less than 20 years of record, and 19 of 25 sites (76.0 percent) with drainage areas less than 15 mi^2 had less than 20 years of record. Weighted least squares (WLS) regression analysis was used to eliminate heteroscedasticity. A different weight was assigned to each site used in the WLS analyses (Neter and others, 1985, p. 167). Weights were assigned according to a function discussed in the following section.

Weighting Procedure

The function used to obtain the weights for the WLS regression analyses was based on a function developed by Tasker (1980). Tasker's function was developed to weight data for differences in time-sampling errors between stations used in a regression analysis to predict peak-flow frequency statistics for ungaged sites. Time-sampling errors for low-flow frequency statistics vary according to the record length at the individual gaging stations in the same manner as those for flow-duration statistics. Tasker stated that, for a regional study, a reasonable weighting function could be derived by use of

$$w_i = 1/(c_o + c_1(1/n_i)) \quad (7)$$

where

w_i is the applicable weight for site i (i = 1, 2, ..., N, where N is the number of sites used in the analysis),

n_i is the number of years of record at site i, and c_o and c_1 are defined below.

An estimate of c_1, denoted as $\hat{c}_1$, was given by Tasker as

$$\hat{c}_1 = \max\left[0, \bar{s}^2\left(1 + \frac{\bar{k}^2}{2}\left(1 + \frac{3\bar{g}^2}{4}\right) + kg\right)\right], \quad (8)$$

where $\bar{s}^2$ is the mean of the variances of the annual series of the base 10 logarithms of the low-flow frequency statistic (such as the $Q_{7,10}$) for all sites used in the analysis, and $\bar{k}$ and $\bar{g}$ are regional estimates of the standardized Pearson Type III deviate, k, and skewness coefficient, g, respectively. Because the duration discharges being regionalized for this study are not fit to any particular distribution, equation 8 was simplified to

$$\hat{c}_1 = \max\left[\, 0, \bar{s}^2 \,\right] = \bar{s}^2, \quad (9)$$

where $\bar{s}^2$ is the mean of the variances of annual series of natural logarithms of the selected duration discharges computed for each gaged site used in the analysis.

An estimate of c_o, denoted as $\hat{c}_o$, was given by Tasker as

$$\hat{c}_o = \max[0, \hat{\sigma}^2(y_i) - \hat{c}_1(\bar{n}_i^{-1})], \quad (10)$$

where $\hat{\sigma}(y_i)$ is the standard error of estimate from the OLS regression, and

$$\bar{n}_i^{-1} = \frac{1}{N}\sum_{i=1}^{N}(1/n_i). \quad (11)$$

Two modifications were made to equation 10 to estimate $\hat{c}_o$ for this study. The first modification was necessary because a base period was used to compute the duration discharges used as the dependent variables for the WLS analyses, whereas the entire period of record is used to compute the low-flow frequency statistics upon which the weighting function in equation 7 is based. Duration discharges that were computed for stations having complete records during the 25-year base period were computed without time-sampling errors; thus, they should be given maximum weight in the regression analyses. The reciprocal of the record length ($1/n_i$) in equations 7 and 11 was adjusted by subtracting 0.04 from each observation to give stations with complete records during the base period zero time-sampling error. This adjustment to equation 11 yielded

$$\bar{n}_i^{-1} = \frac{1}{N}\sum_{i=1}^{N} \left((1/n_i) - 0.04 \right) . \qquad (12)$$

The second modification was necessary because plots of the residuals against the estimated duration discharges obtained from preliminary WLS regression analyses indicated that heteroscedasticity was not eliminated when only the first modification was incorporated into the weighting function. This finding indicated that all of the nonconstant variance in the residuals was not attributable solely to differences in record length. Because the variances of the residuals generally decreased with increasing values of the estimated duration discharges, the use of a constant variance term, $\sigma^2(y_i)$, in equation 10 was inappropriate. The following procedure was performed for the regression analysis for each duration percentile to estimate an error variance term for each site used in the analyses:

1. An OLS regression analysis was performed.
2. Residuals were plotted against the fitted values of the dependent variable to check for heteroscedasticity, outliers, curvature, or other problems.
3. When heteroscedasticity was found, the residuals were separated into three groups of approximately equal numbers according to increasing values of the estimates of the dependent variable.
4. For each group, the variance of the residuals and the mean of the estimated dependent variable were computed and the three points were plotted, revealing an approximately linear relation.
5. An OLS regression analysis was performed to obtain an equation for predicting the variance of the residual for varying levels of the estimated dependent variable.
6. The predicted variances, $\hat{s}^2(y_i)$, were then substituted for the model error term, $\hat{\sigma}^2(y_i)$, in equation 10.

With the modifications for both record length and variance incorporated, the estimate of c_0 becomes

$$\hat{c}_0 = \max\left[0, \hat{s}^2(y_i) - \hat{c}_1\left(\frac{1}{N}\sum_{i=1}^{N}\left((1/n_i) - 0.04\right)\right)\right], \qquad (13)$$

and the weighting function becomes

$$w_i = 1/\left[\hat{c}_0 + \hat{c}_1\left((1/n_i) - 0.04\right)\right] . \qquad (14)$$

Weights for all WLS regression analyses in this study were computed with equation 14. In actual applications, the weights obtained with equation 14 were centered by dividing the weight for each site by the mean of the weights for all sites used in the WLS regression analyses. Centering causes the weights to be dimensionless, thus allowing comparisons between preliminary models having different independent variables and weighting functions. Centering has no effect on the final equations obtained from the regression analyses.

The effect of the weighting procedure on the residuals from the regression analysis for estimating the 99-percent duration discharges is illustrated in figure 12. Graph A indicates that the values of the unweighted residuals decrease with increasing values of the predictions from the OLS regression analysis. For graph B, a WLS regression analysis was performed in which homoscedasticity was assumed, but the weighting function compensates for differences in the number of years of record between the sites. Weights for graph B were obtained by replacing the predicted variances, $\hat{s}^2(y_i)$, in equation 12 with the single model error term, $\hat{\sigma}^2(y_i)$ from equation 10. As in graph A, the residuals seem to decrease with increasing values of the predictions. For graph C, where the weights were computed with equation 14 to compensate for both heteroscedasticity and differences in record length, the variance of the weighted residuals seems constant with respect to the values of the predictions. The residuals in graphs B and C were weighted by multiplying each residual by the square root of its corresponding weight to reflect the effects of the weights.

ESTIMATES OF LOW-FLOW DURATION DISCHARGES

The MOWR selected 72 sites in the four study basins where estimates of natural low-flow duration discharges were desired. Most of the sites were selected because significant uses of water resources exist, are proposed, or could potentially exist within the basin upstream from the sites. Some of the sites were selected because they are presently unaffected by diversions or regulations by dams, and thus could be used to confirm or improve the regression equations when adequate streamflow data for the sites are collected in the future. The USGS, in cooperation with the MOWR, is obtaining low-streamflow measurements at most of these sites. The 72 sites selected for this study are listed in order of their USGS station number in table 8, along with the station name, latitude, longitude, and location for each site. Table 9 lists the basin characteristics measured by use of the GIS software for each of the sites listed in table 8. (Both tables are at back of report.)

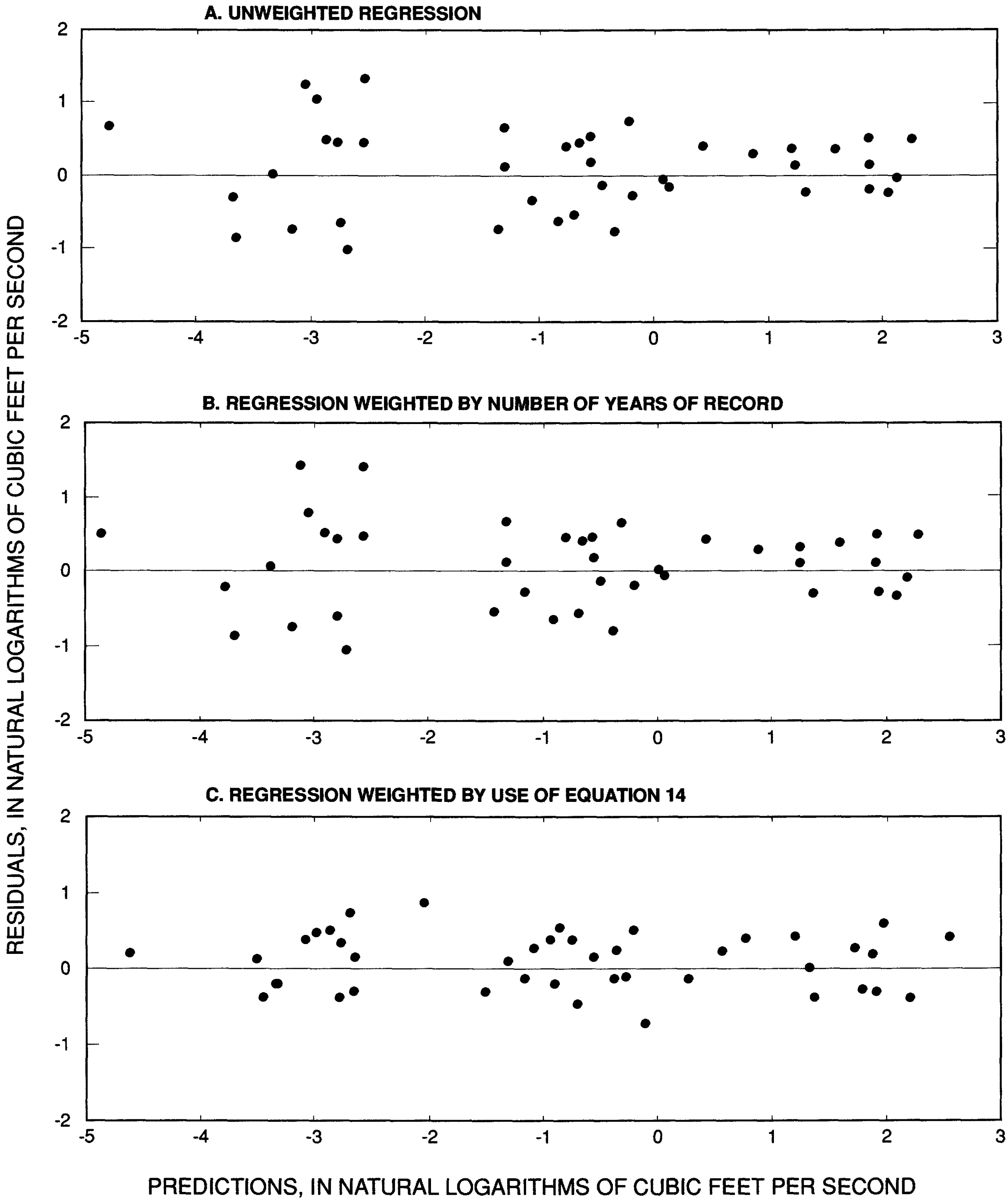


Figure 12. Regression residuals plotted against predictions of 99-percent duration discharge for unweighted regression, regression weighted by number of years of record, and regression weighted by use of equation 14.

Table 6. Summary of regression equations used to estimate duration discharges for the base period at selected sites in Massachusetts

Regression equation	s_r	s_p	$\lvert e_i \rvert_{.5}$
95th percentile			
$\hat{P}_{95} = 0.01130\ (\mathrm{DAREA})^{0.9209}(\mathrm{GWHEAD})^{0.7878}(\mathrm{DRT/TST})^{1.1744}$	34.1%	39.3%	21.7%
98th percentile			
$\hat{P}_{98} = 0.00375\ (\mathrm{DAREA})^{0.9318}(\mathrm{GWHEAD})^{1.0019}(\mathrm{DRT/TST})^{1.5099}$	41.4%	47.5%	27.9%
99th percentile			
$\hat{P}_{99} = 0.00310\ (\mathrm{DAREA})^{0.9973}(\mathrm{GWHEAD})^{0.9911}(\mathrm{DRT/TST})^{1.6186}$	37.9%	44.4%	36.1%

Variables in the above equations are defined as follows:

$\hat{P}_{xx}$ the predicted streamflow at the *xx* duration from the flow-duration curve, in cubic feet per second;

DAREA drainage area of the basin, in square miles;

GWHEAD a surrogate for the effective head on the aquifer discharging to the stream, calculated by subtracting the lowest basin elevation from the mean basin elevation, in feet;

DRT/TST the area of coarse-grained stratified drift in the basin, in square miles, divided by the total length of all streams in the basin, in miles, plus 0.1;

s_r standard error of the regression, in percent, from units of natural logarithms;

s_p standard error of prediction, in percent, from units of natural logarithms; and

$\lvert e_i \rvert_{.5}$ median absolute percentage error of the estimates, from units of cubic feet per second.

Estimates for the Base Period and Water Years 1980–81

The combination of independent variables found to provide the best estimates for each of the dependent variables was the same: DAREA, GWHEAD, and DRT/TST. Regression equations used to estimate the 95-, 98-, and 99-percent duration discharges for the base period at the selected sites are presented in table 6, along with their respective standard errors of regression and prediction and their median absolute percentage errors. These regression statistics are discussed below in the section "Accuracy and Limitations of the Equations."

Smearing adjustments were applied to compensate for retransformation bias in the estimates produced from the regression equations, as discussed above. Adjustments of 1.04981, 1.07223, and 1.06326 were incorporated into the regression constants of the equations for predicting the 95th, 98th, and 99th percentile discharges, respectively, by multiplying the original constants by their respective adjustment factors. The adjusted constants are listed in table 6.

Tables 10–12 (at back of report) provide estimates of the 95-, 98-, and 99-percent duration discharges, respectively, for the base period at the selected sites. The base-period estimates were obtained by use of the regression equations provided in table 6 and basin characteristics for the sites in table 9. Provided with these base-period estimates are 90-percent prediction intervals for the estimates, and estimates of the duration discharges during water years 1980–81. The estimates for water years 1980–81 were obtained by first computing ratios of the known duration discharges for water years 1980–81 to those for the base period for several streamflow-gaging stations located in or near each of the study basins. The computed ratios were then averaged to obtain adjustment factors for use in correcting the base-period estimates to conditions during water years 1980–81. Different adjustment factors, listed in table 7, were computed for each estimated percentile and for each of the study basins.

Table 7. Ratios used to adjust estimates of duration discharges for the base period to conditions during water years 1980–81

[Values are means of ratios between duration discharges computed for water years 1980–81 and those computed for base period for streamflow-gaging stations in or near each basin. These ratios were then multiplied by base-period estimates of duration discharges for selected sites to obtain estimates for water years 1980–81 for those sites]

Basin name	Percentile		
	95th	98th	99th
Blackstone River Basin	1.12	1.19	1.25
Boston Harbor Basin	.94	1.10	1.12
Charles River Basin	1.08	1.08	1.14
Taunton River Basin	1.01	1.04	1.06

Hydrologic Implications of the Regression Equations

The coefficients for each of the independent variables in the regression equations are positive, indicating that an increase in any of the independent variables will result in increased estimates of the duration discharges. Because most streams in humid regions such as Massachusetts gain in discharge as drainage area increases, a positive coefficient for DAREA is expected. GWHEAD is a surrogate for the effective head on the aquifer (the vertical drop between the highest point in the aquifer and the discharge point) that discharges water to the stream in the basin. During low-flow periods, streamflow in most areas of the northeastern United States is derived almost entirely from coarse-grained stratified-drift deposits. Discharge to a stream from an aquifer is directly dependent on the effective head of the aquifer. Because the mean basin elevation generally occurs near the middle of the basin, it serves as a reasonable approximation of the maximum elevation in the aquifer, which is generally confined to the valley. Water tables in the basins generally follow topography; therefore, subtracting the elevation of the stream at the estimation site from the mean basin elevation for the site yields an approximate aquifer head.

DRT/TST is the area of stratified-drift deposits in the basin (DRIFT) divided by the total length of all streams in the basin (TSTREAM), plus a constant of 0.1 to enable transformation of the values into natural logarithms for use in the regression analyses. As indicated above, aquifers in stratified-drift deposits (of which DRIFT is a measure) are the source of most streamflow during periods of low flow. Aquifers with many crossing streams should drain more rapidly than those with few streams, leaving less water in the aquifer to replenish streams during low flow. Losses through evapotranspiration from the stream channels should also increase with increasing stream lengths. Because of these factors, basins with small values of DRT/TST should have less discharge per unit of drainage area during periods of low flow than basins with larger values of DRT/TST, and positive coefficients for DRT/TST in the regression equations should be expected.

Accuracy of the Estimates and Limitations of the Equations

The standard errors of regression listed in table 6 are a measure of the precision with which the regression equations estimate the duration discharges for the sites used in the regression analyses. About 68 percent of the estimated duration discharges for the sites included in the analyses are within the standard errors of regression of their true values. The standard errors of prediction listed in table 6 are estimates of the precision with which the equations estimate duration discharges for sites not used in the analyses. About 68 percent of future predictions made with the regression equations (including those for the base period in tables 10–12) should be within the standard errors of prediction of their true values. The median absolute percentage errors are obtained by computing the absolute values of the differences, in percent, between the estimates obtained from the regression equations and the actual values of the estimated duration discharges for the sites used in the regression analyses. These values are provided because computations of the standard errors of estimate and prediction are influenced by the weights used in the WLS regression analyses and may not be true indicators of precision. The weights used in the WLS regression analyses are estimates computed by means of the procedures described above; the exact weights are not known. One-half of the absolute percentage errors obtained from the regression equations to estimate duration discharges for the sites used in the analyses were less than the median values indicated. Errors for sites not used in the regression analyses should be larger.

The prediction intervals in tables 10–12 provide another means of assessing the accuracy of the estimates for the base period. For each of the individual estimates of the base-period duration discharges in the tables, there is a 90 percent level of confidence that the true value for the site lies between the minimum and maximum values indicated. Conversely, 10 percent of the true values of the duration discharges for the sites where estimates are provided should be outside the ranges indicated.

Values of the independent variables for 9 of the 72 selected sites were outside the ranges of those used in the regression analyses. Prediction intervals for these sites are not provided in tables 10–12. Calculation of exact prediction intervals for these sites is cumbersome. Values of DAREA for sites used in the analyses ranged from 1.61 to 150 mi^2, GWHEAD values ranged from 18 to 1,013 ft, and DRT/TST values ranged from 0.1000 to 0.7377 mi^2/mi (including the 0.1 value added to all sites). The values of DAREA for six of the sites were larger than those for any of the sites used in the regression. The largest DAREA for the selected sites was 263 mi^2, for the Blackstone River at Millville. The values of DRT/TST for three selected sites were larger than those for any of the sites used in the analyses, with a maximum value of 0.9713 mi^2/mi at Town Brook at Quincy.

Ideally, alternative methods should be used to estimate duration discharges when sites have independent variable values outside the ranges of those used in the regression analyses, or when use of regression analyses is inappropriate for other reasons. When low-flow measurements are available, estimates of the streamflow statistics for sites with natural flow can be obtained by use of the graphical-correlation or MOVE.1 methods discussed above. When low-flow measurements are not available, an alternative method to estimate the duration discharges is to multiply the known streamflow statistic at an unregulated gaged site by the ratio of the drainage area for the ungaged site to the drainage area for the gaged site. This method is considered less accurate than use of the cross-correlation techniques, however, and none of these methods are considered to provide estimates of duration discharges superior to those obtained from the regression equations developed for this study. Streamflows for each of the nine sites with independent variable values outside the ranges of those used in the regression analyses are affected by diversions, regulations by dams, urbanization, or all three. It is not possible to estimate natural duration discharges for the nine selected sites by use of cross-correlation because appropriate corrections for these activities to measured discharges at the selected sites are not known, or because an adequate number of streamflow measurements is not available at the site. The most suitable gaged sites for use of the drainage-area-ratio method to estimate duration discharges for the nine selected sites are already included in the regression analyses. Because drainage area (DAREA) is one of the independent variables used in the analyses, and because the drainage-area-ratio method does not account for differences in discharge due to other physical characteristics of the basins, the estimates of the duration discharges obtained from the regression equations are considered to be more accurate than those that would be obtained from the drainage-area ratio method.

The regression equations listed in table 6 are applicable for use at any site with basin boundaries entirely within Massachusetts, provided that the values of the independent variables for the site are obtained from the same GIS data bases used to obtain the data for the sites used in the regression analyses, or from equivalent sources. The values of the independent variables for the site should be within the limits of those used in the regression analyses, as noted above. Other basin characteristics for the site—those not included in the regression equations—should also be similar to those for the sites used in the regression analyses. For instance, some of the largest ponds in Massachusetts are in the Nemasket River subbasin, a part of the Taunton River Basin. The two sites selected in the Nemasket River subbasin, 01107350 and 01107800, have percentage areas of ponds of 19.2 percent and 14.4 percent, respectively. The largest percentage area of ponds for the sites used in the regression analyses is 5.8 percent (Old Swamp River near South Weymouth). Because the Nemasket River sites have much larger percentage areas of ponds than those for the sites used in the regression analyses, the accuracy of the estimates for the Nemasket River sites is questionable.

The regression equations are not likely to provide adequate estimates of natural duration discharges for sites in southeast coastal areas, Cape Cod, and the islands of Martha's Vineyard and Nantucket because these areas—which are almost entirely underlain by coarse-grained stratified drift deposits—are not adequately represented by similar sites in the regression analyses. Basin boundaries determined on the basis of topography are often not coincident with ground-water boundaries in areas dominated by coarse-grained stratified drift. This provides an additional source of uncertainty in the estimated duration discharges for these areas.

The accuracy and limitations of the equations could probably be improved by obtaining measurements of the independent variables from more accurate data bases, by use of more precise methods of measuring the variables from the present data bases, by incorporating new variables, or by incorporating data for additional sites into the analyses. The USGS is currently preparing a new DEM data base that will contain elevation data for the entire country at a scale of 1:24,000. These data are currently available for some areas of Massachusetts; however the 1:250,000-scale data were used exclusively in the analyses to maintain consistency. When the 1:24,000-scale data are available for the entire State, use of these new data in place of the 1:250,000-scale data should provide better measurements of GWHEAD. It may also be possible to measure GWHEAD more directly by intersecting the stratified-drift data layer with the DEM data layer by use of the GIS software. The maximum elevation in the stratified drift could then be computed and used to replace the surrogate mean basin elevation. This method of measuring GWHEAD was not used for this study because of time constraints.

The USGS National Mapping Division is preparing a new GIS data base of hydrography for the entire country at a scale of 1:24,000. This data base, some of which is already available for Massachusetts, is probably not any more accurate than the enhanced hydrography data base already developed for the State; however, it should provide data of equivalent accuracy for adjacent states, possibly enabling sites in adjacent states to be used in future regression analyses. If sites from adjacent states are to be incorporated into the regression analyses, stratified-drift data bases of the same quality as that used for Massachusetts must be available for the other states. An equivalent data base is currently being developed for Connecticut, and maps are available for Rhode Island and parts of New Hampshire that could be used to develop equivalent data bases in those States.

The accuracies of the estimates for water years 1980–81, although unknown, are less than those for the base period. The additional error arises because the estimates for water years 1980–81 are adjustments to the estimates for the base period, and therefore have an added level of uncertainty. The severity of the drought of 1980–81 differed considerably throughout the State. Areas north and west of Boston were generally affected less severely than areas south of Boston. Spatial variation in the severity of the 1980–81 drought is reflected in the variation of the ratios between the duration discharges for 1980–81 and the base period computed for the streamflow-gaging stations used to adjust base period estimates to 1980–81 conditions. Calculated ratios for the 99-percent duration discharges varied the most, with discharges for 1980–81 from 0.50 to 1.81 times those for the base period for all sites used to obtain the adjustments. Variation between the sites used to obtain the adjustments for the individual study basins were somewhat less. Because the spatial variation in the ratios was large, there was little confidence in the use of a single nearby streamflow-gaging station, or only the few streamflow-gaging stations within a major basin, to adjust estimates for the base period to obtain the 1980–81 estimates for the selected sites in the major basin. Therefore, usually about 10 streamflow-gaging stations in and near each study basin were used to obtain the averaged adjustments for the basin.

SUMMARY AND CONCLUSIONS

Physically based models were developed to estimate the natural yields of basins in Massachusetts during times of low flow. Streamflow statistics used in the models to express basin yields are the 95-, 98-, and 99-percent duration discharges calculated from flow-duration curves for a base period of 25 years (water years 1963–87). The model equations were developed by use of weighted-least-squares multiple-regression analyses to relate computed duration discharges at 41 sites to the physical characteristics of the drainage basins for the sites. All physical characteristics were measured by use of a computerized geographic information system. Record-extension techniques were used to adjust duration discharges computed for sites with incomplete records to base-period conditions. Weights assigned to each site included in the regression analyses were determined by use of a function that corrects for length of record at the site and for nonconstant variance of the regression residuals.

Basin characteristics selected to provide the best estimates for each of the duration discharges included drainage area, the amount of stratified drift per unit length of streams in the basin, and a surrogate measure of the effective head of the aquifer in stratified drift deposits. Each of the basin characteristics has a positive correlation with each of the duration discharges. Standard errors of estimation were 34.1 percent, 41.4 percent, and 37.9 percent, and estimated standard errors of prediction were 39.3 percent, 47.5 percent, and 44.4 percent, for the equations predicting the 95-, 98-, and 99-percent duration discharges, respectively. These standard errors are influenced to some extent by the weights used in the weighted-least-squares analyses, and may not be true indicators of the precision of the equations. Median absolute errors obtained by use of the equations to estimate duration discharges for the sites used in the analyses were 21.7 percent, 27.9 percent, and 36.1 percent for the 95-, 98-, and 99-percent duration discharges.

The models were used to predict duration discharges for the base period for 72 sites in the Boston Harbor Basin and in the Blackstone, Charles, and Taunton River Basins in eastern Massachusetts.

Ninety-percent prediction intervals were computed for the estimates at each of the sites. Nine of the 72 selected sites had values of the independent variables that were outside the ranges of those for the sites used in the regression analyses. The 90-percent prediction intervals for these sites are larger than those calculated. Alternative methods were not used to estimate duration discharges for the sites because the accuracies of the alternative methods are considered no better than estimates obtained by use of the regression equations.

The base-period estimates were adjusted to reflect conditions during water years 1980–81, the most recent drought period in most of Massachusetts. Adjustments were based on computed averages of the ratios between the duration discharges computed for water years 1980–81 to those computed for the base period for several streamflow-gaging stations in or near each of the four study basins.

The regression equations are applicable for use at any site with basin boundaries entirely within Massachusetts, except in areas that are almost entirely underlain by coarse-grained stratified drift deposits, such as southeast coastal Massachusetts, Cape Cod, and the islands of Nantucket and Martha's Vineyard. Basin characteristics for the estimated sites should be within the ranges of those used in the regression analyses. The accuracy and limitations of the equations could probably be improved by obtaining measurements of the independent variables from more accurate data bases, by use of more precise methods of measuring the variables from present data bases, by incorporating new variables, or by incorporating data for additional sites into the analyses.

REFERENCES CITED

Ayers, H.D., 1970, Basin yields, *in* Gray, D.M., ed., Handbook of the principles of hydrology: Port Washington, N.Y., Water Information Center, p. 10.1.

Brackley, R.A., Fleck, W.B., and Meyer, W.R., 1973, Hydrology and water resources of the Neponset and Weymouth River Basins, Massachusetts: U.S. Geological Survey Hydrologic Investigations Atlas HA-464, 3 sheets.

Brackley, R.A., and Wandle, S.W., Jr., 1982, Drainage divides, Massachusetts—Nashua and Concord River Basins: U.S. Geological Survey Open-File Report 82-924, 22 maps, scale 1:24,000.

———1983, Drainage divides, Massachusetts-Ipswich and lower Merrimack River Basins: U.S. Geological Survey Open-File Report 83-209, 28 maps, scale 1:24,000.

Cervione, M.A., Jr., 1982, Streamflow information for Connecticut with application to land-use planning: Connecticut Department of Environmental Protection Bulletin 35, p. 16.

Cervione, M.A., Jr., Melvin, R.L., and Cyr, K.A., 1982, A method for estimating the 7-day, 10-year low flow of streams in Connecticut: Connecticut Water-Resources Bulletin 34, 17 p.

Cohn, T.A., Lewis, L.D., Gilroy, E.J., Hirsch, R.M., and Wells, D.K., 1989, Estimating constituent loads: Water Resources Research, v. 25, no. 5, p. 937-942.

Dingman, S.L., 1978, Synthesis of flow-duration curves for unregulated streams in New Hampshire: Water Resources Bulletin, v. 14, no. 6, p. 1481-1502.

Duan, Naihua, 1983, Smearing estimate: a non-parametric retransformation method: Journal of the American Statistical Association, v. 78, no. 383, p. 605-610.

Elassal, A.A., and Caruso, V.M., 1983, USGS digital cartographic data standards: digital elevation models: U.S. Geological Survey Circular 895-B, 40 p.

Environmental Systems Research Institute, Inc., 1987, ARC/INFO users guide, volume 1: Redlands, Calif.

———1990, Understanding GIS, the ARC/INFO method: Redlands, Calif., p. 1-2.

Fennessey, Neil, and Vogel, R.M., 1990, Regional flow-duration curves for ungauged sites in Massachusetts: Journal of Water Resources Planning and Management, v. 116, no. 4, p. 530-549.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, N. J., Prentice-Hall, p. 306.

Gadoury, R.A., and Wandle, S.W., Jr., 1982a, Drainage divides, Massachusetts—Westfield and Farmington River Basins: U.S. Geological Survey Open-File Report 82-635, map, scale 1:24,000.

———1982b, Drainage divides, Massachusetts—Housatonic River Basin: U.S. Geological Survey Open-File Report 82-634, map, scale 1:24,000.

Gay, F.B., and Delaney, D.F., 1980, Hydrology and water resources of the Shawsheen River Basin, Massachusetts: U.S. Geological Survey Hydrologic Investigations Atlas HA-614, 3 sheets.

Gilroy, E.J., Hirsch, R.M., and Cohn, T.A., 1990, Mean square error of regression-based constituent transport estimates: Water Resources Research, v. 26, no. 9, pp. 2069-2077.

Hirsch, R.M., 1982, A comparison of four streamflow record extension techniques: Water Resources Research, v. 18, no. 4., p. 1081-1088.

Iman, R.L., and Conover, W.J., 1983, A modern approach to statistics: New York, John Wiley, 497 p.

Johnson, C.G., 1970, A proposed streamflow data program for central New England: U.S. Geological Survey Open-File Report, 38 p.

Krejmas, B.E., 1982, Drainage divides, Massachusetts—Blackstone and Thames River Basins: U.S. Geological

Survey Open-File Report 82-0631, 12 maps, scale 1:24,000.

Krejmas, B.E., and Wandle, S.W., Jr., 1982a, Drainage divides, Massachusetts—Deerfield and Millers River Basins: U.S. Geological Survey Open-File Report 82-0632, map, scale 1:24,000.

———1982b, Drainage divides, Massachusetts—Connecticut River lowlands and Chicopee River Basin: U.S. Geological Survey Open-File Report 82-0633, map, scale 1:24,000.

Ku, H.F., Randall, A.D., and MacNish, R.D., 1975, Streamflow in the New York part of the Susquehanna River Basin: New York State Department of Environmental Conservation Bulletin 71, 130 p.

Lapham, W.W., 1988, Yield and quality of ground water from stratified drift aquifers, Taunton River Basin, Massachusetts: U.S. Geological Survey Water Resources Investigations Report 86-4053, 69 p.

Linsley, R.K., Jr., Kohler, M.A., and Paulhus, J.L.H., 1982, Hydrology for engineers: New York, McGraw-Hill, p. 444.

Loaiciga, H.A., 1989, Variability of empirical flow quantiles: Journal of Hydraulic Engineering, v. 115, no. 1, p. 82-100.

Lumb, A.M., Kittle, J.L., and Flynn, K.M., 1990, Users manual for ANNIE, a computer program for interactive hydrologic analyses and data management: U.S. Geological Survey Water-Resources Investigations Report 89-4080, 236 p.

Male, J.W., and Ogawa, Hisashi, 1982, Low flow of Massachusetts streams: Amherst, University of Massachusetts Water Resources Research Center Publication 125, 152 p.

Massachusetts Division of Water Resources, 1989, Neponset River Basin, volume 1: Inventory and analysis of current and projected water use: p. 1.

MassGIS, 1990, MassGIS data layer descriptions and a guide to user services: Boston, Massachusetts Executive Office of Environmental Affairs Data Center, 34 p.

McIntosh, W.L., Eister, M.F., and Sparks, D.M., 1982, Geologic map index of Massachusetts, Rhode Island and Connecticut: U.S. Geological Survey Map Index.

Montgomery, D.C., and Peck, E.A., 1982, Introduction to linear regression analysis: New York, John Wiley, 504 p.

Myette, C.F., and Simcox, A.C., 1989 (revised 1991), Water resources and aquifer yields in the Charles River Basin, Massachusetts: U.S. Geological Survey Water-Resources Investigations Report 88-4173, 53 p.

National Oceanic and Atmospheric Administration, 1989, Climatological data, annual summary, New England, v. 101, no. 13, 51 p.

Neter, John, Wasserman, William, and Kutner, M.H., 1985, Applied linear statistical models: Homewood, Ill., Irwin, p. 167.

Novak, C.E., 1985, Water Resources Division data reports preparation guide: U.S. Geological Survey, 199 p.

Ryan, B.F., Joiner, B.L., and Ryan, T.A., Jr., 1985, MINITAB handbook (2d ed.): Boston, PWS-Kent, 385 p.

Searcy, J.K., 1959, Flow-duration curves, manual of hydrology—part 2. Low-flow techniques: U.S. Geological Survey Water-Supply Paper 1542-A, p. 1-33.

Tasker, G.D., 1972, Estimating low-flow characteristics of streams in southeastern Massachusetts from maps of ground water availability, *in* Geological Survey research, 1972: U.S. Geological Survey Professional Paper 800-D, p. D217-D220.

———1980, Hydrologic regression with weighted least squares: Water Resources Research, v. 16, no. 6, p. 1107-1113.

Thomas, M.P., 1966, Effect of glacial geology upon the time distribution of streamflow in eastern and southeastern Connecticut: U.S. Geological Survey Professional Paper 550-B, p. B209-B212.

U.S. Geological Survey, 1976-89, Water resources data, Massachusetts and Rhode Island, water years 1975-1987: U.S. Geological Survey Water-Data Reports MA-RI-75-1 to MA-RI-87-1 (published annually).

———1987, List of U.S. Geological Survey water-supply reports and maps for Massachusetts, Rhode Island, and Connecticut, 98 p.

———1988, National Mapping Division digital data layer of population of the United States, from U.S. Census Bureau census blocks, scale 1:2,000,000.

——— 1991, National water summary 1988–89—floods and droughts; U.S. Geological Survey Water-Supply Paper 2375, p. 329.

U.S. Geological Survey, National Cartographic Information Center, 1985, Digital line graphs from 1:100,000-scale maps: Data Users Guide 2, 75 p.

———1986, Land use and land cover digital data from 1:250,000- and 1:100,000-scale maps, Data Users Guide 4: 36 p.

U.S. Geological Survey, Office of Water Data Coordination, 1977, National handbook of recommended methods for water-data acquisition: chap. 7.

Vogel, R.M., and Kroll, C.N., 1990, Generalized low-flow frequency relationships for ungaged sites in Massachusetts: Water Resources Bulletin, v. 26, no. 2, p. 241-253.

Walker, E.H., and Krejmas, B.E., 1986, Water resources of the Blackstone River Basin, Massachusetts: U.S. Geological Survey Hydrologic Investigations Atlas HA-682, 2 sheets.

Wandle, S.W., Jr., 1982, Drainage divides, Massachusetts—Hudson River Basin: U.S. Geological Survey Open-File Report 81-1199, 6 maps, scale 1:24,000.

Wandle, S.W., Jr., and Frimpter, M. H., 1982, Drainage divides, Massachusetts—Taunton River Basin and Southeast Coastal Basins: U.S. Geological Survey Open-File Report 82-870, 24 maps, scale 1:24,000.

Williams, J.R., Farrell, D.F., and Willey, R.E., 1973, Water resources of the Taunton River Basin, Massachusetts: U.S. Geological Survey Hydrologic Investigations Atlas HA-460, 3 sheets.
Williams, J.R., and Tasker, G.D., 1974a, Water resources of the coastal drainage basins of southeastern Massachusetts, Weir River, Hingham, to Jones River, Kingston: U.S. Geological Survey Hydrologic Investigations Atlas HA-507, 2 sheets.
———1974b, Water resources of the coastal drainage basins of southeastern Massachusetts, Plymouth to Weweantic River, Wareham: U.S. Geological Survey Hydrologic Investigations Atlas HA-507, 2 sheets.

TABLES 8–12

Table 8. Selected sites in the study area for which low-flow estimates are provided

[Listed in order of increasing USGS station number. Distances are in feet (ft), and miles (mi)]

USGS station number	Latitude	Longitude	Station name	Location
			Blackstone River Basin	
01109460	42°12′20″	71°50′06″	Dark Brook at Auburn	At bridge on State Route 12
01109500	42°13′55″	71°50′07″	Kettle Brook at Worcester	75 ft below Webster Street bridge
01109570	42°15′03″	71°50′15″	Tatnuck Brook at Worcester	At outlet to Coes Reservoir
01109658	42°12′46″	71°47′02″	Blackstone River near Millbury	At bridge on U.S. Route 20
01110000	42°13′49″	71°42′41″	Quinsigamond River at North Grafton	800 ft below outlet to Hovey Pond
01110100	42°11′39″	71°41′35″	Quinsigamond River near Grafton	1,000 ft above Fisherville Pond
01110500	42°09′13″	71°39′09″	Blackstone River at Northbridge	100 ft below Sutton Street bridge
01111050	42°04′30″	71°37′35″	Mumford River at Uxbridge	At bridge on State Route 16
01111200	42°06′17″	71°36′28″	West River near Uxbridge	250 ft below West Hill Dam
01111230	42°01′16″	71°34′04″	Blackstone River at Millville	1.4 mi upstream from Branch River
01111300	41°58′52″	71°41′11″	Nipmuc River near Harrisville, R.I.	1.0 mi upstream from mouth
01112250	42°02′55″	71°31′15″	Mill River near Blackstone	At bridge on Elm Street
01112380	42°01′26″	71°29′17″	Peters Brook at Crooks Corner	At bridge on Paine Street
01113750	41°55′43″	71°22′23″	Abbott Run near South Attleboro	At bridge on Mendon Road
			Boston Harbor Basin (Mystic River Subbasin)	
01102480	42°27′39″	71°08′15″	Aberjona River at Winchester	At Swanton Steet bridge
01102500	42°26′50″	71°08′22″	Aberjona River at Winchester	0.5 mi upstream from head of Mystic Lakes
01103015	42°25′20″	71°08′59″	Mill Brook at Arlington	1,000 ft upstream from mouth
			Boston Harbor Basin (Neponset River Subbasin)	
01104840	42°08′28″	71°15′25″	Neponset River at Walpole	At bridge on Main Street (State Route 1A)
01104850	42°09′14″	71°15′52″	Mine Brook at Walpole	At outlet to Turner Pond
01104980	42°10′26″	71°12′31″	Hawes Brook at Norwood	At bridge on Washington Street
01105000	42°10′39″	71°12′05″	Neponset River at Norwood	200 ft above Pleasant Street bridge
01105270	42°08′59″	71°08′58″	Massapoag Brook at Canton	At bridge on Walnut Street
01105300	42°08′39″	71°08′14″	Steep Hill Brook at Canton	At bridge on Bailey Street
01105500	42°09′16″	71°08′47″	East Branch Neponset River at Canton	100 ft below Washington Street bridge
01105554	42°12′33″	71°08′47″	Neponset River near Dedham	At bridge at end of Green Lodge Street
			Boston Harbor Basin (Weymouth-Weir River Subbasin)	
01105582	42°13′25″	70°59′49″	Monatiquot River at Braintree	At bridge on Middle Street
01105585	42°14′52″	70°59′52″	Town Brook at Quincy	200 ft downstream from Miller Stile Road
01105600	42°11′25″	70°56′43″	Old Swamp River near South Weymouth	Between divided lanes of State Route 3, 1.2 mi north of South Weymouth
01105610	42°12′45″	70°55′32″	Whitmans Pond Outlet Tributary at East Weymouth	At bridge on Pleasant Street
01105640	42°14′31″	70°51′36″	Weir River near Hingham	At stone bridge on Main Street
			Charles River Basin	
01103200	42°05′38″	71°28′56″	Charles River at Bellingham	At Depot Street below Box Pond
01103217	42°08′31″	71°27′21″	Hopping Brook near West Medway	At bridge on West Street
01103240	42°07′29″	71°25′52″	Mine Brook near Franklin	At bridge on Pond Street
01103253	42°08′27″	71°25′26″	Chicken Brook near West Medway	At bridge on Village Street
01103300	42°07′21″	71°21′59″	Mill River near Norfolk	At bridge on Miller Street
01103305	42°07′59″	71°21′46″	Charles River near Millis	150 ft upstream from Myrtle Street bridge
01103330	42°09′03″	71°18′18″	Stop River near Medfield	At bridge on South Street
01103395	42°11′17″	71°21′46″	Bogastow Brook near Millis	At Orchard Street bridge
01103400	42°12′36″	71°21′09″	Charles River near Medfield	At bridge on Hospital Road
01103420	42°16′17″	71°18′57″	Charles River at Natick	At bridge on Pleasant Street
01103435	42°17′13″	71°18′05″	Waban Brook near Wellesley	At Wellesley College Golf Course

Table 8. Selected sites in the study area for which low-flow estimates are provided—**Continued**

USGS station number	Latitude	Longitude	Station name	Location
			Charles River Basin—Continued	
01103440	42°17′45″	71°17′18″	Fuller Brook at Wellesley	At bridge on Brook Street
01103500	42°15′22″	71°15′38″	Charles River at Dover	At Mill Street, 0.25 from Dedham Street
01103905	42°16′02″	71°12′16″	Charles River at Dedham	At State Route 128
01104200	42°18′59″	71°13′42″	Charles River at Wellesley	50 ft above bridge on State Route 9
01104258	42°19′10″	71°14′47″	Rosemary Brook near Wellesley	400 ft above mouth
01104470	42°22′04″	71°16′16″	Stony Brook near Waltham	500 ft above Stony Brook Reservoir
01104500	42°22′20″	71°14′03″	Charles River at Waltham	800 ft below Moody Street bridge
			Taunton River Basin	
01106430	42°05′26″	71°00′45″	Trout Brook at Brockton	At bridge on Elliot Street
01106500	42°00′55″	70°57′42″	Matfield River at Elmwood	At intersection State Routes 18 and 106
01106900	42°02′32″	70°53′56″	Poor Meadow Brook at South Hanson	At bridge on Main Street
01106915	42°00′32″	70°54′29″	Robbins Pond Outlet near East Bridgewater	At bridge in Pond Street
01106920	42°01′13″	70°57′09″	Satucket River at East Bridgewater	500 ft below Plymouth Street
01107010	42°03′57″	71°05′43″	Queset Brook at North Easton	At bridge on Main Street
01107050	42°00′40″	71°03′31″	Hockomock River near West Bridgewater	At bridge on Center Street
01107100	41°59′49″	71°58′23″	Town River at Bridgewater	At bridge on Broad Street
01107188	41°58′09″	70°54′03″	Winnetuxet River near Halifax	At bridge on Thompson Street
01107350	41°51′33″	70°55′02″	Nemasket River at Middleboro	At bridge on Vaughn Street
01107800	41°56′01″	70°55′27″	Nemasket River near Middleboro	At bridge on Murdock Street
01108140	41°54′20″	70°59′19″	Poquoy Brook near North Middleboro	At bridge on Richmond Street
01108180	41°52′57″	71°02′54″	Cotley Brook at East Taunton	At bridge on Caswell Street
01108280	41°54′25″	71°03′33″	Forge River near Taunton	At bridge on South Main Street
01108320	41°58′38″	71°08′40″	Canoe River near Norton	At bridge on Plain Street
01108350	42°01′07″	71°07′35″	Mulberry Meadow Brook near Easton	At bridge on Highland Street
01108400	41°55′23″	71°06′23″	Mill River near Taunton	At bridge on Wittenton Street
01108500	42°00′00″	71°15′38″	Wading River at West Mansfield	200 ft downstream from Balcolm Street
01109000	41°56′51″	71°10′38″	Wading River near Norton	200 ft below bridge on State Route 140
01109020	42°03′48″	71°12′57″	Rumford River at East Foxboro	At bridge on Cocasset Street
01109040	41°58′23″	71°10′32″	Rumford River at Norton	At bridge on State Route 123
01109060	41°51′58″	71°07′24″	Threemile River at North Dighton	800 ft downstream from Warner Boulevard
01109070	41°50′25″	71°08′36″	Segreganset River at Dighton	50 ft above culverts on Center Street
01109087	41°47′57″	71°03′37″	Assonet River at Assonet	At bridge on Locust Street

Table 9. Basin characteristics for selected sites in the study area for which low-flow estimates are provided

[Areas are in square miles; stream lengths are in miles; elevations, relief, and GWHEAD (mean elevation minus lowest elevation) are in feet]

USGS number	Drainage area	Area of drift	Longest stream	Total streams	Highest elevation	Lowest elevation	Mean elevation	Total relief	GWHEAD
				Blackstone River Basin					
01109460	11.1	2.91	6.01	20.9	850	499	632	351	133
01109500	31.5	5.37	12.6	38.1	1,348	499	748	849	249
01109570	11.5	1.40	7.18	20.9	1,378	525	846	853	321
01109658	65.1	12.6	18.1	99.5	1,378	420	711	958	291
01110000	25.6	9.83	10.6	39.6	748	358	490	390	132
01110100	37.2	12.5	13.9	57.4	748	298	434	450	136
01110500	141	35.0	29.1	220	1,378	269	589	1,109	320
01111050	56.6	13.7	17.7	110	899	240	533	659	293
01111200	27.8	8.42	11.7	44.0	630	240	405	390	165
01111230	263	70.1	42.7	429	1,378	197	525	1,181	328
01111300	15.9	4.15	7.09	30.3	760	361	532	399	171
01112250	25.3	6.44	14.4	38.4	548	174	342	374	168
01112380	11.8	4.89	4.94	20.2	450	167	280	283	113
01113750	23.8	1.44	11.2	52.6	518	98	258	420	160
				Boston Harbor Basin (Mystic River Subbasin)					
01102480	13.4	6.70	7.39	18.1	249	39	111	210	72
01102500	24.1	10.8	8.45	37.5	347	39	137	308	98
01103015	5.20	2.19	4.88	10.8	347	33	236	314	203
				Boston Harbor Basin (Neponset River Subbasin)					
01104500	250	119	67.9	518	548	30	211	518	181
01104840	11.5	8.11	6.74	20.0	472	147	247	325	100
01104850	5.98	3.64	6.32	8.32	397	147	220	250	73
01104980	8.63	2.20	6.33	13.1	348	98	201	250	103
01105000	34.7	19.5	11.1	57.8	472	85	215	387	130
01105270	10.4	6.19	6.74	26.2	518	98	256	420	158
01105300	6.65	5.51	3.67	12.2	299	134	206	165	72
01105500	27.2	16.5	6.93	51.0	518	98	218	420	120
01105554	83.7	45.9	17.6	150	518	30	194	488	164
01105585	4.22	1.49	2.61	1.71	348	10	98	338	88
01105600	4.47	1.19	4.58	9.18	197	98	146	99	48
01105610	12.6	3.35	6.81	23.4	249	49	145	200	96
				Boston Harbor Basin (Weymouth-Weir River Subbasin)					
01105582	27.6	9.22	9.37	38.9	558	56	169	502	113
01105640	14.6	9.52	7.28	26.6	197	26	97	171	71
				Charles River Basin					
01103200	14.5	3.74	10.5	28.2	548	230	354	318	124
01103217	10.1	3.88	6.74	18.6	509	210	293	299	83
01103240	14.1	6.44	9.95	27.7	450	177	285	273	108
01103253	7.23	1.08	7.24	17.6	397	174	267	223	93
01103300	13.8	9.78	8.12	22.5	450	148	261	302	113
01103305	83.9	37.0	22.6	166	548	138	278	410	140
01103330	12.8	6.86	6.91	24.9	341	138	198	203	60
01103395	23.4	8.84	9.26	42.5	397	138	198	259	60
01103400	140	62.0	32.8	281	548	138	243	410	105

Table 9. Basin characteristics for selected sites in the study area for which low-flow estimates are provided—**Continued**

USGS number	Drainage area	Area of drift	Longest stream	Total streams	Highest elevation	Lowest elevation	Mean elevation	Total relief	GWHEAD
Charles River Basin—Continued									
01103420	156	68.0	39.0	314	548	118	237	430	119
01103435	10.4	6.37	5.64	18.4	348	128	192	220	64
01103440	3.91	2.35	3.12	8.96	299	118	160	181	42
01103500	182	84.0	46.7	380	548	98	229	450	131
01103905	192	86.9	50.5	396	548	79	226	469	147
01104200	211	98.0	61.6	440	548	59	218	489	159
01104258	3.87	2.86	3.34	5.95	299	72	139	227	67
01104470	19.0	8.79	7.08	38.8	397	98	199	299	101
Taunton River Basin									
01106430	5.89	2.36	3.21	7.71	270	98	160	185	62
01106500	40.6	14.6	14.4	174	310	49	132	285	83
01106900	14.6	6.06	9.16	24.8	210	49	106	163	57
01106915	13.3	12.9	8.47	63.7	130	49	69	89	20
01106920	34.7	23.9	15.3	103	210	49	83	180	34
01107010	7.49	1.99	4.41	19.7	431	128	206	316	78
01107050	20.5	7.55	10.5	47.7	431	79	164	366	85
01107100	55.7	29.7	19.4	111	431	49	119	406	70
01107188	36.0	31.2	7.92	51.4	310	30	78	290	48
01107350	49.8	26.9	11.6	53.5	240	52	90	187	38
01107800	69.7	41.6	19.2	82.9	240	30	90	215	60
01108140	8.22	6.92	4.52	10.2	140	30	62	125	32
01108180	7.50	3.75	5.54	8.51	170	30	82	160	52
01108280	9.21	8.54	4.84	12.2	190	32	76	180	44
01108320	18.3	14.0	12.9	50.0	370	72	155	302	83
01108350	8.54	3.57	5.62	25.0	431	98	200	346	102
01108400	41.3	29.6	19.4	93.8	431	59	141	381	82
01108500	19.6	11.1	8.72	39.6	430	118	247	309	129
01109000	43.5	25.6	16.3	82.9	490	69	181	435	112
01109020	5.11	3.83	2.97	13.7	490	197	270	295	73
01109040	20.8	13.6	13.5	53.6	490	85	190	420	105
01109060	84.5	54.7	27.4	176	490	7	157	479	150
01109070	10.6	1.37	6.52	22.4	242	36	111	212	75
01109087	20.7	8.88	8.08	28.0	200	23	113	177	90

Table 10. Estimated discharges at the 95-percent duration for the base period and for water years 1980–81 at selected sites

[Estimated discharges are in units of cubic feet per second. Dashes (--) indicate that prediction intervals were not calculated because one or more of the independent variables for site were outside ranges of independent variables for sites used in regression analyses]

Station number	Estimated base period discharge	Base period 90-percent prediction intervals		Estimated 1980-81 discharge
		Minimum	Maximum	
Blackstone River Basin				
01109460	0.91	0.51	1.61	0.92
01109500	3.93	2.22	6.95	3.97
01109570	1.23	.70	2.18	1.25
01109658	8.06	4.53	14.3	8.14
01110000	3.04	1.70	5.44	3.07
01110100	3.93	2.19	7.05	3.97
01110500	20.7	11.5	37.5	20.9
01111050	7.05	3.97	12.5	7.12
01111200	3.17	1.78	5.64	3.20
01111230	38.3	--	--	38.7
01111300	1.53	.86	2.70	1.54
01112250	2.67	1.50	4.74	2.70
01112380	1.29	.72	2.30	1.30
01113750	1.01	.56	1.85	1.02
Boston Harbor Basin (Mystic River Subbasin)				
01102480	1.48	0.81	2.69	1.39
01102500	2.59	1.43	4.67	2.43
01103015	.83	.46	1.51	.78
Boston Harbor Basin (Neponset River Subbasin)				
01104500	29.8	--	--	32.2
01104840	1.81	.99	3.32	1.70
01104850	.83	.45	1.53	.78
01104980	.68	.38	1.20	.63
01105000	5.20	2.86	9.43	4.89
01105270	1.46	.82	2.62	1.38
01105300	.93	.51	1.72	.88
01105500	3.75	2.08	6.79	3.53
01105554	12.8	7.03	23.5	12.1
Boston Harbor Basin (Weymouth-Weir River Subbasin)				
01105582	2.77	1.54	4.97	2.60
01105585	1.40	--	--	1.32
01105600	.16	.09	.29	.15
01105610	.81	.45	1.44	.76
01105640	1.53	.84	2.78	1.44
Charles River Basin				
01103200	1.07	0.60	1.90	1.15
01103217	.78	.43	1.39	.84

Station number	Estimated base period discharge	Base period 90-percent prediction intervals		Estimated 1980-81 discharges
		Minimum	Maximum	
Charles River Basin—Continued				
01103240	1.42	.79	2.54	1.53
01103253	.29	.16	.53	.31
01103300	2.51	1.37	4.62	2.71
01103305	8.70	4.77	15.9	9.39
01103330	.94	.52	1.70	1.02
01103395	1.30	.71	2.38	1.40
01103400	11.0	5.85	20.7	11.9
01103420	13.2	--	--	14.3
01103435	1.00	.55	1.82	1.08
01103440	.23	.13	.42	.25
01103500	16.7	--	--	18.0
01103905	19.1	--	--	20.6
01104200	22.4	--	--	24.2
01104258	.57	.31	1.06	.62
01104470	1.73	.97	3.11	1.87
Taunton River Basin				
01106430	0.52	0.29	0.94	0.58
01106500	1.53	.81	2.86	1.71
01106900	.92	.51	1.68	1.03
01106915	.32	.17	.62	.36
01106920	1.32	.69	2.52	1.48
01107010	.34	.19	.61	.38
01107050	1.23	.68	2.23	1.38
01107100	4.01	2.16	7.44	4.49
01107188	4.31	2.28	8.16	4.83
01107350	4.03	2.11	7.71	4.52
01107800	7.75	4.09	14.7	8.68
01108140	.90	--	--	1.01
01108180	.79	.43	1.44	.88
01108280	1.31	--	--	1.47
01108320	1.72	.95	3.10	1.92
01108350	.59	.33	1.05	.66
01108400	3.99	2.18	7.31	4.47
01108500	2.60	1.45	4.66	2.91
01109000	5.24	2.88	9.53	5.87
01109020	.48	.26	.86	.53
01109040	2.13	1.19	3.83	2.39
01109060	12.2	6.67	22.4	13.7
01109070	.35	.19	.64	.39
01109087	2.29	1.27	4.14	2.56

Table 11. Estimated discharges at the 98-percent duration for the base period and for water years 1980–81 at selected sites

[Estimated discharges are in units of cubic feet per second. Dashes (--) indicate that prediction intervals for site were not calculated because one or more of independent variables for site were outside ranges of independent variables for sites used in regression analyses]

Station number	Estimated base period discharge	Base period 90-percent prediction intervals		Estimated 1980-81 discharge
		Minimum	Maximum	
Blackstone River Basin				
01109460	0.55	0.27	1.09	0.57
01109500	2.74	1.38	5.43	2.85
01109570	.79	.40	1.57	.83
01109658	5.73	2.87	11.4	5.96
01110000	2.09	1.03	4.21	2.17
01110100	2.64	1.31	5.34	2.75
01110500	15.9	7.82	32.2	16.5
01111050	4.99	2.51	9.94	5.19
01111200	2.15	1.08	4.30	2.24
01111230	29.8	--	--	31.0
01111300	.97	.49	1.92	1.01
01112250	1.77	.89	3.52	1.84
01112380	.84	.42	1.70	.88
01113750	.52	.25	1.07	.54
Boston Harbor Basin (Mystic River Subbasin)				
01102480	.98	.48	2.02	1.08
01102500	1.73	.85	3.52	1.90
01103015	.59	.29	1.20	.64
Boston Harbor Basin (Neponset River Subbasin)				
01104500	22.0	--	--	23.8
01104840	1.32	.64	2.73	1.45
01104850	.57	.27	1.20	.63
01104980	.40	.20	.800	.44
01105000	3.85	1.88	7.90	4.24
01105270	1.02	.51	2.06	1.12
01105300	.65	.31	1.35	.71
01105500	2.70	1.32	5.51	2.97
01105554	9.86	4.78	20.3	10.8
Boston Harbor Basin (Weymouth-Weir River Subbasin)				
01105582	1.82	.90	3.68	2.00
01105585	1.22	--	--	1.34
01105600	.08	.04	.16	.08
01105610	.46	.23	.92	.50
01105640	1.00	.49	2.06	1.10
Charles River Basin				
01103200	.63	0.31	1.25	.68
01103217	.46	.23	.93	.50
Charles River Basin—Continued				
01103240	.91	.45	1.84	.99
01103253	.14	.07	.29	.15
01103300	1.91	0.92	3.99	2.07
01103305	5.98	2.90	12.3	6.45
01103330	.56	.27	1.14	.60
01103395	.72	.35	1.50	.78
01103400	7.14	3.34	15.3	7.71
01103420	8.76	--	--	9.46
01103435	.63	.31	1.30	.68
01103440	.12	.06	.25	.13
01103500	11.4	--	--	12.3
01103905	13.3	--	--	14.4
01104200	16.0	--	--	17.3
01104258	.39	.18	.84	.42
01104470	1.10	.54	2.21	1.19
Taunton River Basin				
01106430	.31	.15	.64	.37
01106500	.77	.36	1.64	.92
01106900	.52	.26	1.08	.62
01106915	.14	.06	.31	.17
01106920	.67	.31	1.47	.80
01107010	.17	.08	.35	.20
01107050	.70	.34	1.42	.83
01107100	2.47	1.17	5.20	2.94
01107188	3.04	1.40	6.58	3.61
01107350	2.57	1.18	5.63	3.06
01107800	5.45	2.52	11.8	6.49
01108140	.59	--	--	.71
01108180	.50	.24	1.05	.60
01108280	.93	--	--	1.11
01108320	1.10	.54	2.23	1.30
01108350	.34	.17	.67	.40
01108400	2.64	1.27	5.47	3.14
01108500	1.82	.90	3.69	2.17
01109000	3.69	1.80	7.57	4.39
01109020	.29	.14	.60	.35
01109040	1.40	.69	2.83	1.67
01109060	9.23	4.46	19.1	11.0
01109070	.16	.08	.34	.19
01109087	1.54	.75	3.14	1.83

Table 12. Estimated discharges at the 99-percent duration for the base period and for water years 1980–81 at selected sites

[Estimated discharges are in units of cubic feet per second. Dashes (--) indicate that prediction intervals for site were not calculated because one or more of independent variables for site were outside ranges of independent variables for sites used in regression analyses]

Station number	Estimated base period discharge	Base period 90-percent prediction intervals		Estimated 1980-81 discharge
		Minimum	Maximum	
Blackstone River Basin				
01109460	0.43	0.23	0.83	0.46
01109500	2.31	1.23	4.35	2.45
01109570	.60	.32	1.14	.64
01109658	5.03	2.66	9.49	5.33
01110000	1.82	.94	3.50	1.93
01110100	2.34	1.22	4.50	2.48
01110500	14.8	7.73	28.5	15.7
01111050	4.34	2.30	8.17	4.60
01111200	1.85	.97	3.52	1.96
01111230	29.1	--	--	30.9
01111300	.78	.41	1.49	.83
01112250	1.49	.79	2.83	1.58
01112380	.70	.36	1.35	.74
01113750	.40	.20	.80	.42
Boston Harbor Basin (Mystic River Subbasin)				
01102480	.85	.43	1.69	.95
01102500	1.53	.78	2.97	1.71
01103015	.45	.23	.88	.51
Boston Harbor Basin (Neponset River Subbasin)				
01104500	22.1	--	--	25.2
01104840	1.14	.57	2.28	1.28
01104850	.48	.24	.97	.54
01104980	.32	.16	.61	.35
01105000	3.52	1.79	6.91	3.94
01105270	.84	.43	1.61	.94
01105300	.55	.27	1.11	.61
01105500	2.42	1.24	4.73	2.71
01105554	9.43	4.78	18.6	10.6
Boston Harbor Basin (Weymouth-Weir River Subbasin)				
01105582	1.59	.82	3.08	1.78
01105585	1.06	--	--	1.19
01105600	.06	.03	.12	.06
01105610	.37	.19	.71	.41
01105640	.88	.44	1.73	.98
Charles River Basin				
01103200	.51	.26	.97	.58
01103217	.37	.19	.72	.43
Charles River Basin—Continued				
01103240	.76	.40	1.47	.87
01103253	.10	.05	.21	.12
01103300	1.68	0.83	3.39	1.92
01103305	5.59	2.86	10.9	6.37
01103330	.47	.24	.93	.54
01103395	.62	.31	1.24	.71
01103400	6.91	3.41	14.0	7.88
01103420	8.52	--	--	9.71
01103435	.54	.27	1.07	.62
01103440	.10	.05	.19	.11
01103500	11.2	--	--	12.8
01103905	13.1	--	--	15.0
01104200	15.8	--	--	18.1
01104258	.32	.16	.67	.37
01104470	.94	.48	1.81	1.07
Taunton River Basin				
01106430	.25	.13	.50	.32
01106500	.65	.32	1.33	.81
01106900	.44	.22	.88	.55
01106915	.12	.05	.26	.15
01106920	.60	.29	1.27	.75
01107010	.13	.07	.26	.16
01107050	.58	.30	1.14	.72
01107100	2.29	1.14	4.61	2.86
01107188	2.96	1.41	6.21	3.70
01107350	2.52	1.20	5.32	3.15
01107800	5.43	2.61	11.3	6.79
01108140	.53	--	--	.67
01108180	.43	.21	.87	.54
01108280	.84	--	--	1.05
01108320	.95	.49	1.85	1.19
01108350	.26	.14	.51	.33
01108400	2.44	1.23	4.83	3.04
01108500	1.58	.81	3.06	1.97
01109000	3.39	1.73	6.66	4.24
01109020	.23	.12	.46	.29
01109040	1.21	.63	2.34	1.51
01109060	8.84	4.48	17.5	11.1
01109070	.12	.06	.25	.15
01109087	1.35	.69	2.65	1.69