Effects of Surficial Geology, Lakes and Swamps, and Annual Water Availability on Low Flows of Streams in Central New England, and Their Use in Low-Flow Estimation

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CONVERSION FACTORS, ABBREVIATIONS, AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	2.54	centimenter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
acre	4,047	square meter
square mile (mi^2)	2.590	square kilometer
cubic foot (ft^3)	0.02832	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01094	cubic meter per second per square kilometer
gallon per minute (gal/min)	0.06309	liter per second
million gallons per day (Mgal/d)	.04381	cubic meter per second
million gallons per day per square mile [$(Mgal/d)/mi^2$]	0.01691	cubic meter per second per square kilometer
foot per mile (ft/mi)	0.189	meter per kilometer

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.

Corrections Incorporated in 2007 Edition

This revised edition incorporates several minor changes. Several lines of text on pages 33-37 were duplicated or transposed in the 1994 edition; they are now placed correctly. Several data values in tables 8 and 9 have been replaced. In each case, the data value originally published was a typographical error or was superseded by reanalysis during the study; the corrected values that appear in this edition were used in the regression analysis.

An error in the computation of 7-day low flows for Middle Branch Westfield River at Goss Heights (station 01180500) is explained and corrected on this page. Recognition and correction of this error allows me to infer that the regression equations presented in this report for the high-relief region of central New England are slightly better than the statistical indices reported in table 3 would indicate.

From August 1965 through November 1967, flows of Middle Branch Westfield River at Goss Heights were occasionally affected by construction of a flood-control reservoir upstream. During these 28 months, there were several periods when daily flows of Middle Branch were abnormally low and steady, or abnormally high and steady, relative to the natural flow of Mill River at Northampton (station 01171500), an adjacent watershed of equal size and comparable terrain. The 7-day 2-year and 7-day 10-year low flows of Middle Branch presented in table 8 were based on a data set that included abnormal (regulated) 7-day low flows for the 1965, 1966, and 1967 climatic years.

To correct this error, I plotted a log-log graph of 7-day low flows for all years from 1941 through 1983 in Middle Branch versus 7-day low flows for the same years in Mill River. The data after construction of the flood-control reservoir on Middle Branch were consistent with those before construction, except for the three years mentioned above (1965-1967) and also 1978. I did not examine daily flows for 1978 for possible regulation. I estimated natural 7-day low flows of Middle Branch for 1966 and 1967 by entering that graph with the 7-day low flows of Mill River. In 1965, the 7-day low flow of Mill River occurred in July, before the start of obvious regulation of Middle Branch, and corresponded exactly to a 7-day period of low flow of Middle Branch, so I assumed that period represented the natural 7-day low flow of Middle Branch for 1965. Results of this exercise were:

CLIMATIC YEAR	7-DAY LOW FLOWS OBSERVED (REGULATED)	7-DAY LOW FLOWS ESTIMATED (NATURAL)
1965	0.33	3.0
1966	0.49	2.8
1967	0.16	4.6

Finally, the 7-day low flows for Middle Branch for 1942-71, with these three estimated values substituted for the observed regulated values, were processed through USGS computer program PKWRCA to estimate 7Q2 and 7Q10 according to a log-Pearson Type III distribution. (Program PKWRCA was written to estimate high-flow frequency, but works as well with low-flow frequency). Results were as follows:

	7Q2	7Q10	
Published in 1994 edition and used in regression analysis:	4.0	0.87	cubic feet per second
Revised as described above	3.9	2.1	cubic feet per second

I replotted the data point for Middle Branch on several graphs of observed 7Q10 versus 7Q10 estimated from individual regression equations (such as figures 8-10 of this report). In every case, replotting moved the data point much closer to the equality line that represents perfect correlation. I conclude that each of these regression equations actually estimates 7Q10 slightly better than the coefficient of determination, standard error of estimate, or PRESS statistic in table 3 would indicate. Of course, if the regressions were re-run with the corrected data from Middle Branch, slightly different equations with equal + and – residuals would result. Nevertheless, the correction of this computational error serves to reinforce or affirm the reliability of the equations and interpretations in this report.

Allan D. Randall May 2007

Effects of Surficial Geology, Lakes and Swamps, and Annual Water Availability on Low Flows of Streams in Central New England, and Their Use in Low-Flow Estimation

By S. William Wandle, Jr. *and* Allan D. Randall

Abstract

Equations developed by multiple-regression analysis of data from 49 drainage basins in Massachusetts, New Hampshire, Rhode Island, Vermont, and southwestern Maine indicate that low flow of streams in this region is largely a function of the amount of water available to the basin and the extent of surficial sand and gravel relative to the extent of till and fine-grained stratified drift. Low flow per square mile from areas of surficial sand and gravel is consistently much greater than that from areas of till and bedrock, but flood plains and alluvial fans seem to contribute less low flow per square mile than do other types of surficial sand and gravel. The areal extent of lakes and swamps also correlates negatively with low flow in multiple-regression equations, presumably because intense evapotranspiration from these localities consumes water that would otherwise become streamflow.

The annual minimum 7-day mean low flows that occur during summer and fall at 2-year and 10-year recurrence intervals (7Q2 and 7Q10) were selected as indices of low flow and were adjusted to a common base period, 1942-71. Central New England was divided into a region of high relief that comprises much of New Hampshire, Vermont, and western Massachusetts, and a region of low relief that generally lies to the east and south but also includes the Lake Champlain lowland of Vermont. In the high-relief region, mean basin elevation proved to be the most significant index of the amount of water available. In the low-relief region, mean annual runoff per square mile was more significant than elevation, particularly when multiplied by the areal extent of sand and gravel and that of till. Dividing the areal extent of sand and gravel by stream length improved the fit of regression equations for the low-relief region.

Regression equations were developed that explained at least 95 percent of the variation in 7Q10 within both the high-relief and the low-relief data sets. Equations proposed for practical application were reasonably consistent with the statistical assumptions of least-squares analysis and yielded 7Q2 and 7Q10 values with standard errors of 1.9 and 1.4 cubic feet per second, respectively, for the high-relief region and 2.2 and 1.6 cubic feet per second for the low-relief region. When error was expressed as a percentage of each observed value, median errors were about 25 percent for 7Q2 in both regions, and about 25 and 55 percent for 7Q10 in the high- and low-relief regions, respectively. The equations do not apply to basin segments that are substantially affected by urbanization, stream regulation, or ground-water withdrawals, and may not be appropriate where basin characteristics fall outside their range in the data set or where the geologic and topographic maps needed for measurement of basin characteristics are unavailable, or are of small scale or mutually inconsistent.

INTRODUCTION

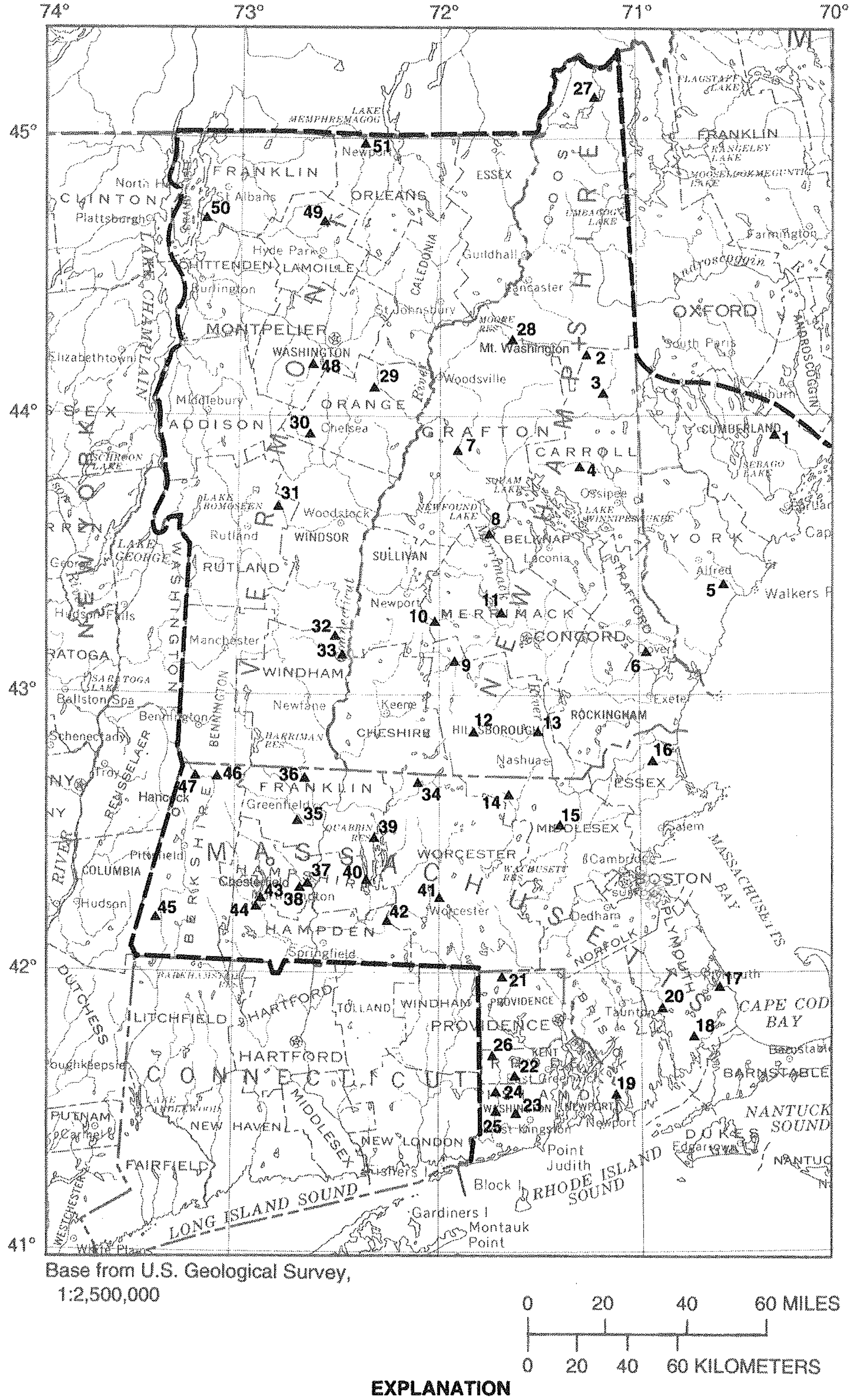
The interaction between aquifers and streams is a central aspect of the water resources of the glaciated Northeastern United States. Streamflow consists mostly of ground-water discharge, especially during periods of dry weather. At the same time, streamflow is the largest potential source of recharge to glacial sand-and-gravel deposits, which are by far the most productive aquifers in the region. In 1982, a comprehensive study of these stream-and-aquifer systems was begun under the Regional Aquifer-System Analysis program of the U.S. Geological Survey, to refine and compile some concepts and typical values of system components that could be applied in evaluating and managing aquifers in the glaciated Northeast (Lyford and others, 1984, p. 3). One objective of the study was to demonstrate and quantify the extent to which aquifer distribution and properties interact with other environmental characteristics to control ground-water discharge to streams, especially during periods of dry weather, when streamflow is low.

Information on the magnitude and frequency of low flows is needed by the government agencies, hydrologists, and engineers who plan or manage many activities related to water resources, such as wastewater discharge, aquatic-habitat protection, water-supply design, aquifer evaluation, and water-quality management. Low-flow periods, when multiple demands may approach or exceed available streamflow, are a threat to all these activities. Therefore, estimates of the magnitude and frequency of low flows at many sites are needed. Where streamflow measurements that encompass a suitable range in flows have been made, low-flow magnitude and frequency generally can be estimated by correlation with nearby gaging stations. Where streamflow measurements have not been made, however, low flows must be estimated from physical properties of the drainage basin. Low-flow-estimation techniques that incorporate properties known to directly affect ground-water storage and discharge are likely to be more reliable than techniques based only on conveniently measurable properties.

This report presents an analysis of the spatial variability of low flow in Massachusetts, New Hampshire, Rhode Island, Vermont, and southwestern Maine, a region referred to herein as central New England (fig. 1). The report first reviews in general terms the causes of low-flow variability in this region, then describes the procedures used to select a data set of 49 drainage basins, to compute low-flow statistics for those basins, and to measure certain geologic, topographic, and climatic properties in each basin. The low-flow statistics analyzed are the annual minimum 7-day mean low flows at the 2-year and 10-year recurrence intervals (7Q2 and 7Q10), which are commonly used in planning and design studies. The basin properties measured included (1) the areal extent of till, fine-grained stratified drift, several categories of coarse-grained stratified drift, alluvium, lakes, and swamps; (2) the length and slope of the main stream channel; and (3) the average annual precipitation, annual runoff, and elevation. The hydrologic significance of these basin properties was evaluated through multiple-regression analysis. That is, the amount by which each basin property improved the accuracy of low-flow estimation by regression equations was taken as a measure of the effect of that property on ground-water discharge to streams. Several regression equations are presented to illustrate the effects of particular properties or computational transformations. Four equations that performed well in statistical tests of accuracy and reliability are proposed as a practical means of estimating low flow at sites where streamflow has not been measured.

SPATIAL VARIABILITY OF LOW FLOWS OF STREAMS IN CENTRAL NEW ENGLAND

In most of central New England, the lowest streamflows each year occur in late summer or early fall. These low flows normally increase downstream as drainage area increases. The rate of increase is seldom uniform, however; low flow per square mile can differ greatly from one stream reach to another or from one drainage basin to another, in response to local differences in environmental characteristics or conditions. The following sections describe expected effects of several environmental characteristics on low flow, cite studies that demonstrate the importance of



EXPLANATION

BOUNDARY OF STUDY AREA, REFERRED TO AS CENTRAL NEW ENGLAND

▲39 STREAMFLOW-GAGING STATION--Number is site number, listed in tables 7-8. Stations 18 and 44 were not included in the data set for regression analysis, but their low flows are shown in figure 4.

Figure 1. Location of central New England and of streamflow-gaging stations selected for analysis of low flow.

some of these characteristics, and present some striking examples of differences in flow from one drainage basin to another that can be explained by the distinctive characteristics of individual basins.

Environmental Characteristics That Cause Variability

Differences in several geologic, climatic, and hydrographic characteristics from one place to another in central New England affect the magnitude of low flow. These characteristics are illustrated in figure 2, and the manner in which each affects low flow is explained below.

Water Availability

Low flows consist of ground water discharged from aquifers in the drainage basin and, thus, are in part a function of the magnitude of ground-water recharge. The amount of water potentially available for ground-water recharge annually is equal to precipitation minus evapotranspiration and is approximately equal to annual runoff (Lyford and Cohen, 1988). In some localities, however, where the water table is at land surface seasonally or perennially, water available for recharge cannot infiltrate into the already-saturated ground to become recharge; instead, it runs off promptly. One way to conceptualize the processes of recharge and rejected recharge is to treat water

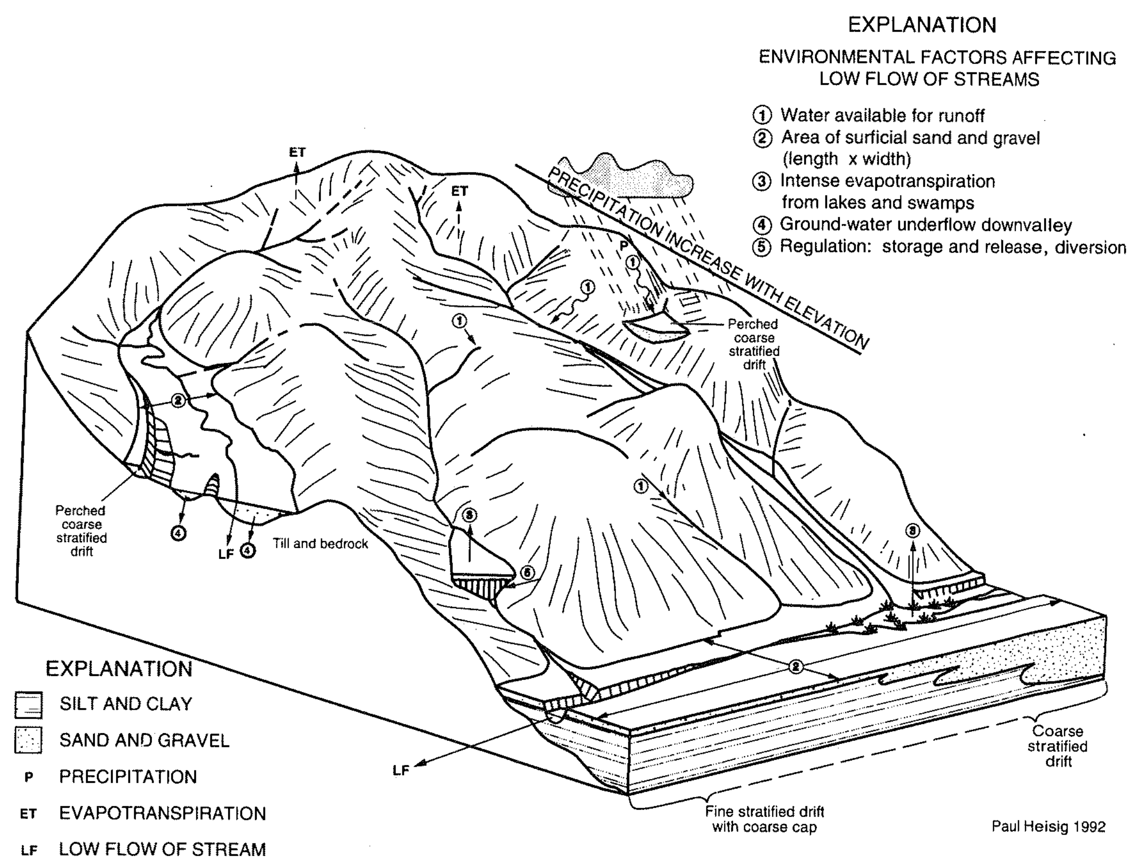


Figure 2. Idealized representation of environmental properties that affect low flow in central New England.

availability as a positive influence on low flow and express its regional variability by contours, while treating geologic or hydrologic properties that locally prevent or limit recharge as separate negative or less positive influences. As explained below, lakes and swamps in central New England correlate negatively with the magnitude of low flow, and till correlates less positively than sand and gravel, partly because appreciable recharge in till areas is rejected. Ground-water discharge during periods of low flow is affected by year-to-year differences in water availability, as evidenced by the correlation of annual low flows with annual precipitation (fig. 3), and also by differences in water availability from basin to basin as a function of elevation, orographic factors, storm tracks, and latitude. Annual precipitation, annual runoff, and basin elevation commonly correlate with each other and with low flow and thus serve as convenient indices of water availability. Seasonal water-availability terms such as summer precipitation minus evapotranspiration, or average summer runoff, might prove to correlate with low flow better than annual terms; nevertheless, these seasonal terms are less useful as indices of water availability because seasonal evapotranspiration is difficult to measure, and seasonal runoff is affected by local geologic and hydrographic properties as well as by the amount of water available.

Surficial Geology

The extent of surficial sand and gravel relative to the extent of till has a powerful effect on the magnitude and timing of ground-water discharge to streams. Surficial sand and gravel includes coarse-grained stratified drift deposited by glacial melt-water, and alluvium deposited by postglacial streams; some studies combine these units and

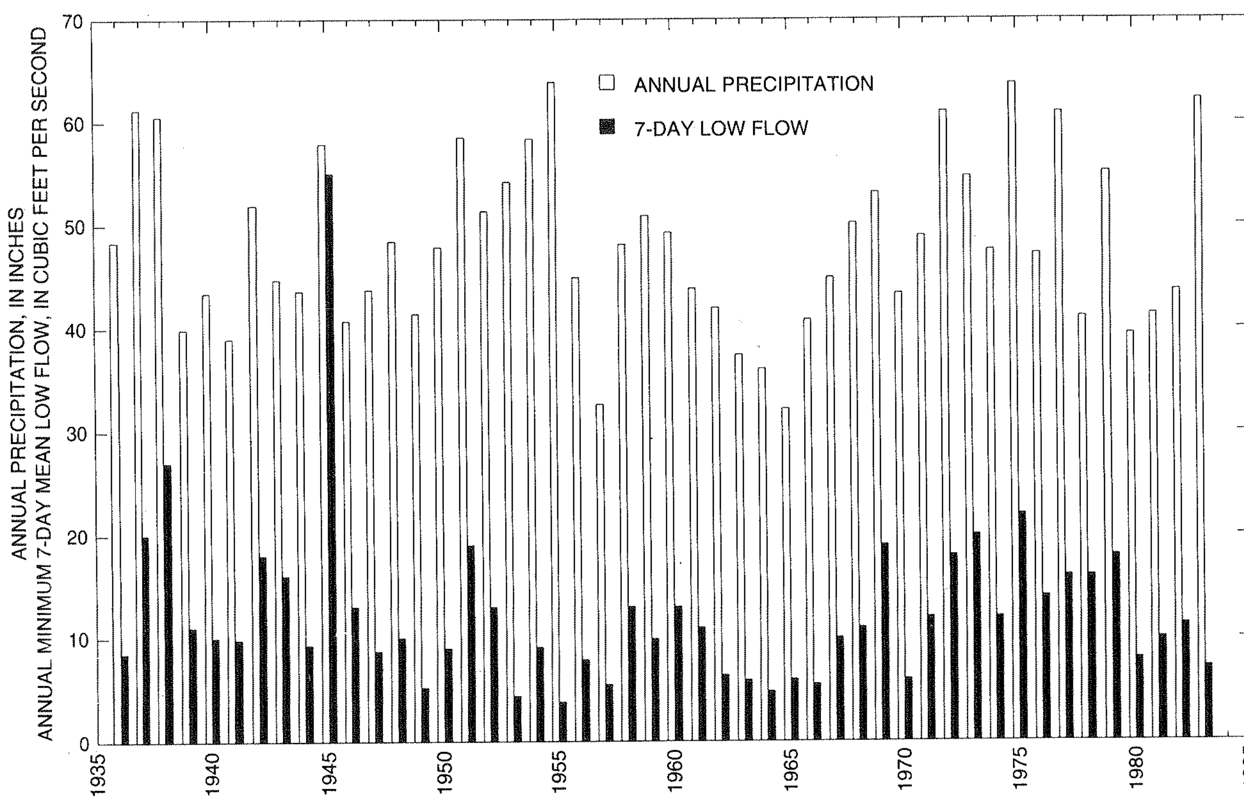


Figure 3. Annual precipitation and annual 7-day low flows for 1936-83 at a pair of sites in central New England. Low flows were measured in West Branch Westfield River at Huntington, Mass; precipitation was measured at Chesterfield, Mass., 11 miles north of Huntington. Site locations are shown in figure 1.

mention only the more abundant coarse stratified drift. The surficial till and the bedrock in uplands have only small capacities to store and transmit water; therefore, precipitation often results in saturation to land surface and thus in rapid runoff (Patric and Lyford, 1980; Newton and April, 1982; Dunne and Black, 1970). Surficial sand and gravel in valleys stores a large fraction of local precipitation and gradually releases this water to streams; it also stores and gradually releases some of the runoff from adjacent uplands (Morrissey and others, 1988). Therefore, most of the water carried by streams in central New England during low-flow periods consists of ground-water discharge from sand and gravel. The residence time of water and, thus, the rate of discharge during periods of low flow is affected by several properties of sand and gravel, including depth to the water table, transmissivity, elevation of the base of the sand and gravel with respect to streams, and extent or width of the sand and gravel deposits to either side of the streams. Accordingly, classification of surficial sand and gravel into categories on the basis of some of these properties might improve correlation with low flow. Two categories--alluvium (flood-plain deposits) and perched deposits (whose base is above streams)--were distinguished and tested in this study.

Lakes and Swamps

Lakes and swamps are found where the water table is at or above land surface and are generally areas of ground-water discharge. They can be expected to decrease low flow of streams for two reasons: (1) Where the water table is already at land surface, precipitation cannot infiltrate to become recharge, but instead becomes surface runoff immediately. (2) Ground water flowing toward stream channels may flow into lakes and swamps or may flow slightly below the surface of low-lying flood plains, all of which are areas of intense evapotranspiration during the growing season; consequently, a considerable amount of ground water that would otherwise contribute to streamflow is lost to the atmosphere.

Underflow

Where a stream channel is incised in till or bedrock, all runoff leaves the drainage basin as streamflow. Where the valley floor is underlain by coarse-grained stratified drift, however, some runoff is transmitted downvalley beneath the stream as underflow, and streamflow is correspondingly decreased. Rates of underflow through stratified drift at two sites in New York have been calculated: 0.33 ft^3/s in a valley 400 ft wide (Jacob, 1938) and 4.1 ft^3/s in a valley 3,500 ft wide (Randall and others, 1988b). Underflow of this magnitude would result in significant depletion of the low flow of small streams. The effect of underflow was not addressed in this study, however, because time was limited and because many of the streamflow-gaging stations selected for study were located near where bedrock outcrops extend across the stream channel and underflow is therefore likely to be negligible. Furthermore, indices of underflow devised in concurrent studies in New York were not consistently significant in regression analyses.

Bedrock

The igneous and metamorphic bedrock that underlies most of New England has been classified into many lithologic types (Zen, 1972), but hydraulic conductivity is similar in all these types and is much lower than that of the stratified drift (Randall and others, 1988a; Frimpter, 1972, p. 56). Therefore, areal differences in bedrock lithology seem likely to have only a small effect on rates of ground-water discharge to streams. To test this assumption, the percentage of each basin studied that is underlain by each of seven categories of bedrock was estimated from maps by Zen (1972). The categories, each of which included metamorphic equivalents, were: carbonates; calcareous sandstone; pelites; pelites mixed with carbonates; quartz sandstone, graywacke, and conglomerate; felsic gneiss, intrusives, and volcanics; and mafic gneiss, intrusives, and volcanics. A semiquantitative appraisal did not indicate any correlation between the percentages of basin area underlain by any of these bedrock categories and the residual variations in low flow not accounted for by water availability, surficial geology, or lake and swamp area. As pointed out by Denny (1982), however, differences in bedrock lithology are the underlying cause of major differences in elevation and relief that affect water availability; therefore, indices of water availability in regression equations might already have accounted for any areal variability in hydraulic properties of bedrock.

Some wells in New England, generally in valleys, have penetrated fracture zones and (rarely) solution cavities in bedrock that are capable of yielding a few hundred gallons per minute. Such features may constitute preferential paths for ground-water discharge from bedrock to streams, but probably the natural gradients and discharges are sufficiently small, scattered, and masked by subsequent flow through stratified drift that, for purposes of streamflow estimation, they can be considered as a uniformly distributed property of the bedrock.

Urbanization and Regulation

Land-use and water-use practices can strongly affect streamflow. Urbanization has been shown to increase storm runoff (Leopold, 1968; Pluhowski and Kantrowitz, 1964) and consequently to decrease ground-water discharge to streams, whereas urban wastewater discharges can augment streamflows (Singh and Stall, 1974). Regulation and diversion of streamflow can severely alter low flows. The drainage basins analyzed in this report were selected to avoid these manmade influences; large urban areas and regulated streams were excluded or, in one basin, regulation was adjusted for, as described later.

Previous Studies of Low-Flow Variability

Several studies have shown that water availability, areal extent of coarse-grained stratified drift, and areal extent of lakes and swamps are major determinants of spatial variability in low flow in the glaciated northeastern United States. Equations developed to estimate 7Q2 and 7Q10 low flows in the Susquehanna River Basin in New York (Ku and others, 1975) incorporate mean annual runoff and area of sand and gravel. An equation developed by Cervione and others (1982) uses the areal extent of coarse-grained stratified drift and the areal extent of till to estimate the 7Q10 low flow of streams in Connecticut; this analysis was an outgrowth of a study by Thomas (1966) that showed that the magnitude of streamflow exceeded for almost any specific percentage of time is a function of mean annual runoff and the areal extent of coarse-grained stratified drift. The equations developed by Cervione and others (1982) and by Ku and others (1975) have subsequently been improved through inclusion of the areal extent of lakes and swamps as an independent variable (Randall and Johnson, 1988). Lapham (1988) found that daily streamflows that are exceeded 90 to 99.9 percent of the time are strongly correlated ($R^2 > 0.84$) with the extent of stratified drift in seven gaged watersheds in and near the Taunton River Basin of southeastern Massachusetts, even though the seven watersheds were gaged for differing periods. Low flows per square mile in the Taunton Basin were smaller than those in Connecticut reported by Thomas (1966), perhaps because the Taunton Basin contains many large lakes and swamps. Barnes (1986) developed equations to estimate 7Q10 and 7Q2 low flow in eastern New York from mean elevation (or mean elevation and mean precipitation together) and areal extent of coarse stratified drift exclusive of swamps and lakes; the areal extent of urbanization proved not to be significant. Some of the studies cited above were designed to estimate low flow per square mile and therefore expressed the areal extent of geologic and hydrographic units as percentages of drainage-basin area.

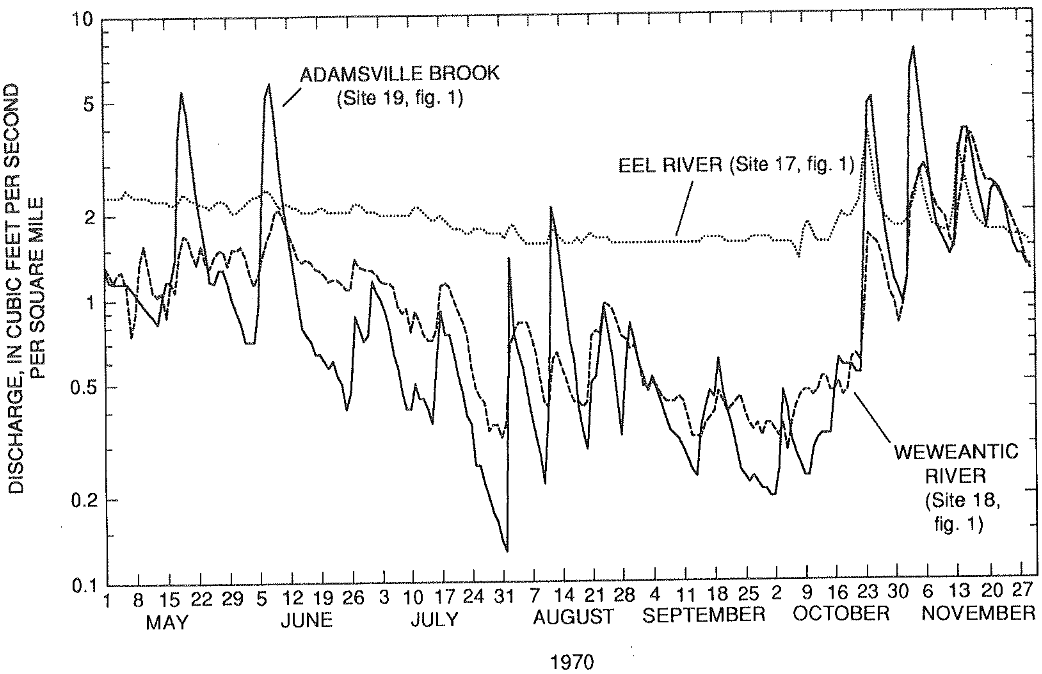
Two studies of low-flow variability in Massachusetts led to conclusions similar to those outlined above but represented surficial geology by a "ground-water factor" based on potential well yield. This factor was originally computed by Tasker (1972) from the areal extent of stratified drift plus till, divided according to potential well yield as shown on maps of southeastern Massachusetts by Williams and others (1973) and Williams and Tasker (1974a, 1974b); the factor is roughly proportional to the average transmissivity of glacial drift in each basin. The second study, based on a more diverse data set of 28 gaged basins throughout Massachusetts (Male and Ogawa, 1982), also found this ground-water factor to be significant in low-flow estimation equations, along with drainage area, annual precipitation, swamp and lake area, and other variables. Neither Tasker (1972) nor Male and Ogawa (1982) considered whether the correlation of low flows with their ground-water factor was better or worse than correlation simply with area of stratified drift or with other differently weighted indices of coarse stratified drift.

Several studies of streamflow in Vermont and New Hampshire have focused on the extent to which water availability controls low flows. Data from the Sleepers River drainage basin in northeastern Vermont, analyzed by M.L. Johnson (1970), show that low flow is positively correlated with mean annual runoff (a measure of water availability) and negatively correlated with areal extent of peat and clayey soils near streams (a measure of swamp area, in that the water table in these poorly drained areas is within 2 ft of land surface, even in summer). An investigation by DeAngelis and others (1984) in the same watershed concluded that annual or seasonal runoff is a function of elevation and found elevation to be strongly correlated with water input (precipitation plus snowmelt) in both wet and dry years. An increase in mean annual precipitation with increasing elevation was also documented by Dingman (1981) and by Knox and Nordenson (1955). Regression equations that use elevation and drainage area to estimate daily streamflows that are exceeded 95 percent of the time in New Hampshire and Vermont were presented by Dingman (1978, 1981). Dingman was unable to consider surficial geology in his regression analysis because adequate maps were not available, as reported by Ives (1977) in a preliminary study. An evaluation of the network of streamflow-gaging stations in Vermont, New Hampshire, Rhode Island, and Massachusetts by C.G. Johnson (1970) produced equations for estimating 7-day 2, 10, and 20-year low flows from drainage area, mean annual precipitation, and minimum January temperature. Other independent variables tested were main-channel length and slope, mean basin elevation, percent forest cover, percent lakes and ponds, maximum 24-hour rainfall, snowfall, and a soils index. The data base included 135 river basins ranging in size from 1.64 to 9,661 mi^2. Minimum January temperature probably functioned as a surrogate for other basin properties that affect low flow in summer, inasmuch as only a small fraction of the 135 basins would have experienced annual low flows in midwinter.

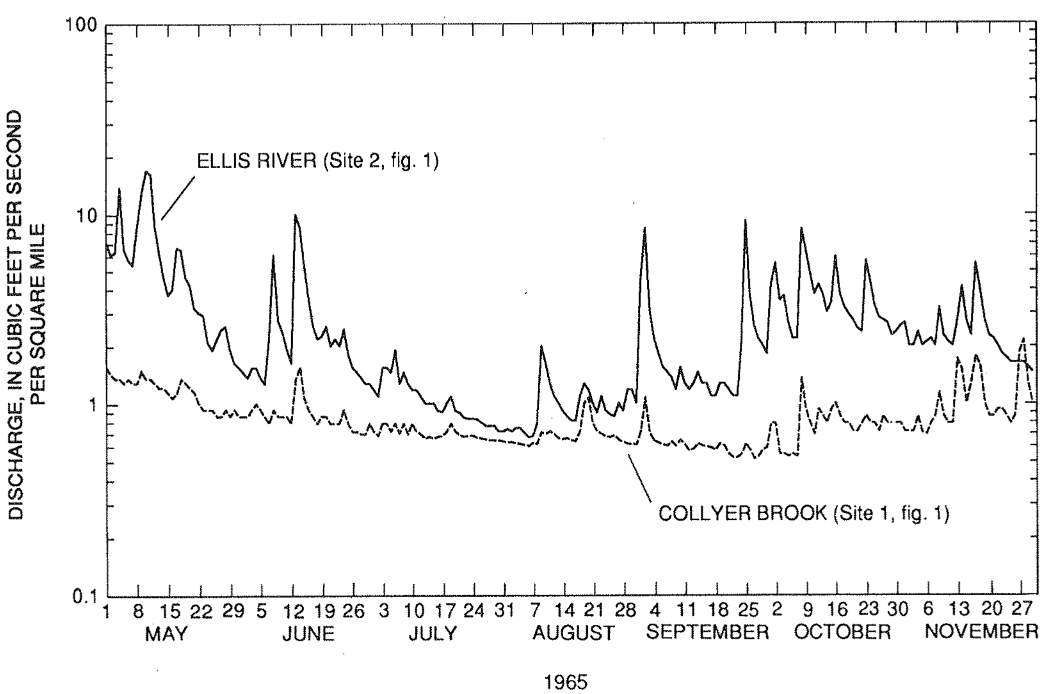
Examples of Low-Flow Variability

The sensitivity of low flows in central New England to some of the environmental characteristics discussed above is illustrated in figure 4. Three basins that are within 33 mi of one another in southeastern Massachusetts (fig. 4*A*) receive similar annual precipitation (Knox and Nordenson, 1955) and have similarly low relief--but nevertheless differ greatly in day-to-day variability of flow and in magnitude of low flow per square mile. The Eel River Basin is underlain entirely by sand and gravel in which the water table is deep enough to allow unrestricted infiltration of rainfall and storage of large volumes of water for discharge to the stream at a steady rate that results in a small range in daily flows (fig. 4*A*). By contrast, streamflows in Adamsville Brook Basin are highly variable because only 10 percent of the basin is underlain by sand and gravel; the remainder is bedrock mantled by till, both of which have such small infiltration, storage, and transmitting capacities that the amount of water stored underground during storms is small and its rate of flow toward streams is slow (fig. 4*A*, table 1). The Weweantic River Basin is underlain largely by sand and gravel, like the Eel River Basin, but has highly variable flow and small low flow per square mile, like the Adamsville Brook Basin (fig. 4*A*). This apparent inconsistency is explained by the closely spaced streams and the large areas of swamps, cranberry bogs, lakes, and ponds in the Weweantic Basin; the percentage of this basin that is underlain by sand and gravel that is unsaturated near land surface and can store more water during storms is estimated to be much closer to that of the Adamsville Brook Basin than to that of the Eel River Basin (table 1). According to the "variable-source-area" concept of streamflow generation (Freeze and Cherry, 1979, p. 218-221; Dunne and Black, 1970), hydrograph peaks can be attributed to precipitation on swamps and saturated soil whose areas increase during storms and decrease thereafter; precipitation on saturated materials cannot infiltrate and is discharged as storm runoff, and thus is not available later to sustain low flows. Regulation of lakes and ponds in connection with the commercial operation of cranberry bogs also affects daily streamflow in Weweantic River Basin.

Low flows per square mile in the basins of Collyer Brook in Maine and Ellis River in New Hampshire are similar in magnitude (table 1, fig. 4*B*) and exceed those of most streams in central



A. Three basins in southeastern Massachusetts, 1970.



B. Two basins in Maine and New Hampshire, 1965.

Figure 4. Hydrographs of daily streamflow from two sets of basins that are near one another but differ greatly in environmental properties.

Table 1. Selected physical characteristics and low flows for two basins in northern New England and three basins in southeastern Massachusetts

[Dash indicates data not available or not compiled]

Characteristic	Stream and site number in figure 1				
	Collyer Brook (1)	Ellis River (2)	Eel River (17)	Weweantic River (18)	Adamsville Brook (19)
Drainage area (square miles)	14.1	10.2	15.1[b]	56.1	8.01
Main-channel slope (feet per mile)	26.0	555	17.0	--	32.2
Mean basin elevation (feet)	350	3,260	134	--	140
Average monthly precipitation (inches):					
May through November 1965	2.69	6.38	--	--	--
May through November 1970	3.34	7.10	--	--	--
Percentage of basin area underlain by:					
Till	38	97	0	10[c]	90
Till and fine stratified drift	49	97	0	10[c]	90
Coarse stratified drift (sand and gravel)	51[a]	3	100	90[c]	10
Swamps and lakes	6.4	<.1	9.0	65[c]	15
Minimum daily flow (cubic feet per second per square mile):					
1965	.51	.77	--	--	--
1970	.85	.49	1.36	.29	.14
Annual minimum 7-day mean low flow, 10-year recurrence interval (cubic feet per second per square mile)	.56	.50	1.18	--	.01

[a]Includes some fine material with a coarse cap.
[b]Determined from ground-water divide indicated by water-table map for Plymouth-Carver area (Hansen and Lapham, 1992).
[c]Estimated.

New England (table 8, at end of report). The two basins are quite different from each other, however, and the reasons for their large low flows are different. Collyer Brook drains a gently sloping basin that contains extensive coarse stratified drift (51 percent of basin area) whose ground-water storage provides abundant discharge to sustain low flows. Ellis River has little stratified drift but has much more water available because it drains an area of high elevation on the eastern slopes of Mount Washington, where seasonal and annual precipitation are correspondingly high (tables 1 and 8). Although the low flows of these two streams per square mile are remarkably similar, maximum daily flows, average flow, and flow variability are all much greater in the Ellis River than in Collyer Brook (fig. 4*B*) because the Ellis River Basin has greater land slope and stream gradient as well as greater water availability.

QUANTITATIVE ANALYSIS OF THE EFFECTS OF SURFICIAL GEOLOGY, LAKES AND SWAMPS, ANNUAL WATER AVAILABILITY, AND RELATED VARIABLES ON LOW FLOWS

To quantify the extent to which low flows in central New England are affected by the environmental characteristics described in the preceding sections, a set of drainage basins representative of the range of conditions in the region was selected, and the 7Q2 and 7Q10 low-flow statistics were computed for each basin. Several environmental characteristics of each basin were measured and correlated with the low-flow statistics, as described further on.

Selection of a Representative Set of Basins

Continuous records of daily streamflow from 274 basins in central New England are available as a product of agreements between the U.S. Geological Survey and State, Federal, and local agencies. The following criteria were used to select the set of basins whose low flow was analyzed in this study:

1. Drainage area is less than 200 mi^2 because considerable effort would be required to compile the physical characteristics of large basins and because low-flow-estimating equations are generally applied to small basins or small segments of larger basins;
2. Streamflow records represent essentially natural (unregulated) flow during low-flow periods or, if flow was regulated, they can be adjusted to represent natural flow through analysis of records from before or after the period of regulation or by correction for the effect of known regulation;
3. Streamflow records are adequate for computation of low-flow statistics;
4. Surficial geologic maps are readily available from published or unpublished sources or can be prepared during the project; and
5. Basins include a range in magnitude of physical characteristics such as elevation, extent of stratified drift relative to drainage area, and abundance of lakes and swamps.

Application of these criteria led to selection of 49 basins. Table 7 (at end of report) identifies these basins and summarizes for each the period of streamflow record and the availability of geologic maps. The location of each gaging station is shown in figure 1. Three stations (nos. 5, 17, and 20) that have short daily-flow records were included in the data set because their basins exemplify particular geologic or hydrographic characteristics. Daily-flow records for these stations were supplemented with discharge measurements at times of base flow.

A lack of surficial geologic maps was a major constraint on this study. Surficial reconnaissance maps of parts or all of 24 basins were prepared during this study, but 21 basins that met the other criteria were excluded from the data set because surficial geologic maps could not be made available.

Information on the extent of streamflow regulation was obtained from water-resources data reports issued annually by the U.S. Geological Survey, from Knox and Soule (1949), and from the station descriptions on file in the New England offices of the U.S. Geological Survey. Most gaged basins in eastern Massachusetts were excluded from the data set because low flow is affected by regulation, diversions, or withdrawals for municipal supplies. An additional four basins in Massachusetts were not considered because they were included in the data set for a concurrent study of low flow in Connecticut.

Computation of Low Flows From Streamflow Records

The first step in analyzing low flows from basins in the data set was to decide what time period should be represented, as explained below. Then, 7Q2 and 7Q10 low-flow statistics were computed and adjusted to represent natural flow for that period, as described in the next two sections.

Selection of Reference Period

As the length of streamflow record increases at a site, accuracy of the computed low-flow statistics also increases, but at a progressively decreasing rate (Benson and Carter, 1973). At least 30 years of record is considered desirable for estimation of 7-day 10-year low flows, and analysis of the relation of low flow to basin properties is facilitated if all records represent the same 30 years. Wet years tend to follow one another, as do dry years (fig. 3), so two 30-year periods that fail to coincide by only a few years might have significantly different exposure to climate cycles.

Selection of a representative 30-year reference period for this project was complicated because many of the 49 stations in the data set were operated for differing periods that only partly coincide, and several stations had less than 30 years of record through 1983 (table 7, at end of report). To facilitate selection of a reference period, low-flow statistics were computed for two 30-year periods (1942-71 and 1951-80) and for the period of streamflow record at each of 31 long-term gaging stations in central New England, seven of which had more than 60 years of record through 1983. As shown in table 2, the 1951-80 flow statistics are essentially the same as those for the long-term records (about 3 percent less flow), and the 1942-71 period was almost as close (8 percent less flow). Either period was considered sufficiently representative of long-term conditions for purposes of this study. The 1942-71 period was selected to facilitate eventual comparison of results with the results of similar studies in Connecticut and the Susquehanna River Basin of New York. The 1942-71 period had been used for analysis of low flow in Connecticut (Cervione and others, 1982; R.L. Melvin, U.S. Geological Survey, written commun., 1983) and coincides with most streamflow records in the Susquehanna River Basin (Eissler, 1979). Records that did not cover this entire period were adjusted to 1942-71 by correlation of annual low flows from the entire period of record through 1983, a procedure that made full use of the observed data, as described in the next section.

Methods Used to Compute Low-Flow Statistics

Estimates of the 7Q2 and 7Q10 low-flow statistics for the 49 stations in the network are listed in table 8 (at end of report). Estimates for long-term gaging stations were obtained from low-flow frequency curves that were based on an analysis of historic daily flows. Estimates for other stations were obtained by correlation with selected long-term stations. Most of the procedures used are explained by Riggs (1972) and summarized by Wandle (1983). A mathematical procedure developed by Stedinger and Thomas (1985) was also used.

A 7-day mean low-flow value was computed for each year of the 30-year reference period from records of daily flow at each of 17 long-term gaging stations. A frequency analysis of these low flows was done through the Geological Survey's National Water Data Storage and Retrieval System (WATSTORE). Computer program A969 (Meeks, 1984) compiles and ranks the annual mean low-flow values and inputs these data to program A193, which fits a Pearson Type III distribution to the logarithms of the 7-day mean low flows, then calculates and plots the coordinates of a theoretical

Table 2. Differences between low-flow statistics for long-term periods of record and those for two 30-year periods of record at 31 gaging stations in central New England

[Difference was computed for each station with the equation: D = 100 (QP-QLT)/QLT, where D = Difference, QP = Low flow for 30-year period, and QLT = Low flow for period of record]

30-year period	Low-flow statistic[a]	Difference from long-term period, in percent		
		Range[b]	Mean	Median
1942-71	7Q2	-24.5 to 6.7	-9.2	-9.3
	7Q10	-35.6 to 24.5	-7.1	-6.4
1951-80	7Q2	-21.9 to 8.9	-3.0	-1.8
	7Q10	-32.6 to 33.1	-3.9	-4.1

[a]7Q2, 7Q10 = Annual minimum 7-day mean low flows that recur once in 2 years, or 10 years, on the average (0.5 and 0.1 nonexceedance probabilities).

[b]For 1942-71, 7Q2 and (or) 7Q10 were higher than for long-term periods at only 5 of 31 stations; three of these were ultimately excluded from the data set, and at the remaining two the low flows were no more than 0.2 cubic foot per second higher than for long-term periods. For 1951-80, differences greater than +10 percent or +2.5 cubic feet per second were recorded only at the same three stations that were excluded from the data set.

frequency curve. An example of such a curve is shown in figure 5. Each Pearson Type III curve was examined for goodness-of-fit, especially to the lower half of the observed data. According to Riggs (1971, 1972), visual confirmation of the mathematically derived Pearson Type III curves is an essential part of an analysis of frequency of annual low flows, and if the theoretical curves do not fit the data adequately, they should be revised graphically. A smooth curve was drawn by hand to replace the Pearson Type III curve for one of the 49 stations in the data set.

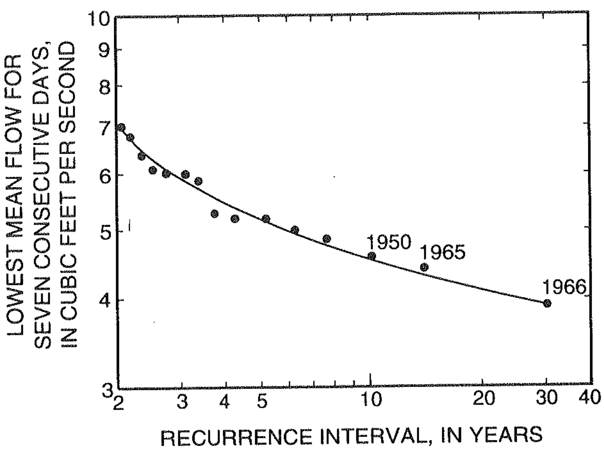


Figure 5. Seven-day low-flow frequency curve for North Branch Hoosic River at North Adams, Mass., 1942-71.

Low-flow statistics for 27 gaging stations that were operated for only part of the 30-year reference period were adjusted to 1942-71 by graphical correlation with index stations, as recommended by Riggs (1972). Data for the entire period of record through 1983 or 1984 were used in this correlation. Index stations were selected from a correlation matrix of concurrent 7-day mean low flows for stations on unregulated streams. The long-term station that had the largest product-moment correlation coefficient with respect to a particular short-term station was selected as the index station, and a log-log plot of observed 7-day low flows for all concurrent years of record at that pair of stations was prepared. A line of relation was drawn that gave more weight to the lowest data points than to others. The line was used to transfer the base-period low-flow statistics for the index station to the short-term station, as shown in figure 6. In this example, 7Q10 at the index station, West Branch Westfield River, is 5.0 ft^3/s; the corresponding 7Q10 value at the short-term station, Bassett Brook, is 0.45 ft^3/s.

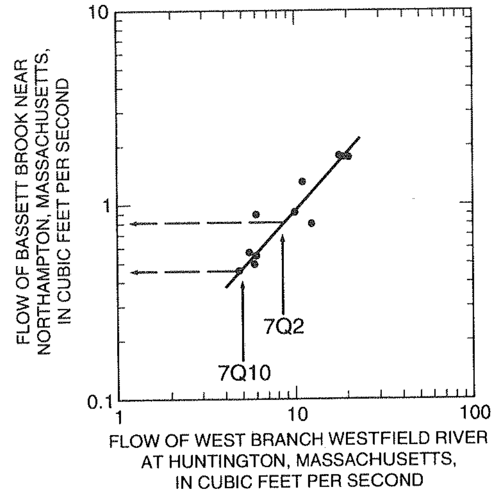


Figure 6. Relation between annual mean 7-day low flows at an index station (West Branch Westfield River) and those at a short-term station (Bassett Brook). Locations are shown in figure 1.

Low-flow statistics for five short-term stations were adjusted to the reference period through a mathematical technique developed by Stedinger and Thomas (1985) that requires a minimum of 10 base-flow values at a site and provides an unbiased estimator for low flows. Base-flow values were obtained from the daily flow hydrograph for dates that were at least 5 days after rainfall or from discharge measurements made during periods of low flow outside the period of daily-flow record. In this technique, the mean and variance of the annual 7-day low flows and the Pearson Type III standard deviate (K) at the site are used to calculate the 7-day low-flow statistics. The mean is computed from the linear relation between the base-flow measurements and daily mean flow at an index station, which ideally should have basin characteristics similar to those of the short-term site. The variance is computed from an estimator that incorporates statistics from the linear relation, number of base-flow measurements, and statistics for the 7-day low flow and concurrent daily mean flow for the index station. The skew coefficient for the index station is assumed equal to that for the short-term site. This technique was applied to Branch Brook, Eel River, and Fall Brook (stations 5, 17, and 20, fig. 1 and table 2), each of which had less than 2 years of daily flow record in addition to base-flow measurements. It was also applied to Ellis River and Big Brook (stations 2 and 27), where graphical correlation of annual low flows proved unreliable because the data were widely scattered.

Near the northern or northeastern border of central New England, prolonged periods of subfreezing temperatures in midwinter can result in low flows that are comparable in magnitude to the lowest observed in July through October. Thus, the annual minimum 7-day low flow in some basins can occur in the winter in some years. Annual 7-day low flows occurred in the winter in some years in only four of the basins analyzed in this study, however, and in three of these, the 7Q2 and 7Q10 low-flow statistics were obtained by correlation with records of streams unaffected by winter minima. Therefore, the data set is essentially a statistically homogeneous population representative of seasonal summer and fall low flows, and is also representative of annual low flows except locally on the northeastern fringe of the study area.

Adjustments to Eliminate Effects of Regulation

The natural flow of streams can be altered by man's activities, especially during low-flow periods. Some streams or adjacent aquifers are tapped as supplemental sources of water when the demand is great, generally during low-flow periods in summer or fall and especially during severe droughts. Most of the many artificial lakes and run-of-the-river impoundments such as mill ponds in central New England are used to periodically impound water and release it from storage, and some facilitate interbasin transfers of water. Many of these occurrences are of such small duration or magnitude that they do not significantly affect 7-day mean low-flow values, which are much less sensitive to unusual regulation than 1-day or instantaneous minimum flows. Longer occurrences of regulation and diversion are usually documented with the streamflow records for the gaging station and are apparent as outliers on the frequency plot of low-flow values and on the daily-flow hydrograph. Because the data set for this study was designed to represent natural streamflow, all stations affected by regulation or diversion were excluded except for one, whose streamflow record was adjusted as follows.

The Souhegan River (site 13 in fig. 1) was subject to intermittent diversions to an adjacent basin for municipal supply of Nashua, N.H., during periods of low flow in the late 1960's. The recession in daily flows of Souhegan River in late September 1964 was much more abrupt than concurrent recessions of nearby streams. Plots of daily flows of the Souhegan River against flows of three nearby streams indicated several periods in 1964 in which the Souhegan River's observed flow should be adjusted upward by an average of 4.6 ft^3/s to represent natural flow. This increased the observed 7-day mean low flow in late September from 8.6 ft^3/s, which had been the annual minimum, to 13.2 ft^3/s; a 7-day mean low flow of 12.8 ft^3/s recorded earlier in September then became the annual minimum. At the time of this study, the only records available for diversions in the summer and fall of 1965, 1966, 1969, and 1970 were monthly pumpage totals, but daily pumpage data were available for diversions in August and September 1971. The 1971 records and correlations of daily flows with other streams for all these years indicated that diversions from the Souhegan River took place for several successive days followed by several days without pumping; therefore, natural flows could not be reconstructed by averaging monthly pumpage over 30 (or 31) days and increasing all observed flows by that amount. Comparison of daily flows of the Squannacook River (site 14, fig. 1) with those of the Souhegan River indicated that the natural minimum 7-day mean low flow of the Souhegan River during the periods of diversion would exceed 13 ft^3/s. The two lowest annual 7-day low flows used to prepare the frequency curve were 11.0 and 12.8 ft^3/s, which occurred in 1963 and in 1964 before the diversions.

Measurement of Environmental Characteristics of Basins in the Data Set

A total of 21 geologic, topographic, climatic, and streamflow characteristics were measured during this study or were compiled from previous studies for each of the 49 basins in the data set. The topographic, climatic, and streamflow characteristics are listed in table 8 (at end of report), and the areal extent of surficial geologic units, lakes, and swamps in each basin are listed in table 9 (at end of report). These areas were measured on the best topographic and geologic maps available by a standardized procedure designed to ensure consistency and accuracy. Areas were measured directly in square miles by an electronic table digitizer calibrated with the appropriate scale factor. A stable scale was used to verify the scale of the map being digitized. The perimeter of each map unit was traced at least twice. If the resulting areas were nearly identical, the average value was used; if they were not, additional run(s) were made to obtain consistent readings, and the results were averaged. The area of the drainage basin as traced on the geologic map was measured as a check on the scale factor and compared with the drainage area measured in previous U.S. Geological Survey studies. A difference of 2 percent or less between the drainage area measured on the geologic map and the value previously obtained was acceptable. Where this criterion was not met, the drainage divide was redrawn on recent topographic quadrangle maps, and the drainage area was recomputed.

Surficial Geology

Maps that show the areal extent of surficial geologic units in many parts of central New England, at scales ranging from 1:24,000 to 1:62,500, were obtained from a variety of sources or were prepared during the study. Sources of geologic data for each basin in the data set are indicated in table 7 (at end of report).

Areas underlain by till were distinguished from those underlain by stratified drift on all maps. Several types of stratified drift were also delineated to the extent feasible during reconnaissance mapping or through reinterpretation of existing maps, and regression analysis was used to determine whether these types differed significantly in their low-flow yield to streams. The areal extent of each geologic unit delineated in each basin is compiled in table 9 (at end of report). The units are designated by the following names and abbreviations and are defined as follows:

Till (TL).--An unsorted sediment of low permeability made up of stones embedded in a matrix that ranges from silty sand to silty sandy clay. It is interrupted in places by large or numerous bedrock outcrops. Most basins contain large areas of till that surround much smaller areas of other surficial units; in such basins the till area was calculated as the basin area minus the sum of the measured areas of the other surficial units.

Constructional topography (CNTP).--Positive landforms (knolls, ridges, terraces) suggestive of stratified drift or known to be underlain by stratified drift but covered by till.

Coarse normal stratified drift (CSNO).--Coarse-grained stratified drift composed of layers ranging from gravel to very fine sand. Includes all surficial coarse-grained stratified drift not classified in any of the following categories.

Coarse perched stratified drift (CSPR).--Coarse-grained stratified drift whose base is above the stream surface profile (and which therefore lacks appreciable saturated thickness). Many of the surficial sand and gravel deposits in mountainous areas of Vermont, New Hampshire, and western Massachusetts are readily identified as being above the stream surface profile; for example, isolated ice-contact deposits perched high on the valley sides, perhaps deposited at a time when meltwater drained through saddles far above the valley floor, and kame terraces at lower altitudes but incised by postglacial streams to the point that till or bedrock is exposed at the base of the terraces and above the stream. Springs commonly emerge at the base of such deposits. Because these perched coarse stratified deposits have a thick unsaturated zone and much smaller saturated thickness than the normal coarse deposits and alluvium that underlie the valley floors, the temporal distribution of ground-water discharge from the two units may differ. Parts of the extensive coarse stratified drift in southern and coastal New England are also thinly saturated and perched above streams, but the distinction cannot be made reliably without extensive well data. Therefore, most coarse stratified drift in these areas of low relief was classified as coarse normal.

Alluvium (AL).--Stream alluvium underlying modern flood plains or alluvial fans; does not include stream terraces higher than the modern flood plains. Alluvium was distinguished from coarse stratified drift, despite the similarity of their hydraulic properties, because the water table lies at shallow depth in areas of alluvium and thus large evapotranspiration was thought to be typical. Alluvium is delineated on most surficial geologic maps, but in a few basins its areal extent had to be inferred through inspection of topographic maps.

Coarse cap (CSCP).--Several feet of fine to very coarse sand to gravel, capping thick, fine-grained stratified drift similar to the fine-drift unit. Although these deposits generally underlie low terraces, the base of the coarse-grained cap is commonly above stream grade.

Fine drift (FD).--Clay, silt, and (or) very fine sand, extending from land surface to substantial depth; does not include flood plains capped by a few feet of overbank silt. Very fine to fine sand layers are a large component of the upper part of the fine drift in many localities, but deltas that contain much fine to very fine sand and little or no finer sediment were mapped as coarse stratified drift.

Lakes and Swamps

The areas occupied by lakes, ponds, and swamps in each basin were generally measured on topographic maps. If a surficial geologic map delineated swamp deposits in localities where the topographic map did not indicate swamps, these deposits were included as swamp areas. Areas of water bodies and swamps were compiled in six categories according to the principal surficial geologic unit that borders and presumably extends beneath each area; the six categories are listed below, and the area in each category within each basin is given in table 9 (at end of report).

- Swamps underlain primarily by till and bedrock.
- Swamps underlain by coarse-grained stratified drift.
- Swamps underlain by fine-grained stratified drift.
- Lakes or ponds underlain primarily by till and bedrock.
- Lakes or ponds underlain by coarse-grained stratified drift.
- Lakes or ponds underlain by fine-grained stratified drift.

In this report, the areas of geologic units that lie beneath swamps, lakes, and ponds are included in the total areas compiled for those geologic units. For example, if a drainage basin of 4 mi^2 were underlain entirely by till, half of which is shown as swamp on topographic maps, table 9 would list the till area as 4 mi^2 and swamps underlain by till as 2 mi^2.

The study plan contemplated combining alluvium with surface-water and swamp areas in most regression analyses; therefore, the few small swamps and lakes within flood plains were not measured separately. The only topographic maps available for some parts of Vermont and New Hampshire were at a scale of 1:62,500 and were published between 1923 and 1957. Presumably some small swamps and lakes that would show on 1:24,000-scale maps do not appear on the 1:62,500-scale maps. This possible underrepresentation of water bodies and swamps in some basins could affect the regression analysis; therefore, recomputation of water and swamp areas as larger scale maps become available would be worthwhile. As a test, areas mapped as temporary or seasonal wetlands and as permanent or saturated wetlands on recent National Wetlands Inventory Maps prepared by the U.S. Fish and Wildlife Service were measured and compiled for 12 basins in the data set. In all 12 basins, the total of these wetland areas equaled or exceeded the total area of lakes and swamps delineated from topographic and geologic maps; the difference ranged from zero to 7.9 percent of basin area, or up to five times the wetland area shown on the topographic maps. Thus, the National Wetlands Inventory interpretation of wetland area is not only larger than indicated on topographic maps, but is also distributed differently. That interpretation was not evaluated as an alternative index of evapotranspiration in regression analysis during this study, however, because National Wetlands Inventory maps for basins in New Hampshire were not yet available.

Annual Water Availability and Topography

Several topographic and climatic characteristics were included in the data set because they were expected to represent water availability and (or) had been used in previous hydrologic analyses to explain variation in streamflow. These characteristics can be readily measured on topographic maps or calculated from published data tabulations, and remain reasonably stable through time. Most of these characteristics had been measured and compiled by C.G. Johnson (1970) or earlier by Langbein and others (1947) and Benson (1962). Updated values of some characteristics were obtained from Johnson and Tasker (1974) and Wandle (1982). The topographic and climatic characteristics used in this study are the following:

Drainage area (DA).--Area of drainage basin, in square miles, as measured on the most recent 1:24,000, 1:25,000, or 1:62,500-scale topographic quadrangle maps. Areas of basins in Massachusetts had recently been recomputed on 1:24,000-scale topographic maps and published in a nine-volume gazetteer (for example, Wandle, 1984). Drainage basins in other states were redrawn during this study wherever recent 1:24,000 or 1:25,000-scale topographic maps were available; otherwise, the areas previously delineated on 1:62,500 scale maps as part of the U.S. Geological Survey's stream-gaging program were used. Drainage areas were redrawn in accordance with the procedures of the U.S. Federal Inter-Agency River Basin Committee (1951), except in extensive areas of sand and gravel where topographic divides are of little hydrologic significance and the effective basin divides are ground-water divides. The Eel River Basin (site 17) is totally bounded by ground-water divides, which were defined from a map of the water table prepared as part of a ground-water investigation of that locality (Hansen and Lapham, 1992). Much of the perimeter of Branch Brook Basin (site 5) and small parts of the perimeter of a few other basins (sites 6, 13, 21, and 38) were sketched as ground-water divides primarily by interpolation between altitudes of perennial streams or ponds near the topographic divide.

Elevation (E).--Mean basin elevation, in feet above sea level, measured on topographic maps by laying a transparent grid over the basin, noting the elevation under each grid intersection, and computing the mean of all these elevations. The grid spacing is selected to provide at least 25 intersections within the basin.

Precipitation (P).--Mean annual precipitation for 1930-49, in inches, interpolated from a map by Knox and Nordenson (1955).

Mean runoff (QM).--Mean annual runoff, in cubic feet per second per square mile, calculated by two methods:

(a) Interpolation from a map of mean annual runoff for 1930-49 by Knox and Nordenson (1955) that is the most rigorously compiled map of its kind for New England. Knox and Nordenson (1955) related precipitation at many stations to altitude and other topographic factors and used that relation to draw lines of equal mean precipitation, which they compared with lines of equal mean runoff based on gaging-station records for the same period. Then, they adjusted both maps until the two sets of lines were consistent.

(b) Computation from streamflow records. For gaging stations operated throughout the reference period (1942-71), mean streamflows for those years were averaged. For other stations, annual mean flows were correlated with those at a nearby long-term station, and mean flows for the missing years or for the reference period were estimated from the correlation graph.

Method (b) was used for all basins in the data set that had at least 10 years of record through 1983. For the three basins with less record, values consistent with method (b) were estimated from a regression equation that related results of the two methods. Method (a) was used for all basins in the low-relief region of central New England (described later). Method (b) probably represents water availability in the data set more exactly than method (a) because each value was generated directly from data for that individual basin, without the errors due to extrapolation and interpolation that are inherent in preparing and later applying a regional map. If so, the effect of water availability on low flow could be more clearly evaluated through regression analysis with values generated by method (b) than with those generated by method (a). For regression equations to be of practical use, however, the explanatory variables must be regionalized by some means such as method (a). Thus, both methods are potentially useful.

Length (L).--Length of the main channel, in miles, from the gaging station or site of interest to the basin divide.

Slope (SL).--Slope of the main channel, in feet per mile, measured from elevations at points 10 percent and 85 percent of the distance along the main channel from the gaging station to the basin divide.

Latitude (LA).--Latitude of stream-gaging station, in decimal degrees, as measured on topographic maps.

Longitude (LO).--Longitude of stream-gaging station, in decimal degrees, as measured on topographic maps.

Application of the Multiple-Regression Technique

Multiple regression can be used to analyze and quantify the relations between low flows at gaged sites and a suite of basin characteristics. Multiple regression is a statistical technique that estimates values of a dependent variable as a function of values of two or more independent variables. It is based on a criterion of minimizing the squares of the differences between observed and predicted values of the dependent variable. The massive computations required in regression analysis are done quickly by computer through programs available in statistical software packages. The task of the investigator is to (1) select and measure a set of independent variables expected to be significantly correlated with the dependent variable, (2) select a suitable form(s) of the estimating equation, and (3) test for the presence of correlation among independent variables or other violations of hydrologic and statistical practice. Differences between observed and estimated values of the dependent variable (residuals) are analyzed in an effort to detect causal factors not yet represented among the variables. Alternative ways of manipulating or expressing the independent variables can sometimes remove the correlation among these variables or improve the fit of the regression equation.

Standard multiple-regression techniques were used in this study to define the relations between 7-day mean flows at the 2- and 10-day recurrence intervals (the dependent variables) and various combinations of basin characteristics (the independent variables). Forward stepwise multiple linear-regression procedures (P-Stat Inc., 1985) were used in the initial regression analyses. Because forward stepwise procedures do not always achieve optimum selection of independent variables, later regressions were run to test specified sets of variables and data manipulations that were of interest. Independent variables that were significant at the 0.05 level were retained in the equations; that is, the regression coefficient of each independent variable in the equations has at least a 95-percent probability of being significantly different from zero. Statistical indices of fit and of correlation of independent variables, influence of individual data points, and normality of residuals were computed and used along with plots of residual error against predicted low flows to evaluate how well the tested equations explained the observed variation in low flows and met the statistical assumptions of regression analysis. Fractional-power and logarithmic transformations of independent and dependent variables were each tested in several equations, while other equations used natural (untransformed) values.

A suite of 21 measured basin characteristics was tested in the multiple-regression analysis. All 21 are listed in tables 8 or 9 and defined in the earlier section "Measurement of Environmental Characteristics of Basins in the Data Set." Several additional independent variables were devised by combining two or more individual measured basin characteristics. Conceptually, the low flow from a basin was expected to equal the sum of the following three components:

1. Yield from stratified drift: the area of stratified drift multiplied by a regression coefficient whose magnitude represents low flow per unit area from this terrane. The simplest approach was to combine all measured types of stratified drift into a single variable; alternatively, two or more variables were formed by selective combinations of types, or more complex variables were devised in which area was divided by stream length to test the effect of width or shape of stratified-drift deposits.
2. Yield from till: the area of till multiplied by a regression coefficient that represents low flow per unit area. Variables were devised that combined till with geologic units whose water-transmitting properties are similar to

those of till (fine-grained stratified drift and till-covered constructional topography).

3. Negative yield (that is, a decrease in streamflow or ground-water discharge) caused by evapotranspiration from areas where the water table is at or near land surface--wetland or lowland area multiplied by a regression coefficient that represents evapotranspiration per unit area. Combinations of variables tested included the area of all swamps and lakes, or only those surrounded by stratified drift, or only those connected to the stream network, or the area of swamps and lakes plus the area of alluvium.

Some index of water availability also was included in each equation. Mean annual precipitation, mean annual runoff, elevation, and elevation combined with latitude were tested as indices; all but the first of these incorporate, to some degree, the effect on water availability of average basinwide evapotranspiration. Water-availability terms were conceptualized in two alternative ways. In some equations, they were treated as reservoirs or sources of low-flow yield independent of the geologic terms. In others, they were treated as weighting factors that were multiplied by the areas of geologic units to adjust low-flow yield from each geologic unit for annual water availability. Topographic characteristics thought to affect rates of runoff (stream slope and length) were also tested in some equations.

Streamflow is generally assumed to be a function of drainage area, among other factors. Drainage area is not used as an independent variable in the equations presented in this report but is indirectly incorporated in the geologic variables or in mean runoff. Simple regression of 7Q10 against drainage area alone, for the entire data set and each of the subsets described in the next paragraph, yielded coefficients of determination (R^2) of 0.45 to 0.52 and standard errors (S.E.) of about 4.5 ft^3/s, both inferior to results of regression equations presented further on that incorporate the concepts summarized above. Drainage area alone is not an adequate indicator of regional variations in low flows because the basin properties that affect low flows do not vary uniformly with drainage area.

Division of Central New England Into Regions of High and Low Relief

Early regression analysis that used the entire data set showed low flow to be significantly correlated with many basin characteristics, but coefficients of determination (R^2) were less than 0.83, and plots of observed low flow against estimated values showed excessive scatter. In streamflow-regionalization studies, scatter can sometimes be decreased if the study area is divided into two or more homogenous regions, even if the causes of scatter are not understood or not readily quantified (Riggs, 1973, p. 10-11; Wandle, 1977). This approach proved helpful in central New England, where geomorphology varies widely as a function of bedrock geology (Denny, 1982). Most of Vermont, central and northern New Hampshire, northwestern Massachusetts, and northwestern Maine comprise an upland of steep-sided mountains with gentle accordant crests and deep, narrow valleys (Denny, 1982, p. 3, p. 14; Fenneman, 1938, p. 349, p. 352). Coarse alluvium covers large parts of the valley floors; surficial stratified drift is relatively scarce, and part of it is perched on the valley sides above stream surface profiles. Upland tributaries with steep gradients are sustained by summer showers and seem to contribute a substantial fraction of summer runoff; undoubtedly they also contribute significantly to recharge of valley-fill aquifers (Morrissey and others, 1988). In contrast, Rhode Island, most of Massachusetts, coastal Maine and New Hampshire, and northwestern Vermont comprise an area of lesser relief, with lower summit elevations and smaller stream gradients (Denny, 1982, figs. 10-11). Stratified drift is relatively extensive, fills even moderately small valleys, and is continuous across many saddles between hills. Therefore, central New England was classified into regions of high and low relief according to a map by Denny (1982, fig. 10). Denny laid grid lines spaced 4 mi apart on 1:250,000-scale topographic maps with a contour interval of 100 ft and calculated a relief value for each grid block as the difference in altitude between the highest contour line in the block and the contour line next below the lowest in the same block. He contoured the relief values at a 200-ft interval and published the resulting map at a 1:4,000,000 scale with a metric contour interval.

In the present study, Denny's contours were used to define three relief zones: greater than 300 m, 300 to 200 m, and less than 200 m. The outline of each drainage basin in the central New England data set was overlain on Denny's map, and the percentage of the drainage basin in each relief zone was estimated. Thirty-five basins were entirely in the zone with relief greater than 300 m or the zone with relief less than 200 m, and 11 were mostly in one of those zones but partly in the intermediate zone. One basin (site 11, fig. 1) was entirely in the intermediate zone, however, and two basins (sites 37 and 45) had large percentages of their area in all three zones. The latter three basins were included in both regional data sets and proved compatible with both in regression analysis. A simplified version of Denny's map is presented as figure 7. The high-relief region in figure 7 is virtually the same as Denny's zone of more than 300-m relief, except that it omits a few small isolated areas of lower relief. The low-relief region combines all zones of less than 300-m relief as shown by Denny. Therefore, basins would be classified as high relief unless they lie almost entirely in the low-relief region shown in figure 7.

The fact that relief can be used to divide central New England into regions that are relatively homogeneous with respect to low flows does not necessarily mean that relief would prove equally useful as an independent variable in multiple-regression analysis. Any future effort to refine the interpretations in this report might, however, test various measures of maximum or average relief in regression equations as an alternative to division of the data set into regions of high and low relief.

Interpretation of Regression Equations

Equations developed from multiple-regression analysis of the high-relief data set are presented in table 3. Equations developed from the low-relief data set are presented further on in table 5. The hypothesis that residuals are normally distributed could not be rejected at the 0.05 alpha level for any of those equations, as indicated by R values of 0.966 or greater from correlation of the residuals with their normal scores (Ryan and others, 1985, p. 179; Looney and Gulledge, 1985, table D2). Regression coefficients for the terms in those equations are all significant at the 0.05 level. Each equation number refers to a specific array of independent variables and (or) scale transformations. The letter *A* or *B* after the number indicates that the particular equation estimates 7Q2 or 7Q10 respectively, but the equation number may be cited alone to refer to any equation(s) that incorporates that array of terms.

Accuracy of regression equations is expressed in tables 3 and 5 in terms of the standard error of estimate, the coefficient of determination or multiple R-squared (R^2), and the prediction-sum-of-squares (PRESS) statistic. Standard error of estimate is a measure of how well these equations reproduce the observed 7-day low-flow statistics. Standard error is defined as the standard deviation, adjusted for degrees of freedom, of the residual errors (differences between observed and computed values) about the regression relation used to compute the dependent variable. Coefficient of determination (R^2) is a measure of the variation in low flows explained by the basin characteristics in the equation. It represents the proportion of total variation in the dependent variable that is accounted for by the independent variables; a value of 1.0 indicates a perfect correlation. The PRESS statistic is computed by summing the squared residuals from equations defined by sequentially deleting each basin, redefining the regression equation without that basin, then calculating the residual for that basin. Graphs in which observed 7-day low-flow statistics are plotted against values estimated from regression equations also indicate the ability of regression equations to reproduce the observed 7-day low-flow statistics.

High-Relief Region

The equations in table 3, all developed from the high-relief data set, illustrate how various environmental characteristics or combinations thereof affect low flows. They also illustrate the effects of scale transformation and inclusion of particular basins in this data set of 26 basins. These two aspects are discussed in turn in the next two sections.

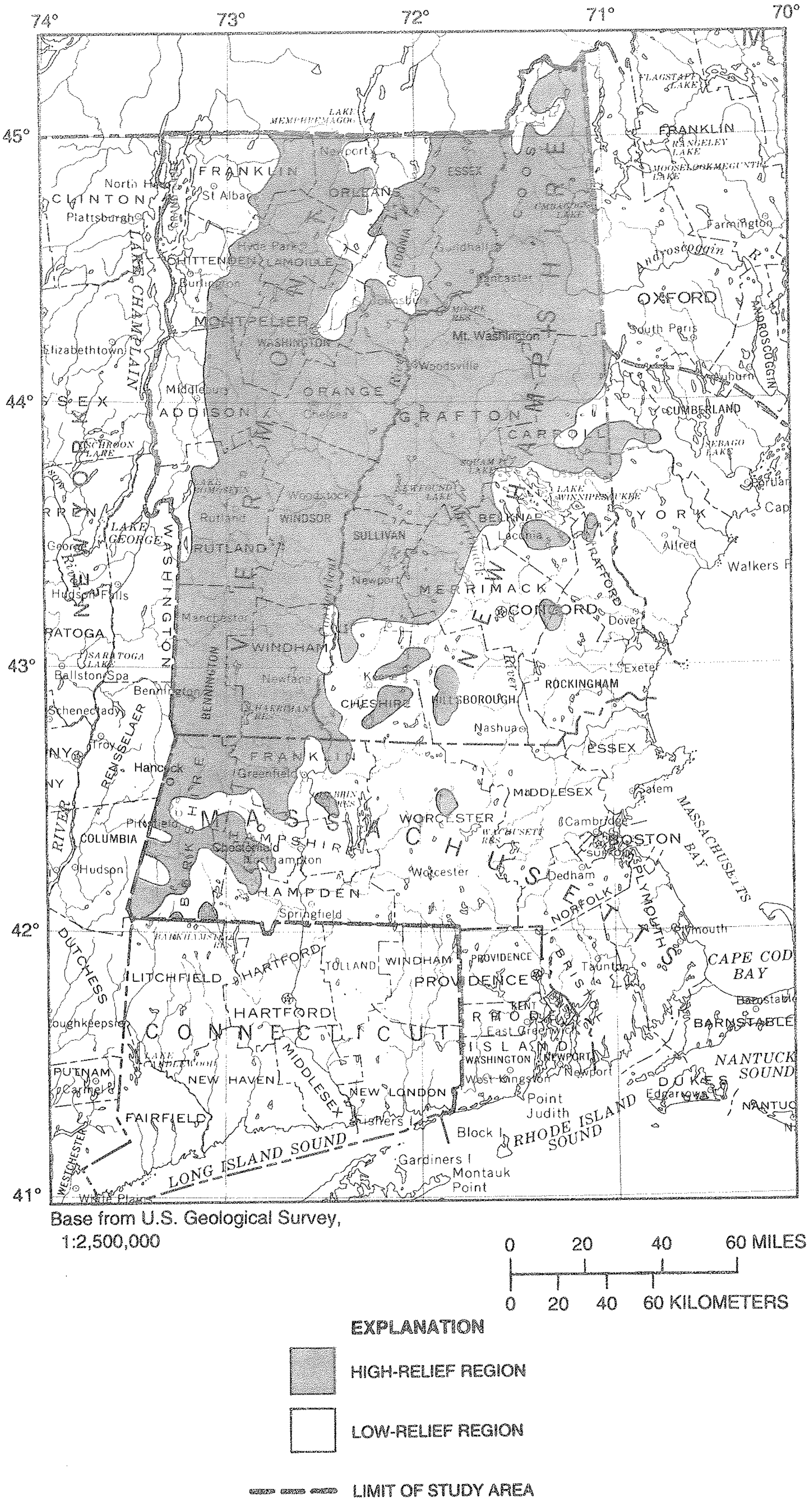


Figure 7. Locations of regions of high and low relief (region boundaries based on Denny,1982, fig. 10).

Table 3. Regression equations for estimation of low flows in the high-relief region of central New England

[Basin characteristics, on the right side of each equation, are aligned under generic column headings insofar as possible, to facilitate comparison of equations; the abbreviation for each characteristic is defined in the column head(s) to which the characteristic pertains. Arrow (←) means a characteristic pertaining to that column is part of a term in one or more preceding columns. Dash (--) means no characteristic pertaining to that column is included in the equation. Log means logarithm to the base 10. Location of the high-relief region is indicated in figure 7]

A. Regression Equations

Equation number	Low-flow statistic*		Regression constant	Area (square miles) underlain by: Till and fine-grained stratified drift — TL = Till; FD = Fine-grained stratified drift	Coarse-grained stratified drift — TCS = Total coarse; includes: AL = Alluvium; CSPR = Coarse perched; CSCP = Coarse cap; CSNO = Coarse normal	Terranes of high evapotranspiration — SL = Swamps & lakes (TSL = total; SLCS = in coarse stratified drift; SLTF = in till and fine drift); AL = Alluvium	Water availability — E = Elevation (feet above sea level); QM = Mean runoff per unit area (cubic feet per second per square mile)
1*A*	7Q2	=	-12.2	+0.13 TL	+0.73 TCS	--	+0.0070 E
1*B*	7Q10	=	-10.2	+.086 TL	+.55 TCS	--	+.0056 E
2*B*	7Q10	=	-5.94	--[a]	+1.47 TCS	-2.43 TSL	+.0038 E
3*A*	7Q2	=	-7.16	+.139 TL	+2.48 TCS	-4.33 (TSL+AL)	+.0044 E
3*B*	7Q10	=	-5.77	+.096 TL	+2.07 TCS	-3.78 (TSL+AL)	+.0034 E
4*B*	7Q10	=	-5.77	+.095 (TL + FD)	+2.06 TCS	-3.79 (TSL+AL)	+.0034 E
5*B*	7Q10	=	-6.11	+.083 TL	+2.66 (CSPR+CSCP) +1.49(CSNO+AL)	-2.82 (TSL+AL)	+.0036 E
6*B*	7Q10	=	-7.88	+.112 TL	+2.06 TCS	-3.88 (TSL+AL)	+3.55 QM
7*B*	$(7Q10)^{0.6}$	=	-1.16	+.032 (TL + FD)	+.44 TCS	-.78 (TSL+AL)	+.0010 E
8*B*[b]	$(7Q10)^{0.6}$	=	-1.42	+.033(TL + FD)	+.42 TCS	-.73 (TSL+AL)	+.0012 E
9*A*	$(7Q2)^{0.6}$	=	-1.12	+.034 (TL + FD)	+.37 (TCS-AL)	-.63 TSL	+.0012 E
9*B*	$(7Q10)^{0.6}$	=	-1.20	+.024 (TL + FD)	+.38 (TCS-AL)	-.70 TSL	+.0011 E
10*A*	$(7Q2)^{0.6}$	=	+.86	+.000026 (TL+FD-SLTF)(E)	+.00012 (TCS-AL-SLCS)(E)	←	←
10*B*	$(7Q10)^{0.6}$	=	+.46	+.000020 (TL+FD-SLTF)(E)	+.00012 (TCS-AL-SLCS)(E)	←	←
11*A*	$(7Q2)^{0.6}$	=	+.84	+.000024 (TL+FD)(E)	+.000090 (TCS)(E)	--	←
11*B*	$(7Q10)^{0.6}$	=	+.44	+.000018 (TL+FD)(E)	+.000092 (TCS)(E)	--	←
12*A*	log (7Q2)	=	-7.24	+1.08 log(TL+FD+4TCS)	←	--	+1.94 logE
12*B*	log (7Q10)	=	-9.64	+1.14 log(TL+FD+8TCS)	←	--	+2.54 logE

*7Q2 and 7Q10 are mean flows for 7 consecutive days that occur as the lowest 7-day mean flow in the year at an average frequency of once in 2 or 10 years, respectively.

[a]Tested but not significant at the 0.05 level.

[b]Equation based on 23 watersheds, excluding 3 of lesser relief; all other equations based on 26 watersheds.

**Computed as $100\{[1/(n-p-1)] \text{ sum } ([(qo - qe)/qo]^2)\}^{0.5}$ where qo = observed low flow, qe = low flow estimated by regression equation, n = number of basins, and p = number of independent variables in equation (G.D. Tasker, U.S. Geological Survey, written commun., 1990). Most of the standard error in percent is due to inaccurate estimation of three small low flows (see text).

†Percent error computed as 100[(qo - qe)/qo].

††The DFITS statistic is computed for each basin for each equation. It is a scaled measure of the change in the predicted value of the dependent variable for that basin that results from regenerating the equation after deleting data for that basin from the data set. The larger the value listed, the more influence a single basin has within its neighborhood of the data array.

[c]Value in parentheses computed after low flows estimated by the regression equation had been detransformed to cubic feet per second by raising to the 1.667 power.

[d]Value in parentheses computed after low flows estimated by the regression equation had been detransformed to cubic feet per second by taking the antilog.

Effects of Environmental Characteristics on Low Flows

Surflcial Geology

All types of equations tested were significantly improved when drainage area was replaced by two independent variablesarea of till and area of coarsegrained stratified drift. The percentage improvement was much greater for naturalvalue equations than for logarithmic equations, but all types of equations were consistent in indicating that, at 7Q10 low flow, groundwater discharge per square mile from coarse stratified drift is four to eight times that from till. This conclusion is based on (1) the ratios of regression coefficients for terms that include area of till and area of coarse stratified drift, respectively, in equations that do not have severe inflation of regression coefficients due to collinearity, and (2) the ratios of weighting factors for till and stratified drift within the complex expressions used in loganthmic equations. Accordingly, this geologic contrast is an essential component of general low4low estimating equations for this region, even though the percentages of basin area covered by coarse stratified drift are commonly small and are similar in many localities.

In equation 5 (table 3), the stratified drift is divided into two broad categories-deposits that extend below stream surface profiles (including alluvium) and deposits perched above streams. The perched category includes many thick but largely unsaturated deposits on the valley sides (referred to as coarse perched' in this report) and a few relatively thin stream-terrace and outwash deposits that cap finegrained sediments (referred to as coarse cap"). The deposits that extend below stream grade would include any productive

Table 3. Regression equations for estimation of low flows in the highrelief region of central New England--Continued

B. Statlstical Indlces Pertaining to Each Equatlon[e]

Equation number	Coefficient of determination (R^2)	Standard error of estimate (units of 7Q10 or 7Q2)	Standard error of estimate (cubic feet per second)	Standard error of estimate (percent)**	Median percent error of estimate†	Prediction sum of squares (PRESS) statistic	Maximum variance inflation factor	Maximum DFITS statistic††
1*A*	81.6		3.86	253	38	630	3.6	2.6
1*B*	75.1		3.36	676	63	533	3.6	3.3
2*B*	84.4		2.66	3226	51	277	2.4	2.8
3*A*	96.5		1.73	128	24	101	12.0	1.4
3*B*	95.3		1.49	353	22	91	12.0	2.9
4*B*	95.3		1.49	354	21	92	12.1	3.1
5*B*	95.7		1.46	311	38	98	26.4	3.2
6*B*	93.0		1.82	379	41	146	12.8	4.1
7*B*	93.9 (97.0)[c]	0.47	(1.20)[c]	(139)[c]	(23)[c]	(54)[c]	12.1	.94
8*B*	94.0 (97.2)[c]	.48	(1.21)[c]	(118)[c]	(31)[c]	(49)[c]	8.0	1.1
9*A*	93.6 (95.7)[c]	.56	(1.92)[c]	(108)[c]	(23)[c]	(136)[c]	6.2	1.5
9*B*	93.3 (95.7)[c]	.49	(1.43)[c]	(128)[c]	(24)[c]	(81)[c]	6.2	1.5
10*A*	87.5 (90.9)[c]	.75	(2.68)[c]	(121)[c]	(28)[c]	(240)[c]	3.4	.83
10*B*	85.8 (91.8)[c]	.69	(1.91)[c]	(263)[c]	(26)[c]	(113)[c]	3.4	.80
11*A*	87.2 (90.2)[c]	.76	(2.77)[c]	(115)[c]	(32)[c]	(236)[c]	4.2	.93
11*B*	85.1 (90.2)[c]	.70	(2.09)[c]	(1251)[c]	(30)[c]	(146)[c]	4.2	.90
12*A*	86.8 (82.3)[d]	.23	(3.85)[d]	(61)[d]	(30)[d]	(522)[d]	1.2	1.2
12*B*	77.1 (79.6)[d]	.35	(3.41)[d]	(167)[d]	(37)[d]	(448)[d]	1.2	.95

[e] The regression analysis included an incorrect estimate of 7Q10 for one station. Evaluation of this error (see page vi) suggests that the equations in this table estimate 7Q10 slightly better than the statistical indices presented here would indicate.

aquifers in the basins studied. Both categories are illustrated in figure 2. The ratio of regression coefficients for the two categories of coarse stratified drift in equation 5 indicates that the perched deposits yield more water per unit area than the deposits that extend below stream grade. Possible explanations for this finding include:

(a) Infiltration of precipitation through the thick unsaturated zone that is typical of most deposits perched on the valley sides can take several weeks or months and thereby delay ground-water discharge to streams.

(b) The alluvium and the upper layers of many coarse stratified-drift deposits on the valley floor include highly permeable gravel that may drain so quickly that little water remains in storage above the stream profile to augment low flow during long periods without recharge. By contrast, moderately permeable deposits perched above the stream profile have such a thin saturated zone that their transmissivity is small, and their ground water is likely to discharge to streams over a relatively long time span that includes periods of low flow. The improvement in fit that resulted from incorporating alluvium in the negative wetland-evapotranspiration term, discussed further on, may reflect slight ground-water discharge at low flow from the gravelly alluvium instead of (or in addition to) high evapotranspiration from flood plains.

(c) As relief increases, commonly an increased proportion of the stratified drift lies above stream profiles; thus, the "coarse perched" variable might actually function in regression analysis as a surrogate for some other aspect of watershed relief.

Despite the apparent contrast in low-flow yields from these two categories of stratified drift, equation 5*B* has only marginally better predictive capacity than equation 3*B*. Therefore, as a practical matter, the effort required to distinguish the two categories is probably not justified for purposes of low-flow estimation.

Fine-grained stratified drift is more like till than like coarse-grained stratified drift in grain size and hydraulic properties and, therefore, could reasonably be combined with till for purposes of regression analysis. This combination causes little change in regression coefficients or statistics (compare eq. 4 with eq. 3). The high-relief region contains only small areas of fine drift, however, and these are restricted to a few basins. Therefore, regression equations might be insensitive to low-flow yield from fine-grained stratified drift. Equations 7 through 12 also combine fine-grained stratified drift with till.

Lakes, Swamps, and Related Indices of Evapotranspiration

Areal extent of lakes and swamps is significantly and negatively correlated with low flow (eq. 2 in table 3). Combining the area of alluvium with that of lakes and swamps improved the statistical indices of fit and the significance of regression coefficients (compare eq. 3 with eq. 2, and eq. 11 with eq. 10). This improvement is consistent with the hypothesis that large evapotranspiration from low-lying flood plains as well as from swamps and lakes can significantly decrease low flow, but might also be explained by rapid drainage of ground water from alluvium before periods of low flow, as discussed earlier in the section on surficial geology.

Terms that combine alluvium with lakes and swamps are strongly correlated with geologic terms representing sand and gravel because both terms tend to increase with increasing drainage area and because area of alluvium is a major component of both terms. In many of the narrow valleys of the high-relief region, the area covered by flood plains and alluvial fans nearly equals or even exceeds the area covered by surficial coarse-grained stratified drift and, at the same time, may equal or exceed the area of swamps and lakes in the watershed. The strong correlation, or collinearity, is confirmed by variance inflation factors (Montgomery and Peck, 1982, p. 299) between 12 and 26 in equations 3 through 7 (table 3), all of which combine alluvium with swamps and lakes. Equation 9*B* (table 3) differs from equation 7*B* only in that 9*B* does not include alluvium in either the coarse stratified drift or the evapotranspiration term; this change substantially improves collinearity but slightly degrades statistical indices of fit.

If two explanatory variables in regression equations have a strong linear correlation with each other, their regression coefficients are likely to be inflated and to have large variances, although the equation may nevertheless predict well within the range of the data (Montgomery and Peck, 1982, p. 292-3; SAS Institute, 1982, p. 54). Comparison of equations in table 3 suggests that incorporation of an evapotranspiration term inflates the apparent low-flow yield from sand and gravel relative to that from till while substantially improving fit. For example, equation *1B* implies that 7Q10 per unit area of coarse stratified drift (TCS) is 6.4 times that per unit area of till (0.55/0.086 = 6.4), whereas equation *3B*, which differs only in including an evapotranspiration term, implies that the low-flow contribution from coarse stratified drift is 21.6 times that from till. A similar contrast is evident between equations 9 and 11.

The effect of evapotranspiration from lakes, swamps, and flood plains on low flow is less than that of coarse stratified drift and was not significant in some equations tested. Its effect may have been limited by the range and precision of basin characteristics in the data set. The area covered by swamps and lakes did not exceed 6 percent in any basin and was less than 2 percent in 21 of 26 basins. Also, a few basins were delineated on 15-minute topographic maps, whose scale may have precluded showing small swamps or lakes.

Annual Water Availability

Elevation, precipitation, and mean annual runoff per square mile were tested as indices of water availability and performed similarly. Elevation proved superior in terms of standard error and other statistical indices (compare eq. 6 with eq. 3) and therefore was used in most regression equations presented in table 3.

Because elevation (or mean runoff per square mile) is treated as an independent term in equations 1 through 9 (table 3), its contribution to estimated low flow would be the same in all basins of the same elevation, regardless of basin area. The effect of basin area is incorporated in the geologic terms. A more plausible treatment would be to compute low flow as the product of water availability times basin area--that is, as elevation (or mean runoff per square mile) multiplied by the area(s) of one or more geologic units. Equations 10 (table 3, fig. 10) and 11 (table 3) treat elevation in this way. They have favorable statistical indices of collinearity and influence but do not estimate low flow as well as equation 9.

Effects of Scale Transformations and Data Distribution on the Interpretation

Fractional-Power Transformations

Scale transformations are often applied to the independent and (or) dependent variables in regression analysis to make the relation linear and the residual variance constant (Montgomery and Peck, 1982, p. 89). In equation *7B*, the 0.6 power of 7Q10 is estimated from the same untransformed basin properties that were used to estimate 7Q10 in equation *4B*. The transformation decreased the influence of the larger values, as indicated by the DFITS statistic (table 3) and by the spacing of data points in figure 8. Statistical indices of fit for natural and transformed equations are differently scaled and hence not directly comparable, but when equation *7B* is detransformed by raising estimated 7Q10 values to the 1.67 power, the coefficient of determination and standard error (shown in parentheses in table 3) indicate a better fit than comparable values for equation *4B*. Fractional-power transformations of equations 1 through 6 generally gave similar results.

Influence of Large Low Flows

Low flows from three basins are considerably larger than the rest and thus have a potential for large leverage or influence on the placement of the least-squares regression line. When observed low flows are plotted against estimated low flows, however, the large values generally fall close to the projection of a line drawn through the more numerous smaller values (figs. 8-10). This consistency indicates that the equations apply reasonably well to both large and small low flows. The DFITS statistic, defined in table 3, measures the influence of individual basins; most equations are subject to much greater than average influence from two to five basins, as indicated by absolute values of DFITS greater than 0.9 for those basins. Only one of the three basins with large low flows (Ammonoosuc River, site 28) is consistently among the influential basins, however. Thus, inclusion of the large low flows in the data set apparently did not seriously distort the regression equations.

The variance among residuals for the three large low flows is commonly smaller than the variance for lesser flows (figs. 8, 9). Constant variance

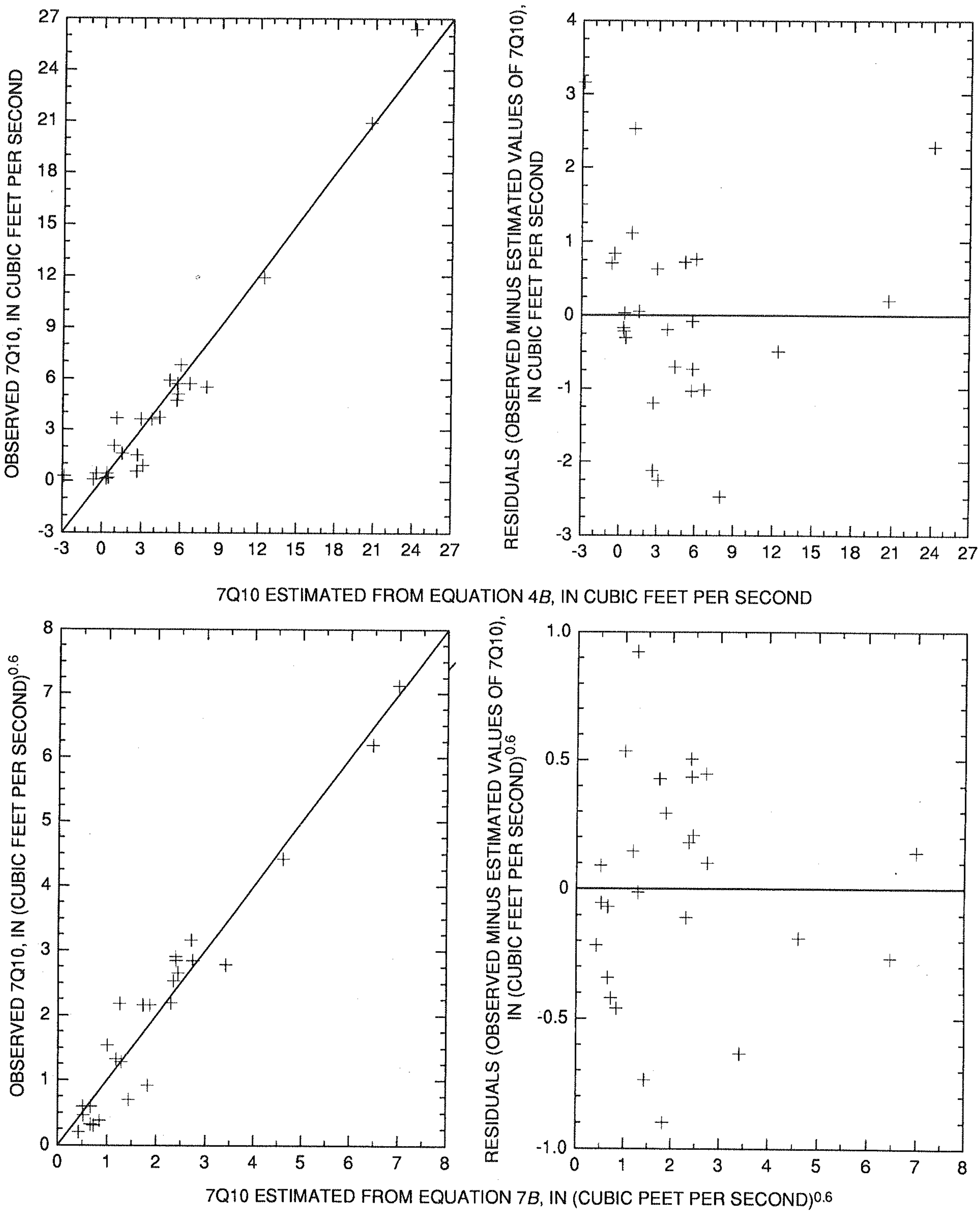


Figure 8. Annual minimum 7-day mean low flows at 10-year recurrence interval (7Q10) in the high-relief region of central New England, as estimated from equation 4*B* (top) and equation 7*B* (bottom), in relation to observed 7Q10 and to the residual differences between estimated and observed 7Q10. Equations are given in table 3.

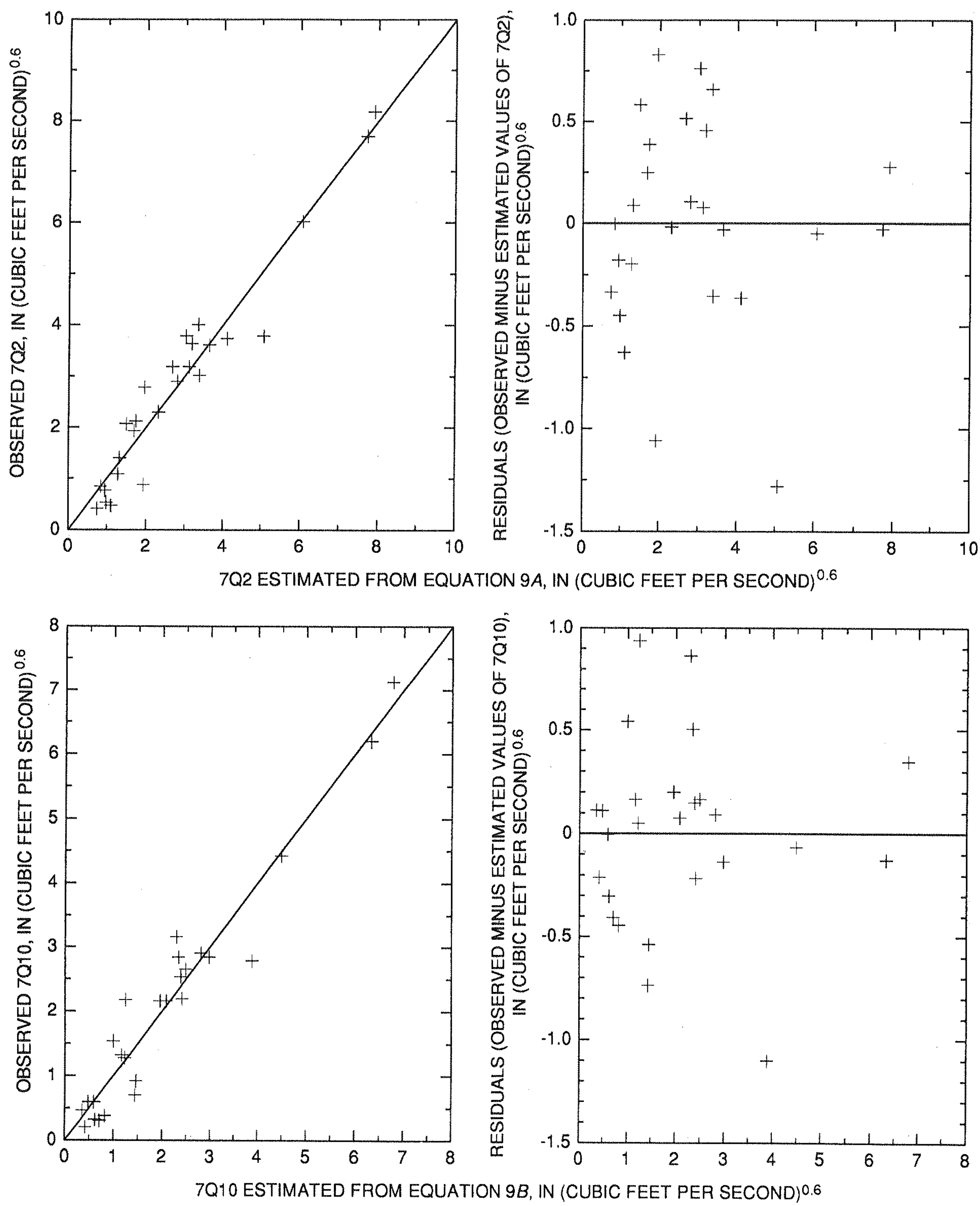


Figure 9. Annual minimum 7-day mean low flow at 2-year and 10-year recurrence intervals (7Q2, 7Q10) in the high-relief region of central New England, as estimated from equations 9*A* (top) and 9*B* (bottom), in relation to observed values and to the residual differences between estimated and observed values. Equations are given in table 3.

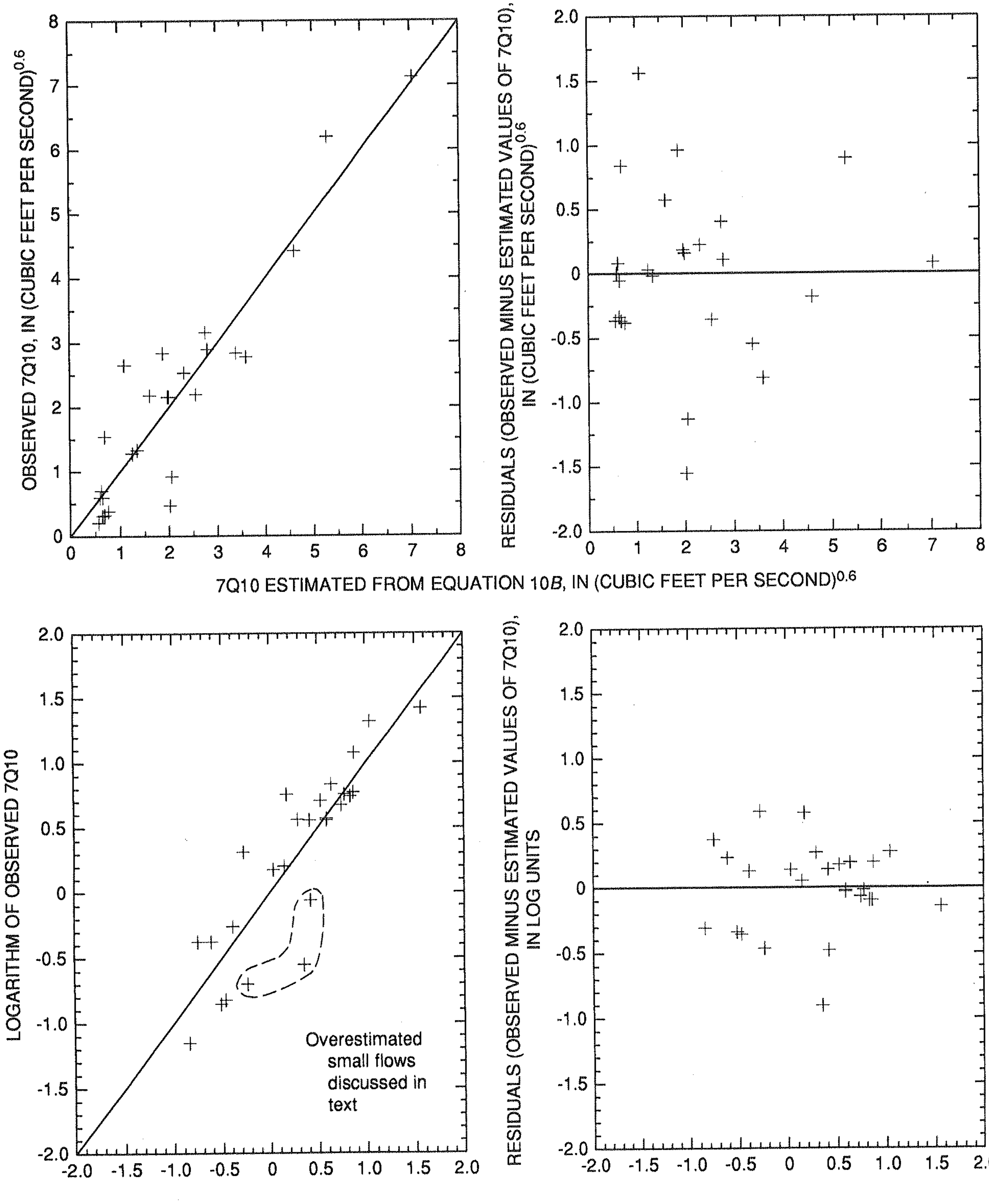


Figure 10. Annual minimum 7-day mean low flows at 10-year recurrence interval (7Q10) in the high-relief region of central New England, as estimated from equation 10*B* (top) and 12*B* (bottom), in relation to observed values and to the residual differences between estimated and observed values. Equations are given in table 3.

is a basic assumption of least-squares regression, and its absence can impair the validity of statistical tests (Iman and Conover, 1983, p. 369). The low standard errors for equations 7 and 9 (table 3) are in part a reflection of an excellent fit to the three largest values (figs. 8, 9). Therefore, a question arises as to whether these statistics overstate the ability of the equations to estimate low flows in general. To answer this question, data for the three basins whose observed low flows exceeded 11 ft^3/s were deleted from the array of values estimated by equations 9*A* and 9*B*, and standard errors were recomputed. The recomputed standard errors were 0.60 and 0.52, respectively, or 2.03 ft^3/s and 1.45 ft^3/s after detransformation. These results were nearly the same as those based on all 26 basins (table 3) and were smaller than comparable values given by most other equations. Therefore, the degree of heteroscedasticity in equations 9*A* and 9*B* (fig. 9) is probably not a serious problem.

Logarithmic Transformations

Many investigators have transformed data to logarithms before regression analysis to improve the statistical properties of the data set. Male and Ogawa (1982, p. 29), however, present and cite evidence that natural-value equations are probably superior to logarithmic transformations as a means of estimating short-term low flows, including 7-day mean flows. Barnes (1986) found that low flows in eastern New York could be estimated more accurately by natural-value equations than by logarithmic transformations, and Cervione and others (1982) used natural-value equations to estimate low flows in Connecticut. Furthermore, logarithmic transformations of the high-relief data set for central New England could cause conceptual and practical difficulties. In this report, low flow is conceptualized as the sum of contributions from several terranes (till, stratified drift, and subdivisions thereof) minus the amount lost by evapotranspiration from several terranes (lakes, swamps, flood plains). This concept is not expressed or evaluated by ordinary logarithmic equations, which equate low flow to the *product* of several basin properties, each raised to some power. Also, logarithmic equations are sensitive to very small values of low flows or basin properties and to the magnitude of arbitrary constants that must be added to all values to permit logarithmic transformation of zero values. Many of the individual basin properties in the high-relief data set are zero or very small in some basins (table 9).

A form of logarithmic equation was developed that avoids both of these difficulties. It can be expressed in general terms as follows:

$$\log(\text{low flow}) = a \log(p A_1 + qA_2 + ... rA_n) + b \log(\text{water input}),$$

where a and b are regression constants;

p, q, and r are weighting factors; and

A_1, A_2, and A_n are the areas of selected basin terranes or properties.

Equation 12 (table 3, fig. 10) is the best of several equations of this form that were tested. Translated to natural values, equation 12*B* becomes:

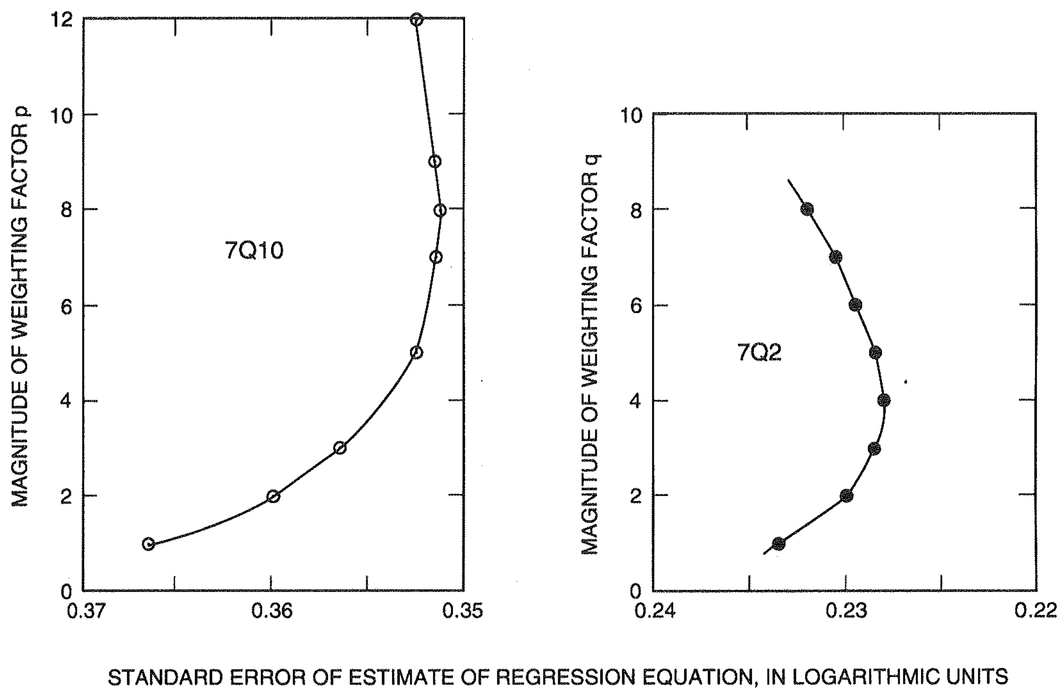
$$7Q10 = (0.229 \times 10^{-9}) [(TL + FD + 8TCS)^{1.14} (E)^{2.54}],$$

where TL is area of till; FD is area of fine-grained stratified drift; TCS is area of coarse-grained stratified drift; and E is elevation.

Equation 12 is conceptually reasonable in that each geologic terrane is weighted according to its contribution to low flow as determined by regression analysis. The weighting factor of 8 applied to coarse-grained stratified drift is that which minimized the standard error of estimate of the regression equation, as determined through trial and error (fig. 11). Logarithmic equations included in the basin-terrane term the area of lakes and swamps and (or) alluvium with various negative weights were also tested; none of these trials lowered the standard error significantly, however.

Equation 12 is reasonable also in that low flow is proportional to the product of elevation, which represents water input, and area of each relevant geologic terrane. Furthermore, adjustments to avoid zero values or unduly influential very small values are not needed because elevation cannot approach zero in the high-relief region, and although the areas of some geologic terranes could approach zero, the area term in this particular equation is a sum that equals or exceeds basin area.

Equation 12 meets statistical requirements for collinearity and influence statistics (table 3). Residuals have an approximately normal distribution and are reasonably homoscedastic (fig. 10). Statistical indices of fit, however, in log units or detransformed to natural values (table 3), are less impressive than corresponding statistics for equations 3 through 11. Comparison of residuals for



EXPLANATION

⊙ log (7Q10) = a log[TL + FD + (p)TCS] + b log(E)

● log (7Q2) = c log[TL + FD + (q)TCS] + d log(E)

where

a,b,c,d = coefficients fitted by regression analysis;

p,q = weighting factors that represent the ratio of low flow per square mile from coarse stratified drift to that from till and fine stratified drift;

TL = area of till;

FD = area of fine stratified drift;

TCS = area of coarse stratified drift;

E = mean basin elevation; and

7Q2,7Q10 = mean flows for 7 consecutive days that occur as the lowest 7-day mean flow in the year at an average frequency of once in 2 or 10 years, respectively.

Figure 11. Standard error of logarithmic regression equations for high-relief region of central New England as a function of weighting factor applied to area of coarse stratified drift.

individual basins after detransformation to cubic feet per second indicated that equation 9*B* estimates the three largest low flows far better than equation 12*B*, by an average of 7.1 ft^3/s or 41 percent. Equation 9*B* also estimates 7Q10 values smaller than 12 ft^3/s and smaller than 1 ft^3/s slightly better than equation 12*B*, by an average of 0.15 ft^3/s for each group of 7Q10 values.

Influence of Small Low Flows

The relatively poor fit of equation 12 results from the relatively large influence of basins whose 7Q10 is less than 1.0 ft^3/s. The high-relief data set includes nine such basins (fig. 8), which span 50 percent of the data range in logarithmic equations (fig. 10) but only 13 percent of the data range in fractional-power equations (figs. 8 through 10) and 4 percent in natural-value equations (fig. 8). Among these nine basins, 7Q10 is only weakly correlated with till area and virtually uncorrelated with other basin characteristics tested (table 4). Among basins with large low flows, by contrast, 7Q10 correlates moderately well with area of coarse stratified drift and even better with the product of coarse stratified drift and elevation. The poor correlation among the small low flows might

Table 4. Correlation of selected basin characteristics with large and small values of annual minimum 7-day low flow at the 10-year recurrence interval (7Q10) in the high-relief region of central New England

Basin characteristic correlated with 7Q10 low flow[a]	Correlation coefficient (R) For 9 high-relief basins, 7Q10 less than 1.0 cubic foot per second	For 17 high-relief basins, 7Q10 more than 1.08 cubic feet per second	For all 26 high-relief basins
Elevation (E)	0.172	0.231	0.181
Coarse-grained stratified drift (TCS)	.079	.652	.731
minus alluvium (TCS-AL)	.083	.646	.709
minus alluvium, lakes, swamps (TCS-AL-SLCS)	.101	.703	.757
minus alluvium, lakes, swamps; then multiplied by elevation (TCS-AL-SLCS)(E)	.147	.897	.908
Till (TL)	.510	.649	.711
plus fine drift, minus swamps, lakes; then multiplied by elevation (TL+FD-SLTF)(E)	.611	.870	.871

[a]Each basin characteristic or combination thereof is followed in parentheses by its abbreviation as used in regression equations in table 3.

reflect inaccuracy in the observed 7Q10 values, inasmuch as the observed values for seven of the nine basins were obtained by correlation because those basins have less than 10 years of record within the reference period. Alternatively, low flows in some of these nine basins might be significantly influenced by basin characteristics not tested, such as underflow. Three of the nine basins (sites 9, 29, and 43, table 9) have 7Q10 low flows that are only a small fraction of 7Q2. This behavior could result from unusually large underflow past the measurement site or from unusually large evapotranspiration. Low flows at all three sites (identified in fig. 10) are overestimated by equation 12 and most other equations, whereas low flows in the other six basins that have low flows of less than 1 ft^3/s are reasonably consistent with equation 12 and other equations.

Selection of Equations for Practical Application

Equation 8*B* incorporates the same drainage-basin properties as equation 7*B* but is based on a smaller data set of 23 basins. The three basins with intermediate relief (sites 11, 37, and 44 in fig. 1) were excluded. Equations 7*B* and 8*B* have nearly identical regression coefficients and statistical indices of fit. Errors in estimating low flows from the three intermediate basins were within the range of error at the other 23 basins in all equations. Therefore, equations developed for the high-relief region can be used to estimate low flow on the fringes of the region regardless of what fraction of a basin lies within the region boundary shown in figure 7.

Equations 9, 10, 11, and 12 (table 3) are all reasonably suitable for estimating low flows at ungaged sites. Each is presented in versions *A* and *B* to estimate 7Q2 and 7Q10, respectively. Equation 9 represents the high-relief data set compiled for this report more exactly than the other equations, as indicated by the several statistics of fit after detransformation. This equation tends to overestimate low flow from very small basins, however, probably because the water-availability term (elevation) contributes equally to basins of all sizes. Equations 10 through 12 are conceptually superior to equation 9 in that they make the effect of water availability proportional to area; also, they are less influenced by collinearity and by individual basins. Equations 11 and 12 are easier to use than equations 9 and 10 because they do not require measurement of lake, swamp, and alluvium areas. Equations 10 and 11 seem to underestimate low flow from high-altitude watersheds, however, for reasons not understood. Future reevaluation of the data set could perhaps improve the fit of these conceptually advantageous equations. Equation 9 was selected to illustrate estimation of low flow at ungaged sites further on in this report because it fits the available data more closely than the other equations.

Low-Relief Region

The equations in table 5 were developed from the low-relief data set of 26 basins and illustrate

Table 5. Regression equations developed for estimation of low flows in the low-relief region of central New England

[Basin characteristics, on the right side of each equation, are aligned under generic column headings insofar as possible, to facilitate comparison of equations; the abbreviation for each characteristic is defined in the column head(s) to which the characteristic pertains. Arrow (←) means a characteristic pertaining to that column is part of a term in one or more preceding columns. Dash (--) means no characteristic pertaining to that column is included in the equation. Log means logarithm to the base 10. Location of the low-relief region is indicated in figure 7]

				A. Regression Equations			
				Area (square miles) underlain by:			
				Till and fine-grained stratified drift	Coarse-grained stratified drift	Terranes of high evapotranspiration	Water availability
Equation number	Low-flow statistic*		Regression constant	TL = Till FD = Fine-grained stratified drift	TCS = Total coarse stratified drift, including alluvium L = Stream length	SLCS = Swamps & lakes in coarse stratified drift AL = Alluvium DA = Drainage area	QM = Mean runoff per unit area (cubic feet per second per square mile) DA = Drainage area
13*A*	7Q2	=	+0.114	--[a]	+0.88TCS	--[a]	+0.35(QM-1.7)DA
13*B*	7Q10	=	+.037	--[a]	+.58TCS	--[a]	+.32(QM-1.7)DA
14*B*	7Q10	=	-.554	+0.12 TL	+1.08TCS	-3.24(SLCS+AL)	+.25(QM-1.7)DA
15*B*	7Q10	=	-2.91	+.22 TL	+8.36(TCS/L)	-1.57(SLCS+AL)	+.21(QM-1.7)DA
16*B*	7Q10	=	-2.88	+.13 (TL+FD) QM	+4.92(TCS/L)QM	-1.71(SLCS+AL)	←
17*B*[b]	7Q10	=	-2.79	+.14 (TL+FD)QM	+4.92(TCS/L)QM	-1.88(SLCS+AL)	←
18*B*	$(7Q10)^{0.75}$	=	-.088	$+.016\ (TL+FD)QM^2$	$+1.19(TCS/L)QM^2$	-14.0(SLCS+AL)/DA	←
19*A*	$(7Q2)^{0.75}$	=	-.076	+.037(TL+FD)QM	+3.01(TCS/L)QM	-18.1(SLCS+AL)/DA	← [c]
19*B*	$(7Q10)^{0.75}$	=	-.20	+.021(TL+FD)QM	+2.58(TCS/L)QM	-15.7(SLCS+AL)/DA	← [c]
20*B*	log (7Q10)	=	-2.98	+1.57log[TL+FD+6TCS-16(SLCS+AL)]		←	+4.13logQM[c]

*7Q2 and 7Q10 are mean flows for seven consecutive days that occur as the lowest 7-day mean flow in the year at an average frequency of once in 2 or 10 years, respectively.

[a]Tested but not significant at the 0.05 level.

[b]Equation based on 23 watersheds, excluding 3 of greater relief than the rest; all other equations based on 26 watersheds.

[c]Mean runoff interpolated from maps by Knox and Nordenson (1955); in other equations mean runoff was computed from records of runoff from each basin, adjusted to 1941-70.

**Computed as $100\{[1/(n-p-1)]\ \text{sum}\ ([(qo - qe)/qo]^2)\}^{0.5}$ where qo = observed low flow, qe = low flow estimated by regression equation, n = number of basins, and p = number of independent variables in equation (G.D. Tasker, U.S. Geological Survey, written commun., 1990). Most of the standard error in percent is due to inaccurate estimation of five small low flows (see text).

†Percent error computed as 100[(qo-qe)/qo].

††The DFITS statistic is computed for each basin for each equation. It is a scaled measure of the change in the predicted value of the dependent variable for that basin that results from regenerating the equation after deleting data for that basin from the data set. The larger the value listed, the more influence a single basin has within its neighborhood of the data array.

[d]Value in parentheses computed after detransformation to cubic feet per second, which was done by raising estimated low-flow values to the 1.333 power.

[e]Value in parentheses computed after detransformation to cubic feet per second, which was done by taking the antilog of estimated low flows.

the apparent effects of several basin characteristics or combinations thereof on low flows, as explained in the following section. Standard error expressed in cubic feet per second and coefficient of determination were the most useful indices of fit; standard error expressed in percent varied widely and seemed overly sensitive to a few small basins, as explained in a subsequent section on effects of scale transformations and individual basins.

Effects of Environmental Characteristics on Low Flows

Surflcial Geology

All equations indicate that low flow (ground-water discharge) per unit area from coarse stratified-drift is several times greater than that from till. Equation 13 suggests that low flow from areas of till is significant. In equation14, the regression coefficient for till area is much smaller than that for coarse stratified drift area. The same is true of equations 15 through 19, althoug the coefficients for terms that incorporate coarse stratified drift must be divided by stream length, whose mean value is 11.1 mi, before they are compared with coefficients of similar terms that incorporate till.

Dividing coarse stratified drift into perched deposits and deposits that extend below stream profiles did not improve regression equations significantly, perhaps because these two categories cannot be accurately distinguished in most low-relief basins without abundant data. In this study, stratified drift was assumed to extend below stream grade unless bedrock outcrops or boreholes provided evidence to the contrary. Combining fine-grained stratified deposits with till also had little effect; the final equations in table 5 do so to include the entire basin area in one or the other of the two geologic terms. Dividing the total area of coarse-grained stratified drift by the length of the main stream channel gave some improvement in fit (compare eq. 15 with eq. 14); this combination of variables was tested because large values tend to be associated with broad expanses of stratified drift, from which ground water might drain more slowly over long periods than from narrow riparian aquifers of equal area.

Lakes, Swamps, and Related Indices of Evapotranspiration

Areas of lakes and swamps bordered by stratified drift and those bordered by till were tested as independent variables in equation 13, as was total area of lakes and swamps. Each was negatively correlated with low flow, but regression

Table 5. Regression equations for estimation of low flows in the low-relief region of central New England--Continued

B. Statlstical Indlces Pertaining to Each Equatlon								
		Standard error of estimate						
Equation number	Coefficient of determination (R^2)	(units of 7Q10 or 7Q2)	(cubic feet per second)	(percent)**	Median percent error of estimate†	Prediction sum of squares (PRESS) statistic	Maximum variance inflation factor	Maximum DFITS statistic†† for any basin
13*A*	83.2		3.79	519	37	610	1.3	3.4
13*B*	79.1		2.80	960	58	267	1.3	2.1
14*B*	88.3		2.20	759	59	235	29.9	4.2
15*B*	90.4		1.98	9,347	46	167	17.5	4.0
16*B*	92.4		1.73	8,977	61	110	11.7	2.6
17*B*	92.4		1.80	418	31	114	12.7	2.9
18*B*	94.8 (96.0)[d]	0.70	(1.24)[d]	(358)[d]	(28)[d]	(58)[d]	1.3	1.9
19*A*	93.7 (94.5)[d]	1.04	(2.23)[d]	(245)[d]	(28)[d]	(197)[d]	1.4	2.2
19*B*	92.3 (93.7)[d]	.85	(1.57)[d]	(586)[d]	(54)[d]	(88)[d]	1.4	2.0
20*B*	78.5 (75.0)[e]	.44	(4.10)[e]	(279)[e]	(80)[e]	(525)[e]	1.0	1.4

coefficients were not significant at the 0.05 level. No improvement resulted from treating riparian lakes separately from isolated kettlehole lakes. Nevertheless, the area of lakes and swamps bordered by stratified drift and the area of alluvium were both important negative components of equations 14 through 20 (table 5); tests in which either component was deleted from combined terms degraded the statistical indices for these equations. As in the high-relief data set, the negative significance of evapotranspiration terms that include alluvium could be interpreted as reflections of substantial evapotranspiration from flood plains and (or) rapid drainage of any water stored above stream profiles in permeable alluvium. As in the high-relief data set, terms that combine alluvium, lakes, and swamps were highly correlated with geologic terms that also include alluvium.

Annual Water Availability

Four variables were tested as alternative indices of water availability. Elevation proved not to be significant in this region of low and rather uniform relief. The other three variables--precipitation and mean runoff interpolated from maps by Knox and Nordenson (1955) and mean runoff computed for each basin from records of streamflow--were of nearly equal significance. The two estimates of mean runoff were only moderately well correlated (R = 0.9, fig. 12). Equations that incorporated mean runoff computed from streamflow records generally fit slightly better than equations that incorporated either of the interpolated indices of water availability, presumably because the computed runoff values exactly represent the average amount of water available for runoff in each basin over the reference period used to compute the low-flow statistics. By contrast, values of either precipitation or mean runoff based on regional maps incorporate errors from two interpolation steps (preparation of the map and use of the map). Also, even a perfect map of precipitation would not account for regional variation in evapotranspiration and thus would not exactly represent runoff. Mean runoff cannot, however, be computed from streamflow records at the sites of interest when regression equations are applied to estimate low flow at ungaged sites. Accordingly, equation 19 (table 5) is presented in a form that is suitable for estimating low flow at ungaged sites because it incorporates mean runoff values from Knox and Nordenson (1955). In equations 13 through 15 (table 5), mean runoff is an independent term, centered and converted to units of cubic feet per second. Centering of runoff values, which was done by subtracting 1.7 $(ft^3/s)/mi^2$, approximately the mean runoff for the entire region, resulted in improved fit and smaller regression constants. In equations 16 through 19, each geologic term is multiplied by mean runoff per square mile for that particular basin. This formulation, which seems conceptually reasonable and further improved fit, allows low-flow yields from till and from stratified sand and gravel to be proportional to their different water-transmitting properties, to the area of each, and also to average water availability in the basin.

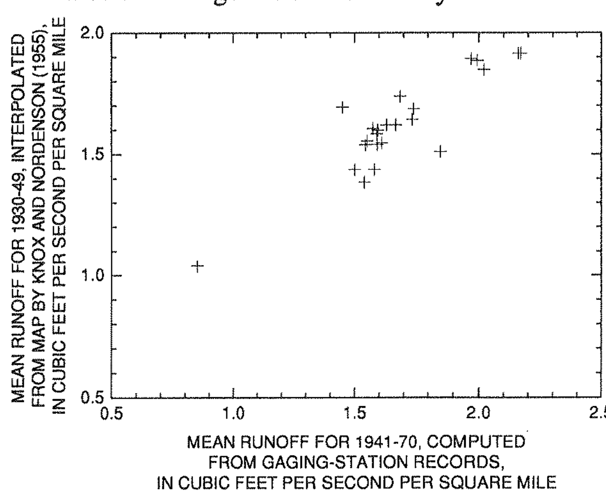


Figure 12. Correlation between mean runoff determined by two alternative methods for all basins in the low-relief data set that have more than 10 years of streamflow record.

Effects of Scale Transformations and Data Distribution on the Interpretation

Fractional-Power Transformations

Equation 16 fits the data moderately well, but the geologic and water-loss terms have some collinearity, and plots of observed against predicted low flows are curved (fig. 13). Equations 18 and 19 incorporate the same basin characteristics as equation 16 but express the evapotranspiration term as a percentage of basin area and transform the dependent variable (low flow) to the 0.75 power. These manipulations served to eliminate collinearity, decrease the influence of individual watersheds, and improve the linearity and fit of the regression equation (figs. 13 and 14, table 5). Stronger transformations of the dependent variable, such as the 0.5 power, resulted in curvature in plots of observed values against predicted values.

Logarithmic Transformations

Several logarithmic equations, similar in form and rationale to equation 12 for the high-relief region, were also considered. The equation with the smallest standard error in logarithmic units is presented as equation 20 (table 5, fig. 15). The weighting factors for area of coarse-grained stratified drift and area of swamp, lake, and alluvium in equation 20*B* were evaluated as shown in figure 16. The left curve in figure 16 indicates that the standard error of the logarithmic regression equation is minimized when the ratio (p) of low-flow yield from coarse stratified drift to low-flow yield from till plus fine drift is taken to be about 16 (although any ratio from 10 to 30 works nearly as well). The other two curves indicate that the standard error can be further decreased if the areas of lake, swamp, and alluvium, which have a negative effect (depletion) on low flow, are incorporated in the

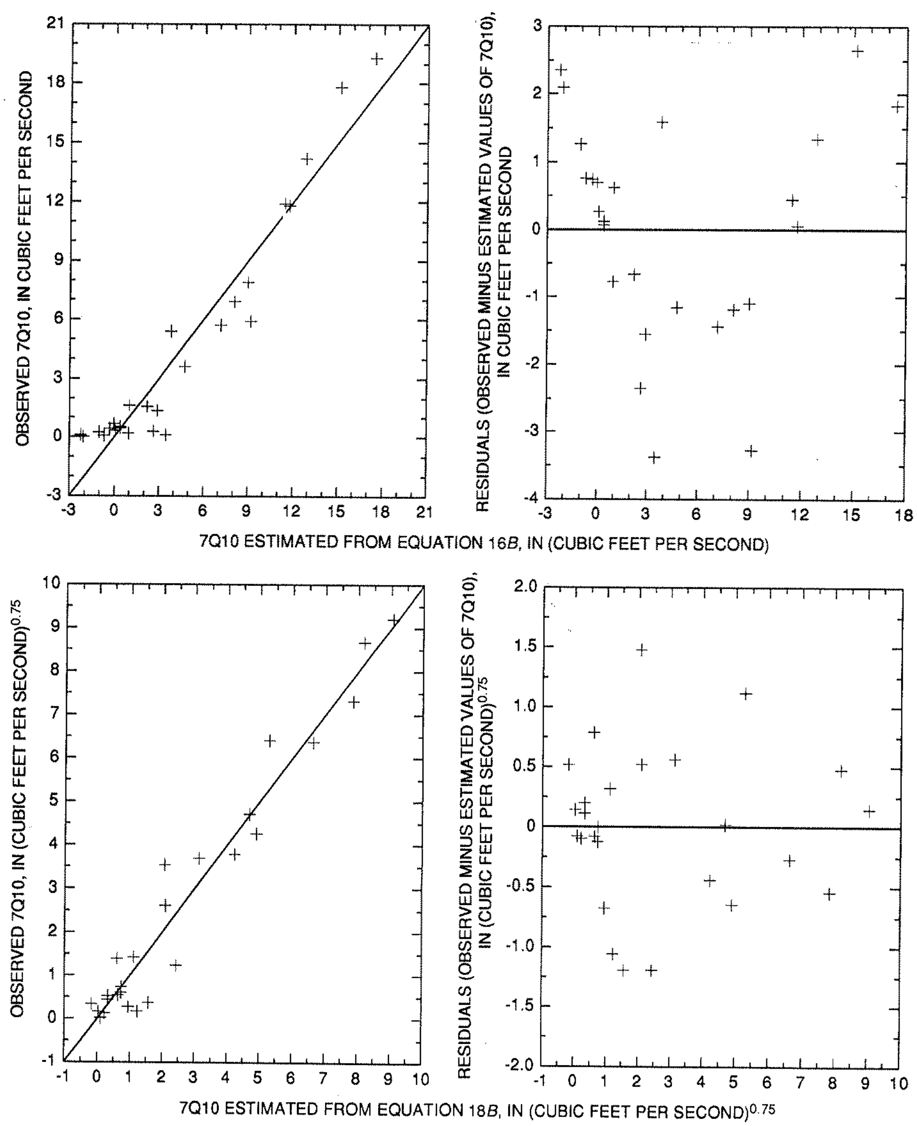


Figure 13. Annual minimum 7-day low flow at a 10-year recurrence interval (7Q10) in the low-relief region of central New England, as estimated by equations 16*B* and 18*B*, in relation to observed 7Q10 and to the residual differences between estimated and observed values. Equations are given in table 5.

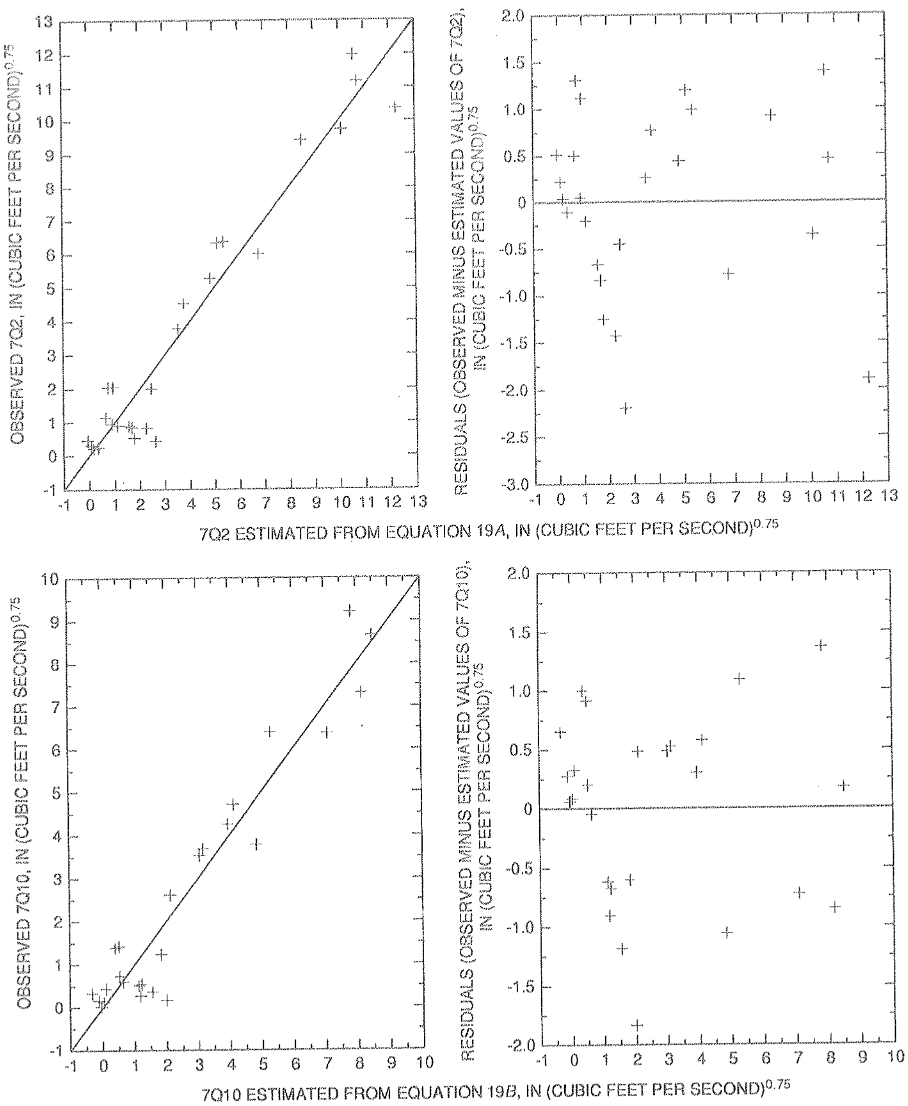


Figure 14. Annual minimum 7-day low flows at 2-year and 10-year recurrence intervals (7Q2, 7Q10) in the low-relief region of central New England, as estimated by equations 19*A* and 19*B*, in relation to observed values and to the residual differences between estimated and observed values. Equations are given in table 5.

equation. The smallest and most sharply defined standard error resulted when p = 6 and r = 16; these are the weighting factors used in equation 20*B* (table 5). The two terms in equation 20*B* are not colinear (variance inflation factor = 1), but the internal components of the first term correspond to the highly colinear terms in equation 14.

Influence of Small Low Flows

Flows less than 1.0 ft^3/s span more than half the range of 7Q10 values expressed as logarithms (fig. 15) but span only 5 percent and 10 percent of the data range in natural-value and fractional-power equations, respectively. Therefore, these small values are particularly influential in equation 20*B*. The smallest flow is so much smaller than the rest (fig. 15) that it has the potential for substantial influence, but the DFITS statistics in table 5 indicate that individual basins have even greater influence on many other equations.

Logarithmic equation 20*B* yielded reasonably accurate estimates of some small 7Q10 values, which fall on the trend of the larger values when observed 7Q10 is plotted against the estimated

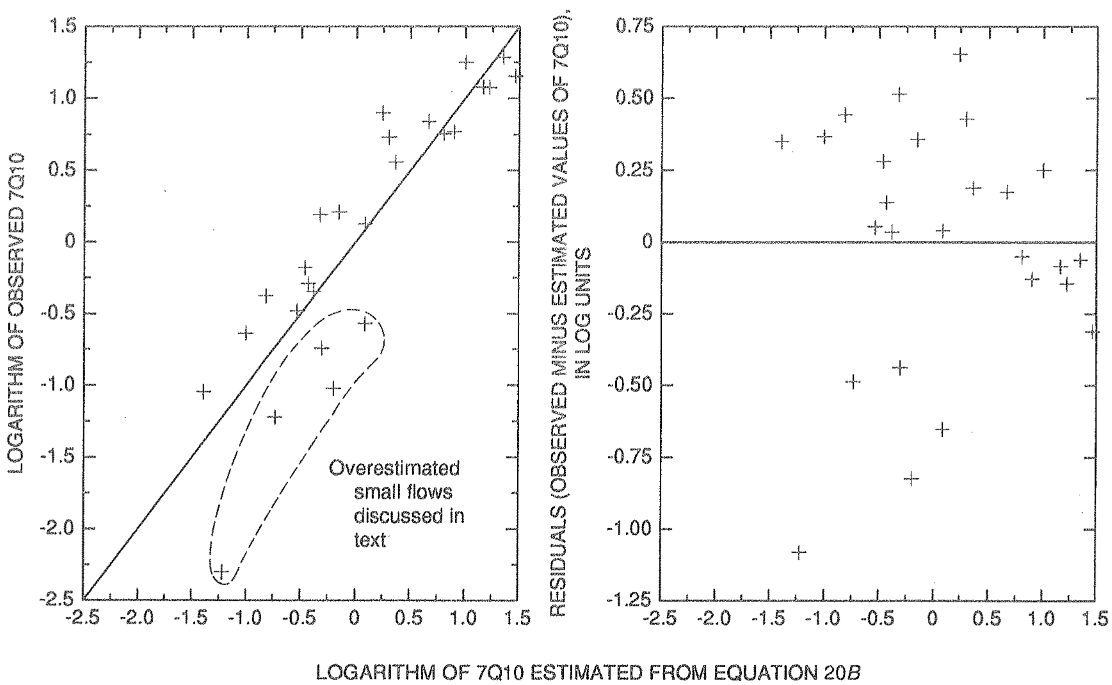
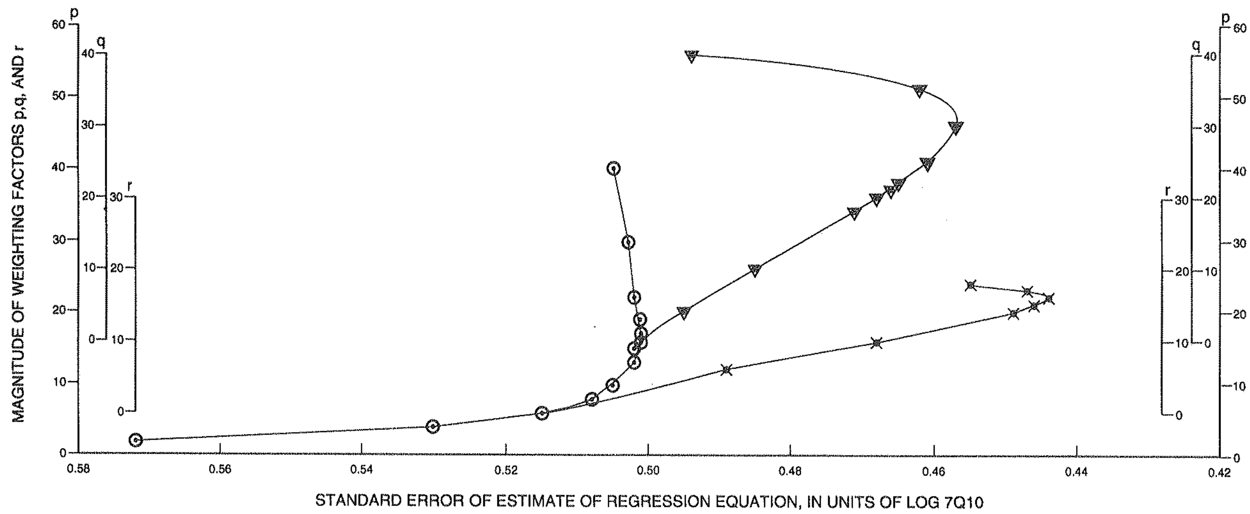


Figure 15. Annual minimum 7-day low flow at a 10-year recurrence interval (7Q10) in the low-relief region of central New England, as estimated by equation 20*B*, in relation to observed 7Q10 and to the residual differences between estimated and observed values.

values (fig. 15). Five small values (identified in fig. 15) were substantially overestimated, however. Three of these five (sites 15, 16, 21, table 8) were overestimated by several other equations as well. These same five basins also account for most of the standard error expressed in percent (table 5) for all equations. One of these basins, Hop Brook (site 39), covers less than 4 mi^2, and its 7Q10 is so small that overestimation by 0.1 ft^3/s constitutes a 2,000-percent error. Probably the low-flow statistics calculated for these five basins, like those calculated for the three basins in the high-relief region that also were persistently overestimated, fail to represent total low-flow yield from their respective basins because the correlation technique used to estimate low-flow statistics is imprecise or, more likely, because measured low flows were depleted by significant underflow, by some unknown surface diversion, or by unusually large evapotranspiration that is not proportional to the areas of swamp, lake, and alluvium treated as indices of riparian evapotranspiration in this study. In all five basins, 7Q10 is relatively small with respect to 7Q2 (4 to 42 percent of 7Q2, whereas the median for the data set is 59 percent); low percentages could be explained by a constant depletion or diversion comparable in magnitude to 7Q2. Reevaluation of the consistently overestimated small flows in both high-relief and low-relief regions, including development of a useful index of underflow, might significantly improve logarithmic equations 12 and 20.

Selection of Equations for Practical Application

Equation 17*B* incorporates the same basin characteristics as equation 16*B* but is based on 23 rather than 26 basins; the three basins in areas of intermediate relief (sites 11, 37, and 44, fig. 1 and tables 7-9) were excluded. Regression coefficients and statistical indices of fit for equations 16B and 17B are nearly identical. Errors in estimating low flows from the three intermediate basins were within the range of error at the other 23 basins in all equations. Therefore, equations developed for the low-relief region can be applied to basins that are close to, or overlap, the boundary between regions (fig. 7).



EXPLANATION

⊙ log 7Q10 = a log[TL + FD + (p) TCS] + b log QM

▼ log 7Q10 = c log[TL + FD + 16TCS - (q)(SLCS + AL)] + d log QM

✕ log 7Q10 = e log[TL + FD + 6TCS - (r)(SLCS + AL)] + f log QM

where

a,b,c,d,e,f = coefficients fitted by regression analysis;

p,q,r = weighting factors that represent the ratio of (1)low-flow yield (or depletion) per square mile from the next basin characteristic(s) in the equation to (2) the low-flow yield per square mile from till and fine stratified drift;

TL = area of till;

FD = area of fine stratified drift;

TCS = area of coarse stratified drift;

SLCS = area of swamps and lakes in coarse stratified drift;

AL = area of alluvium;

QM = mean runoff per square mile; and

7Q10 = Mean flow for 7 consecutive days that occurs as the lowest 7-day mean flow in the year at an average frequency of once in 10 years.

Figure 16. Standard error of logarithmic regression equations for the low-relief region of central New England as a function of weighting factors applied to area of coarse stratified drift and area of lakes, swamps, and alluvium.

Equation 18*B* seems to best represent the low-relief data set as constituted for this report, but its low standard error in part reflects a close fit to the largest watersheds, as indicated by an error variance that tends to decrease as low flow increases (fig. 13). Furthermore, it incorporates mean runoff computed from gaging-station records, which cannot be extrapolated accurately to most ungaged sites without an interpretive effort comparable to that by Knox and Nordenson (1955). Equation 19*B* (fig. 14, table 5) fits the data set nearly as well, however. Equations 19*A* and *B* incorporate mean runoff interpolated from Knox and Nordenson (1955), have negligible collinearity, and have constant error variance over the range of predicted low flows; therefore, they are suggested for estimating 7Q2 and 7Q10, respectively, at ungaged sites.

APPLICATION OF REGRESSION EQUATIONS TO ESTIMATE LOW FLOW AT UNGAGED SITES

The regional regression equations developed in this report provide a means of transferring to ungaged sites the information on magnitude of low flows obtained from a network of gaging stations throughout central New England. This estimation technique is preferred to the method of extrapolating low flows from a single nearby site whose information may be biased or a poor indicator of low flows at the desired site.

The following equations, first presented in tables 3 and 5, were deemed most suitable for practical application, as explained earlier:

High-Relief Region:

$$7Q2 = [-1.12 + 0.37\,(TCS\text{-}AL) + 0.034\,(TL+FD) - 0.63(TSL) + 0.0012(E)]^{1.667} \quad (9A)$$

$$7Q10 = [-1.20 + 0.38(TCS\text{-}AL) + 0.024(TL+FD) - 0.70(TSL) + 0.0011(E)]^{1.667} \quad (9B)$$

Low-Relief Region:

$$7Q2 = [-0.076 + 3.01(TCS/L)QM + 0.037(TL + FD)\,QM - 18.1(SLCS + AL)/DA\,]^{1.333} \quad (19A)$$

$$7Q10 = [-0.20 + 2.58(TCS/L)QM + 0.021(TL + FD)\,QM - 15.7(SLCS + AL)/DA\,]^{1.333} \quad (19B)$$

The symbols used in these equations are defined as follows. All area measurements are in square miles.

TCS = Total area of surficial sand and gravel deposits, including coarse-grained stratified drift and postglacial alluvium.

AL = Area of alluvium, including flood plains and alluvial fans of modern streams.

TL = Area of till, including any bedrock outcrops.

FD = Area of surficial fine-grained stratified drift--clay, silt, and (or) very fine sand.

TSL = Total area of swamps and lakes.

SLCS = Area of swamps and lakes bordered by coarse-grained stratified drift.

DA = Area of drainage basin.

E = Mean basin elevation, in feet.

QM = Mean runoff per unit area, in cubic feet per second per square mile (from Knox and Nordenson, 1955).

L = Length of main stream channel, in miles.

7Q2 = 7-day low flow, in cubic feet per second, at the 2-year recurrence interval (0.5 nonexceedance probability).

7Q10 = 7-day low flow, in cubic feet per second, at the 10-year recurrence interval (0.1 nonexceedance probability).

Accuracy and Limitations

Equations 9 and 19 are useful, but not perfect, as indicated in tables 3 and 5 by their coefficient of determination, standard error of estimate, median percent error of estimate, and PRESS statistic. Further improvement in accuracy would require use of longer streamflow records, better methods of quantifying basin characteristics shown to be significant in this study, incorporation of other basin characteristics, and (or) an improved formulation of the low-flow model (regression equation). Because these regression equations are imperfect, estimation of low flows from actual measurements at the site of interest is preferable, whenever possible, to estimation from these equations. At sites near some borders of central New England, estimating techniques developed for adjacent regions (for example, Barnes, 1986; Cervione and others, 1982) could also be applied; any large discrepancies between low-flow estimates by those techniques and estimates by the equations presented in this report would suggest caution in use of the results. Transferring low flows from a gaged site to a nearby ungaged site on the basis of drainage area alone is an unrelieable practice because many variables can affect low flows, as illustrated by figure 4 as well as by the regression analyses in this report.

These estimating equations are applicable to unregulated streams in central New England where the basin characteristics are within the extremes of the data base listed in table 6. The standard error of prediction for sites with characteristics outside these ranges may be significantly higher than for sites where all basin characteristics are within these ranges. The equations do not apply to basins affected by urbanization, regulation, ground-water withdrawals, or diversions. They can be applied, however, to unaffected segments of basins if results for those segments can be added to (or subtracted from) low flows computed from

Table 6. Range and statistical distribution of values of basin characteristics used in selected regression equations

[mi^2 = square miles, ft = feet, $(ft^3/s)/mi$ = cubic feet per second per mile, $(ft^3/s)/mi^2$ = cubic feet per second per square mile]

Basin characteristics[1] or combinations thereof used in equations 9 and 19	Minimum	Maximum	Mean	Median	Standard deviation	Standard error of the mean	Units
	High-relief region (equation 9)						
TCS	0.04	21.53	4.50	2.45	5.43	1.07	mi^2
AL	0	4.34	1.36	.765	1.38	.27	mi^2
TCS - AL	0	17.99	3.15	1.28	4.30	.84	mi^2
TL + FD	3.36	118.35	40.96	39.87	34.07	6.68	mi^2
TSL	0	7.06	.80	.28	1.55	.31	mi^2
E	870	3,260	1,585	1,445	512	100	ft
	Low-relief region (equation 19)						
TCS	0.02	42.01	8.72	6.50	10.34	2.03	mi^2
L	3.85	34.20	11.16	7.90	8.38	1.64	mi
QM	1.034	1.92	1.63	1.61	.20	.039	$(ft^3/s)mi^2$
(TCS/L)QM	.008	3.92	1.09	.83	.91	.18	$(ft^3/s)mi$
TL + FD	0	128.48	26.45	7.35	37.23	7.30	mi^2
(TL + FD)QM	0	205.4	42.9	12.5	59.6	11.70	ft^3/s
SLCS	0	8.41	1.34	.52	1.88	.37	mi^2
AL	0	8.26	.79	.03	1.78	.35	mi^2
DA	2.85	171.00	35.18	13.22	46.69	9.16	mi^2
(SLCS + AL)/DA	0	.225	.055	.051	.051	.010	none

[1]Abbreviations are defined as follows:

- TCS = Total area of surficial sand and gravel deposits, including coarse-grained stratified drift and post-glacial alluvium.
- AL = Area of alluvium, including flood plains and alluvial fans of modern streams.
- TL = Area of till, including any bedrock outcrops.
- FD = Area of surficial fine-grained stratified drift--clay, silt, and (or) very fine sand.
- TSL = Total area of swamps and lakes.
- SLCS = Area of swamps and lakes bordered by coarse-grained stratified drift.
- DA = Area of drainage basin.
- E = Mean basin elevation.
- QM = Mean flow per unit area (from Knox and Nordenson, 1955).
- L = Mean channel length.

streamflow measurements at other sites on the same stream. They are designed to estimate the low flows that occur in summer or autumn and are ordinarily the lowest of the year, and do not apply to midwinter low flows that may be comparably low in some years near the north-eastern fringe of the study area.

Estimation Procedure

The 7Q2 and 7Q10 low flows in natural-flow streams in central New England can be estimated by means of the procedures listed below:

(1) Determine whether daily-flow records or discharge measurements at times of low flow along the stream of interest have been obtained. Information on the location of continuous-record gaging stations, partial-record stations, and other sites with discharge measurements is provided in annual water-data reports (U.S. Geological Survey, 1984, for example) and, for streams in Massachu-setts, in a nine-volume series of gazetteer reports (Wandle, 1984, for example). If adequate data are available for the site of interest, estimate low-flow statistics from daily-flow records or from discharge measurements, or use 7Q2 and 7Q10 values already estimated for most gaged sites in Massachusetts and reported in the gazetteer reports. Inclusion of recently collected data in the site evaluation would be advisable.

(2) If enough measurements have been made at other sites along the same stream and its tributaries, construct a profile that shows the changes in a suitable low-flow statistic with distance along the stream, or that shows measured flows if the measured flow at some nearby site corresponds to a suitable low-flow statistic (Riggs, 1972). Then, interpolate from the profile to estimate low flow at the site of interest. If data are inadequate for estimation of low flows by procedures 1 or 2, continue with procedure 3.

(3) Determine whether the low flow of the stream is affected by regulation or diversion, whether large ground-water withdrawals from stratified-drift aquifers along the stream are likely, and whether a substantial part of the basin is urbanized. Low flow is natural if these conditions are absent. A field inspec-tion at the time of low flow would help assess the possibility of regulation or diversions in the stream reach above the site and the poten-tial for zero flow at sites on small drainage areas. If flow is natural, continue with procedure 4 to estimate low flows by means of the regional equations.

(4) Locate the site of interest in figure 7 and select low-flow equation 9 for the high-relief region or equation 19 for the low-relief region.

(5) Delineate the drainage-basin divide above the site of interest on the most recent topographic quadrangle map(s) available and compute the drainage area. Also measure mean basin elevation (for eq. 9) or channel length (for eq. 19) on these map(s).

(6) Select a surficial geologic map(s) on which the following units are shown or can be inferred: till, coarse-grained stratified drift (including any overlain by thin surficial till), alluvium, and fine-grained stratified drift. Select maps that show the full extent of stratified drift, not just the fraction thereof deemed to constitute productive aquifers. Map scale should be at least 1:62,500. Consult the index maps by McIntosh and others (1982a, 1982b) for the availability of surficial maps and inquire about more recent mapping. In some areas, surficial geology can be reasonably inferred from county soils maps; in other areas, reconnaissance mapping may be required. Transfer the drainage-basin divide (procedure 5) to the surficial geologic map.

(7) Visually compare the topographic and surficial maps for major differences in landforms, rivers, lakes, ponds, and swamps. Resolve any differences that would affect the indepen-dent variables and use the map that best represents the physical and topographic characteristics of the basin to compute these variables.

(8) Check the scale of the maps against a stable scale if a scale factor will be used to convert from digitizer or planimeter units to square miles.

(9) To facilitate measurement of swamp areas, draw around each swamp a line that just encloses the area defined by swamp symbols. Include the areas of lakes and swamps as part of the underlying geologic units in addition to compiling them separately.

(10) Measure areas of the appropriate surficial geologic units, except for the till area, and compute necessary basin characteristics. Calculate the till area as drainage area minus sum of the areas of

stratified-drift units. For basins that contain only a small amount of till or isolated areas of till, however, an easier method would be to measure those areas and then calculate the area of the largest stratified-drift unit. Refer to the section "Surficial geology" for methods of computation.

(11) Determine whether basin characteristics fall within the ranges used in development of the regression equations in this report (table 6).

(12) Compute the independent variables required for the appropriate equations from the measurements of basin characteristics, and use the equations to compute the low-flow indices. If a negative flow is computed, treat it as zero.

(13) If estimates of low flow more precise than those provided by these equations will be needed, plan to obtain discharge measure-ments during base-flow periods.

Sample Computation

The following example illustrates the procedure for estimating low-flow statistics for central New England streams as described in the preceding section.

Problem: Compute the annual minimum 7-day mean low flows at the 2- and 10-year recurrence intervals (7Q2 and 7Q10) for a site on Kinderhook Creek in Hancock, Mass. (fig. 1) at latitude 42°33'29", longitude 73°18'18" at Brodie Mountain Road.

1. Refer to figure 7, which indicates this site to be in the high-relief region. Therefore, equation 9 is applicable; 7Q2 may be estimated from equa-tion 9*A*, 7Q10 from equation 9*B*. In addition, the topographic map index covering Massachusetts, Rhode Island, and Connecticut indicates that this site is within the borders of the Hancock, Mass.-N.Y. $7^1/_2$-minute topographic quadrangle map. A geologic map index for this area (McIntosh and others, 1982a) indicates the most detailed surficial map available to be that by Holmes (1967), part of which has been reproduced as figure 17 to show the geologic units above the site of interest.

2. Check whether streamflow data, including discharge measurements, are available for this site. A gazetteer (Wandle, 1984) contains a location map for streamflow-measurement sites and a list that includes drainage areas for selected sites. The drainage area for this site is reported to be 4.93 mi^2.

3. Follow the procedures described in the section "Measurement of Environmental Characteristics of Basins in the Data Set (p. 14)" to obtain values for the following variables:

- Areas of sand and gravel units shown on the surficial geologic map by Holmes (1967):
  - alluvium in modern flood plain (including enclosed swamp deposits) = 0.26 mi^2
  - alluvial fan deposits = 0.18 mi^2
  - ice-contact deposits = 0.075 mi^2
  - stream-terrace deposits = 0.078 mi^2
- Other information (derived from $7^1/_2$-minute topographic quadrangle map):
  - Area of swamps and lakes outside of the alluvium unit = 0.006 mi^2. The swamp and lake area within the alluvium unit (about 0.09 mi^2) is not separately compiled.
  - Drainage area = 4.93 mi^2
  - Mean basin elevation = 1,860 ft

4. Compute the following quantities required by equation 9 from the values given above:

- Total area of sand and gravel (TCS) = 0.26 + 0.18 + 0.075 + 0.078 = 0.593 mi^2
- Area of alluvium (AL) = 0.26 + 0.18 = 0.44 mi^2
- Elevation (E) = 1,860 ft
- Total area of swamps and lakes (TSL) = 0.006 mi^2
- Total area of till plus fine-grained stratified drift, computed as drainage area minus total area of sand and gravel = 4.93 - 0.59 = 4.34 mi^2

5. Substitute these quantities in equations 9*A* and 9*B* as follows:

$$9A:\ 7Q2 = [-1.12+0.37\,(TCS-AL)+0.034(TL+FD) -0.63(TSL)+0.0012(E)]^{1.667}$$
$$= [-1.12+0.37\,(0.593-0.44) + 0.034(4.34) - 0.63(0.006) + 0.0012(1{,}860)]^{1.667}$$
$$= [1.31]^{1.667}$$
$$= 1.57\ ft^3/s.$$

$$9B:\ 7Q10= [-1.20+0.38(TCS-AL)+0.024(TL+FD) -0.70(TSL)+0.0011(E)]^{1.667}$$
$$= [-1.20 + 0.38(0.593-0.44) + 0.024(4.34) - 0.70(0.006) + 0.0011(1{,}860)]^{1.667}$$
$$= [1.00]^{1.667} = 1.00\ ft^3/s.$$

These results could be compared with results from a study of low flow in the Hudson River Basin of New York by Barnes (1986). A field inspection during the low-flow period in summer and fall may be warranted to ensure that the lakes

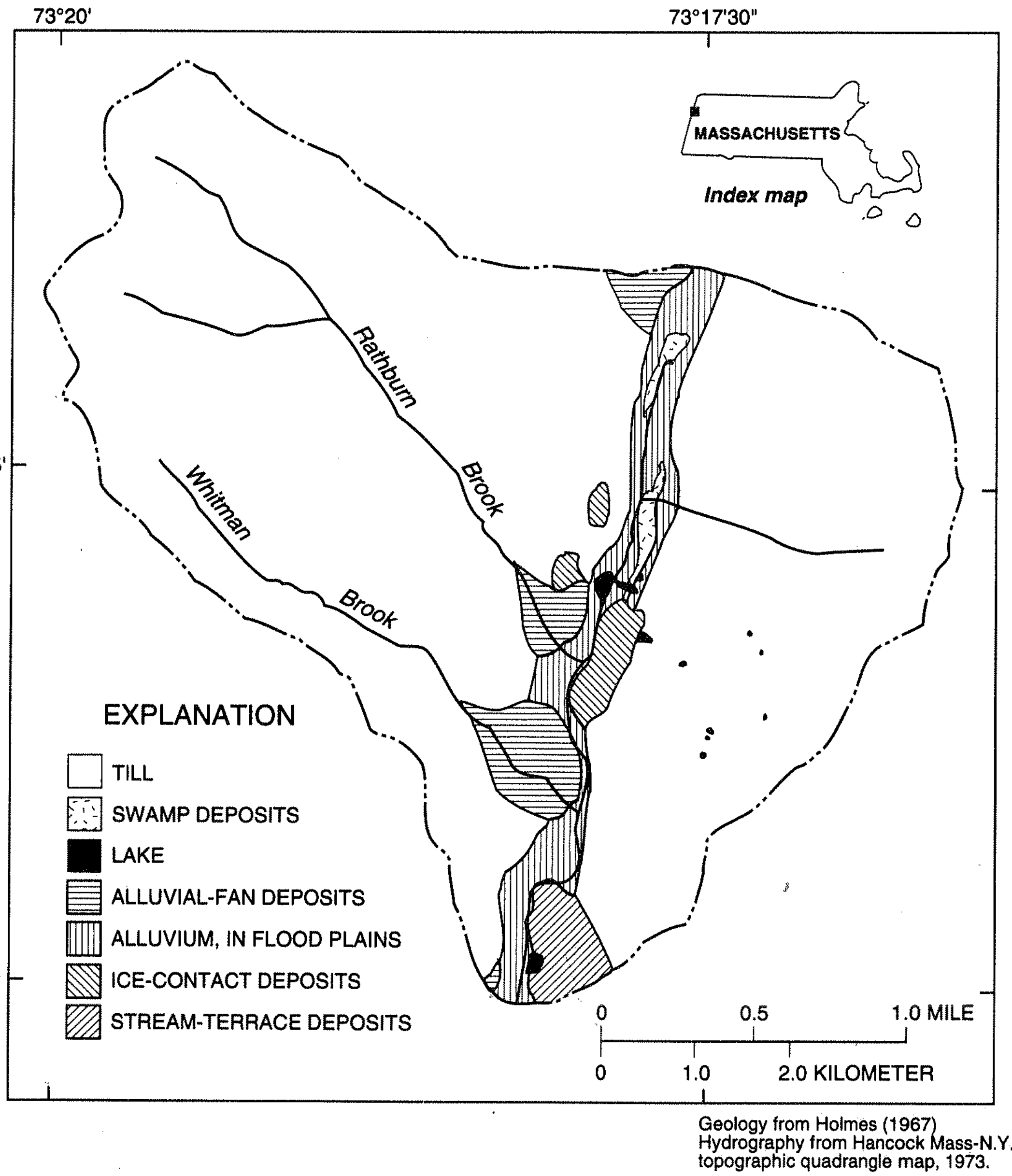


Figure 17. Example of surficial geologic map delineating geologic units used to estimate low flow in the high-relief region (from Holmes, 1967).

along the main channel are not regulated.

SUMMARY AND CONCLUSION

This study investigated, through regression analysis, relations between the low flow of streams in central New England and a suite of basin characteristics that represent surficial geology, water availability or input to the basin, and water loss through evapotranspiration in swamps, lakes, and lowlands, all of which were expected to affect low flow. Because any independent or explanatory term in regression equations can serve as a surrogate for other basin characteristics with which it is correlated, demonstration that a particular basin characteristic explains part of the areal variability in low flow does not constitute unequivocal proof of its hydrologic function. Nevertheless, regression analysis is one method of developing and testing inferences as to hydrologic relations, as well as developing practical means for estimating low flow at ungaged sites.

The area of study included Massachusetts, New Hampshire, Rhode Island, Vermont, and southwestern Maine. The data base for regression analysis consisted of topographic, climatic, geologic, and streamflow characteristics from a sample of 49 gaged river basins. The explanatory variables, or basin characteristics, included mean basin elevation; latitude and longitude; main-channel length and slope; annual precipitation; mean annual flow; and areal extent of till, alluvium, coarse- and fine-grained stratified-drift deposits, swamps, and lakes. Areas of the various geologic units were measured on published geologic quadrangle maps, unpublished maps in the files of the U.S. and State Geological Surveys, and reconnaissance maps of surficial geology prepared for this study. Low-flow statistics (the response variables) were represented by the minimum 7-day mean low flows at the 2- and 10-year recurrence intervals (7Q2 and 7Q10) that occur between early August and late October. These seasonal low flows also constitute the annual low flows, except in some basins near the northeastern limit of the study area, where annual low flows occur in midwinter in some years. Low-flow statistics were calculated for each of the 49 basins from a low-flow frequency analysis of streamflow records from 1942-71, or, if the record did not cover this 30-year period, from graphical or mathematical correlation with index stations. For this study, central New England was divided into a high-relief region comprising much of New Hampshire, Vermont, and western Massachusetts, and a low-relief region lying generally to the east and the south of the high-relief region but also including the Lake Champlain lowland of Vermont.

The 21 measured basin characteristics were tested singly and in combination as estimators of 7-day low flows through regression analysis in each of the two regions. All regression equations were consistent in indicating that:

1. The contribution from surficial sand and gravel to low flow of streams is much greater than the contribution from equal areas of till-mantled bedrock, probably four to eight times greater.
2. Much of the variation in low flow from one locality to another can be explained by differences in surficial geology, chiefly the extent of surficial sand and gravel relative to that of till, and differences in water input or availability in the basin, which can be represented by elevation, by mean annual runoff, or by mean annual precipitation.

This study also provides support for the concept that evapotranspiration from lakes and swamps reduces low flows by capturing ground water that would otherwise have discharged to streams. The areal extent of swamps and lakes was negatively correlated with low flow in both regions, and, although its significance as a solo variable was small or complicated by correlation with other terms, its presence as a component of negative terms or its exclusion from the area of the underlying geologic units improved the regression equations. The sensitivity of regression analysis to the areal extent of swamps and lakes was probably limited by the composition of the central New England data set. In the high-relief region, the percentage of basin area covered by swamps and lakes did not exceed 6 percent and was less than 2 percent in 21 of 26 basins. Also, the areal extent of swamps and lakes in a few basins could have been underestimated because it was measured on 15-minute topographic maps, whose scale might not have allowed delineation of small swamps or lakes. In the low-relief region, swamps and lakes are more abundant and evenly distributed from 0.5 to 23 percent of basin area, but some geologic interpretations are inconsistent. A few basins contain extensive low-lying swampy areas that are crossed by streams, but alluvium was not shown on available geologic maps nor readily inferred from the topography. In other basins, swamps shown on topographic maps within areas mapped as alluvium were not separately measured because the study plan contemplated that alluvium would be combined with swamps and lakes. Clarification of these few inconsistencies, or definition of wetlands from National Wetlands Inventory maps, might permit more precise evaluation of the effect of swamps and lakes on low flow.

Previous studies have combined alluvium (flood plains, alluvial fans) with coarse-grained stratified drift in regression analysis on the premise that both consist largely of permeable sand and gravel. This study found that statistical indices of fit are improved when area of alluvium is either combined with area of swamps and lakes to form an independent variable that has a strong negative correlation with low flow, or instead is merely excluded from the area of coarse stratified drift. In areas of high relief, part of the stratified drift is perched on the valley sides in such a way that its base is above the stream surface profile and hence it is largely unsaturated. Regression analysis suggested that low flow per square mile from these perched deposits exceeds that from the areas of stratified drift and alluvium on the valley floor, where permeable sediment extends below the stream profile. These two findings are probably related. They could reflect large evapotranspiration losses from low-lying flood plains and (or) small ground-water discharge to streams from alluvium, much of which consists of highly permeable gravel that may drain down to the level of the stream so quickly that little water remains to discharge to streams at times of low flow.

Underflow was not quantified nor tested in regression analysis during this study and probably is negligible at measurement sites that lie where stream channels cross bedrock outcrops. In each region of central New England, however, nearly all regression equations overestimated the small low flows observed in a certain few basins, in each of which 7Q10 was unusually small relative to 7Q2. These discrepancies, which were small in cubic feet per second but large when expressed as a percentage of the observed flows, might be accounted for by underflow of several tenths of a cubic foot per second or more at the sites involved.

Regression equations were developed that explain about 95 percent of the spatial variation in low flow within data sets for both high-relief and low-relief regions. The equations suggested for practical application (eq. 9 and 19) met guidelines for normality of residuals, significance of regression coefficients, absence of collinearity, and constant variance. They also had standard errors of estimate under 2.3 ft^3/s (7Q2) and 1.6 ft^3/s (7Q10), which were among the lowest achieved. To use these equations to estimate the 7Q2 or 7Q10 at an ungaged site, one must first measure areal extent of coarse-grained stratified drift, fine-grained stratified drift (if any), till, alluvium, lakes, and swamps, and also measure elevation (for basins in the high-relief region) or mean runoff and stream length (for basins in the low-relief region). Practical application of these equations is limited in some areas because geologic and other maps needed to determine these basin characteristics are unavailable, of small scale, or inconsistent. The analysis of periodic streamflow measurements made under a range of base-flow conditions at each site of interest generally yields more precise estimates of low flow than regional regression equations and is advisable when circumstances permit.

Most equations presented in this report, including those suggested for practical application, use basin properties scaled in ordinary (natural) units of measurement. Logarithmic transformations were also tested, but standard errors (after detransformation) and coefficients of determination are not as favorable because the logarithmic regression equations are highly sensitive to large percentage differences among the smallest low flows, some of which were persistently overestimated, as explained above. Quantification of underflow and perhaps other aspects of upland hydrology might lead to logarithmic regression equations that are more accurate than the equations presented in this report, especially for estimation of low flows from small, till-covered upland basins.

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Table 7. Streamflow records and geologic maps available for basins in the low-flow data set

Site number in figure 1	Station number from data-collection network of the U.S. Geological Survey	Station name	Drainage area (square miles)	Relief[1]	Period of record (water years, ending Sept. 30)[2]	Sources of surficial geologic maps used for this investigation[3]
1	01059800	Collyer Brook near Gray, ME	14.1	L	1965-82D	O, W
2	01064300	Ellis River near Jackson, NH	10.2	H	1965-83	R
3	01064400	Lucy Brook near North Conway, NH	4.68	H	1965-83	R
4	01064800	Cold Brook at South Tamworth, NH	5.43	H	1964-73D	R
5	01069700	Branch Brook near Kennebunk, ME	9.86	L	1967D, 1981, 83D, A 1964-66, 68Q	O, N
6	01073000	Oyster River near Durham, NH	12.1	L	1935-83	R, U
7	01075500	Baker River at Wentworth, NH	56.0	H	1941-51D	R
8	01078000	Smith River near Bristol, NH	85.8	H	1919-83	R, M, B
9	01084500	Beards Brook near Hillsboro, NH	55.4	H	1946-71D	R
10	01085800	West Branch Warner R. near Bradford, NH	5.80	H	1963-83	R
11	01087000	Blackwater River near Webster, NH	128	HL	1919-20, 1928-83	R
12	01093800	Stony Brook tributary near Temple, NH	3.60	H	1964-83	R
13	01094000	Souhegan River at Merrimack, NH	171.0	L	1910-76D	R, U, M, G
14	01096000	Squannacook River near West Groton, MA	63.7	L	1950-83	U, H, R
15	01097300	Nashoba Brook near Acton, MA	12.3	L	1964-83	U
16	01101000	Parker River at Byfield, MA	21.3	L	1946-83	U, H, G
17	01105876	Eel River near Plymouth, MA	15.1	L	1971D, 1969-70, 86Q	H
(18)[4]	01105895	Weweantic River at South Wareham, MA	56.1	—	1971D, 1969-70, 86Q	H
19	01106000	Adamsville Brook at Adamsville, RI	8.01	L	1941-78D	R, U
20	01107400	Fall Brook near Middleborough, MA	9.32	L	1967D, 1966, 68, 1978-81Q	U, G, I

Table 7. Streamflow records and geologic maps available for basins in the low-flow data set--Continued

Site number in figure 1	Station number from data-collection network of the U.S. Geological Survey	Station name	Drainage area (square miles)	Relief[1]	Period of record (water years, ending Sept. 30)[2]	Sources of surficial geologic maps used for this investigation[3]
21	01111300	Nipmuc River near Harrisville, RI	16.0	L	1965-83	R
22	01115630	Nooseneck River at Nooseneck, RI	8.19	L	1964-81D, 1961-63Q	G, R
23	01117468	Beaver River near Usquepaug, RI	8.87	L	1975-83	B, G, M
24	01117800	Wood River near Arcadia, RI	35.1	L	1965-81D	G, R
25	01118000	Wood River at Hope Valley, RI	73.0	L	1942-83	G, R, M
26	01126200	Bucks Horn Brook at Greene, RI	5.52	L	1965-74D	G, R
27	01127880	Big Brook near Pittsburg, NH	5.99	H	1965-83	R
28	01137500	Ammonoosuc River at Bethlehem Junction, NH	88.4	H	1940-83	R
29	01139800	East Orange Branch at East Orange, VT	8.86	H	1959-83	R
30	01142500	Ayers Brook at Randolph, VT	30.5	H	1940-83	R
31	01150800	Kent Brook near Sherburne, VT	3.40	H	1964-74D	R
32	01153500	Williams River at Brockways Mills, VT	103	H	1941-83D	S
33	01154000	Saxtons River at Saxtons River, VT	72.2	H	1941-82D	R
34	01162500	Priest Brook near Winchendon, MA	19.3	L	1917-83	U, R
35	01169900	South River near Conway, MA	24.1	H	1967-83	G, U, P
36	01170100	Green River near Colrain, MA	41.4	H	1968-83	G, C
37	01171500	Mill River at Northampton, MA	54.0	HL	1940-83	G, H, U
38	01171800	Bassett Brook near Northampton, MA	5.46	L	1964-74D	U
39	01174000	Hop Brook near New Salem, MA	3.39	L	1949-82D	U
40	01174900	Cadwell Creek near Belchertown, MA	2.85	L	1962-83	F, T

Table 7. Streamflow records and geologic maps available for basins in the low-flow data set--Continued

Site number in figure 1	Station number from data-collection network of the U.S. Geological Survey	Station name	Drainage area (square miles)	Relief[1]	Period of record (water years, ending Sept. 30)[2]	Sources of surficial geologic maps used for this investigation[3]
41	01175670	Sevenmile River near Spencer, MA	8.68	L	1961-83	U
42	01176000	Quaboag River at West Brimfield, MA	150	L	1913-83	G, I, F, U
43	01180500	Middle Br. Westfield R. at Goss Heights, MA	52.7	H	1911-83	G, F
(44)[4]	01181000	West Br. Westfield R at Huntington, MA	93.7	--	1936-83	--
45	01198000	Green River near Great Barrington, MA	51.0	HL	1952-71D	F, S
46	01332000	North Branch Hoosic River at North Adams, MA	40.9	H	1932-83	F, R
47	01333000	Green River at Williamstown, MA	42.6	H	1950-83	F, R
48	04287000	Dog River at Northfield, VT	74.0	H	1935-83	R
49	04292100	Stony Brook near Eden, VT	4.29	H	1964-74D	R
50	04292700	Stone Bridge Brook near Georgia Plains, VT	8.50	L	1964-74D	R
51	04293000	Missisquoi River near North Troy, VT	131	H	1932-83	S

[1]RELIEF

H High relief, greater than 300 meters (Denny, 1982)
L Low relief, less than 200 meters (Denny, 1982)
HL Intermediate or transitional

[2]PERIOD OF RECORD

D Discontinued at end of last year listed; others continue after 1983.
Q Discharge measurements during indicated years.
A Data from D'Amore (1983).

[3]SOURCES OF MAPS

B U.S. Geological Survey Bulletin.
C County soils map.
F U.S. Geological Survey Open-File Report.
G U.S. Geological Survey Geologic Quadrangle Map.
H U.S. Geological Survey Hydrologic Investigations Atlas.

[3]SOURCES OF MAPS--Continued

I U.S. Geological Survey Miscellaneous Geologic Investigations.
M Rhode Island Water Resources Coordinating Board Ground-Water Map.
N New England Intercollegiate Geological Conference Report 76th meeting.
O Maine Geological Survey open-file report.
R Unpublished maps prepared for this study by C.T. Hildreth and F.D. Larsen (each under contract), E.H. London and J.R. Stone (Geologic Division, U.S. Geological Survey), or A.D. Randall.
S Unpublished maps in the files of the State Geological Survey.
T Master's thesis, University of Massachusetts, by W.C. Leonard.
U Unpublished maps in the files of the U.S. Geological Survey (Geologic Division or Water Resources Division).
W U.S. Geological Survey Water-Resources Investigations Report.

[4]Not in data set for multiple-regression analysis.

Table 8. Topographic, streamflow, and climatic characteristics of basins in the low-flow data set

[--, not compiled]

Site number (fig. 1)	Station number	Drainage area (square miles)	Main channel slope (feet per mile)	Main channel length (miles)	Mean basin elevation (feet)	Mean annual precipitation (inches)	Annual minimum 7-day mean low flow, in cubic feet per second at indicated recurrence interval		Mean annual runoff (cubic feet per second per square mile)		Location of gaging station (decimal degrees)	
							2-year	10-year	from records[a]	from map[b]	latitude	longitude
1	01059800	14.13	26.0	5.7	350	42.50	11.70	7.90	1.85	1.51	43.9175	70.3172
2	01064300	10.17	555.0	6.1	3,260	55.00	8.60	5.08	3.32	--	44.2200	71.2500
3	01064400	4.68	481.0	3.7	1,470	45.00	.64	.42	2.35	--	44.0694	71.1750
4	01064800	5.43	437.0	3.6	1,660	46.00	.29	.14	2.34	--	43.8158	71.2975
5	01069700	9.86	25.0	8.6	180	42.50	7.49	5.39	1.45[c]	1.44	43.3789	70.5822
6	01073000	12.10	21.5	7.9	200	41.40	.87	.51	1.54	1.39	43.1500	70.9700
7	01075500	55.95	187.0	14.8	1,740	47.90	8.50	5.90	1.89	--	43.8680	71.9097
8	01078000	85.80	22.6	21.5	1,260	44.63	9.00	5.70	1.63	--	43.5700	71.7500
9	01084500	55.40	78.3	12.2	1,140	47.00	1.76	.28	1.66	--	43.1100	71.9300
10	01085800	5.80	456.0	2.8	1,470	49.00	.35	.15	1.98	--	43.2592	72.0264
11	01087000	128.00	24.5	32.5	1,100	44.75	19.90	11.90	1.57	1.61	43.2958	71.6961
12	01093800	3.60	230.0	3.4	1,420	48.00	.23	.07	1.98	--	42.8600	71.8333
13	01094000	171.00	31.2	34.2	810	43.70	22.60	14.20	1.59	1.60	42.8600	71.5100
14	01096000	63.69	43.5	15.0	650	43.00	10.90	5.90	1.59	1.58	42.6300	71.6600
15	01097300	12.31	22.6	6.5	230	41.00	.33	.095	1.50	1.44	42.5100	71.4100
16	01101000	21.30	6.23	10.9	120	40.70	.43	.18	1.58	1.44	42.7500	70.9500
17	01105876	15.10	17.0	7.1	134	45.00	20.80	17.80	1.95[c]	1.84	41.9417	70.6231
19	01106000	8.01	32.2	6.0	140	43.00	.16	.06	1.73	1.64	41.5583	71.1297
20	01107400	9.32	6.83	8.0	103	44.50	2.59	1.55	1.90[c]	1.80	41.8653	70.5432
21	01111300	16.02	35.1	7.2	540	45.00	.78	.27	1.74	1.69	41.9811	71.6864

Table 8. Topographic, streamflow, and climatic characteristics of basins in the low-flow data set--Continued

Site number (fig. 1)	Station number	Drainage area (square miles)	Main channel slope (feet per mile)	Main channel length (miles)	Mean basin elevation (feet)	Mean annual precipitation (inches)	Annual minimum 7-day mean low flow, in cubic feet per second at indicated recurrence interval		Mean annual runoff (cubic feet per second per square mile)		Location of gaging station (decimal degrees)	
							2-year	10-year	from records[a]	from map[b]	latitude	longitude
22	01115630	8.19	29.5	4.7	430	47.00	2.53	1.33	2.17	1.92	41.6267	71.6331
23	01117468	8.87	37.2	7.9	310	46.50	2.61	1.61	2.16	1.92	41.4925	71.6286
24	01117800	35.09	31.1	10.7	360	47.00	11.80	6.90	2.02	1.85	41.5739	71.7211
25	01118000	73.00	16.2	14.0	300	47.00	27.40	19.30	1.99	1.89	41.5000	71.7200
26	01126200	5.52	28.7	4.4	490	48.00	.93	.66	1.97	1.89	41.6931	71.7439
27	01127880	5.99	285.0	4.4	2,110	43.00	3.36	2.05	2.65	--	45.1350	71.2064
28	01137500	88.40	72.0	21.1	2,510	52.07	33.20	26.40	2.33	--	44.2700	71.6300
29	01139800	8.86	152.7	5.5	1,780	45.00	1.14	.20	1.77	--	44.0900	72.3400
30	01142500	30.50	80.4	10.2	1,320	39.06	3.50	1.60	1.45	--	43.9300	72.6600
31	01150800	3.40	500.0	1.6	2,430	46.00	.80	.55	2.41	--	43.6733	72.8092
32	01153500	103.00	56.5	21.6	1,340	44.00	9.20	5.50	1.58	--	43.2100	72.5200
33	01154000	72.20	87.4	17.4	1,320	43.00	6.30	3.70	1.59	--	43.1400	72.4900
34	01162500	19.30	27.2	11.8	1,110	43.24	1.20	.33	1.59	1.54	42.6800	72.1200
35	01169900	24.09	84.5	11.8	1,160	47.00	3.00	1.50	2.18	--	42.5419	72.6942
36	01170100	41.39	71.8	17.4	1,380	46.00	5.50	3.66	2.24	--	42.7033	72.6711
37	01171500	54.00	94.8	16.4	870	46.80	9.20	5.70	1.69	1.74	42.3200	72.6600
38	01171800	5.46	39.9	4.2	400	46.00	.80	.45	1.45	1.69	42.3025	72.6878
39	01174000	3.39	68.2	5.8	1,020	44.50	.13	.005	1.67	1.62	42.4800	72.3300
40	01174900	2.85	165.0	3.8	900	45.00	.21	.09	1.63	1.62	42.3356	72.3700
41	01175670	8.68	47.8	7.4	880	42.00	.36	.23	1.61	1.55	42.2650	72.0053

Table 8. Topographic, streamflow, and climatic characteristics of basins in the low-flow data set--Continued

Site number (fig. 1)	Station number	Drainage area (square miles)	Main channel slope (feet per mile)	Main channel length (miles)	Mean basin elevation (feet)	Mean annual precipitation (inches)	Annual minimum 7-day mean low flow, in cubic feet per second at indicated recurrence interval: 2-year	10-year	Mean annual runoff (cubic feet per second per square mile): from records[a]	from map[b]	Location of gaging station (decimal degrees): latitude	longitude
42	01176000	150.00	8.62	28.3	840	41.50	25.00	11.80	1.54	1.54	42.1800	72.2600
43	01180500	52.70	79.0	19.5	1,420	48.20	4.00[d]	.87[d]	1.88	--	42.2586	72.8731
45	01198000	51.00	54.2	15.2	1,180	44.20	5.90	3.60	1.55	1.55	42.1900	73.3900
46	01332000	40.90	77.4	10.6	1,840	55.30	6.90	4.70	2.25	--	42.7000	73.0900
47	01333000	42.60	33.0	27.5	1,620	45.90	6.90	3.60	1.95	--	42.7090	73.1970
48	04287000	74.01	61.7	14.0	1,490	38.00	10.10	6.80	1.55	--	44.1800	72.6400
49	04292100	4.29	310.0	4.0	1,510	42.00	.75	.42	2.56	--	44.6939	72.5833
50	04292700	8.50	49.2	5.7	340	33.00	.86	.42	.85	1.03	44.7036	73.1817
51	04293000	131.00	19.1	22.6	1,400	46.65	30.00	20.90	2.02	--	44.9700	72.3900

[a]Computed from streamflow records at the station, directly (for long records) or by correlation with index stations, except as footnoted otherwise.

[b]Interpolated from map by Knox and Nordenson (1955), only for stations in the low-relief region.

[c]Streamflow record too short to compute mean runoff; estimate is based on equation that relates mean runoff computed from records to mean runoff interpolated from map, as illustrated in figure 12.

[d]Value based on data set that included 7-day low flows affected by regulation in 1965, 1966, and 1967 climatic years. As explained on page vi, substitution of estimated natural (unregulated) 7-day flows for these years changed the estimates of 7-day low flows at this station to 3.9 cubic feet per second at the 2-year recurrence interval, and 2.1 cubic feet per second at the 10-year recurrence interval.

Table 9. Areal extent of surficial geologic units, swamps, and lakes

[Values are in square miles]

Site number (fig. 1)	Station number	Surficial geologic units								Swamps and lakes					
			Coarse stratified drift							Swamps, underlain by			Lakes, underlain by		
											Stratified drift			Stratified drift	
		Till	Constructional topography	Coarse normal	Coarse perched	Alluvium	Coarse cap	Fine stratified drift		Till	Coarse	Fine	Till	Coarse	Fine
1	01059800	5.33	0	7.2	0	0	0.04	1.55		0.04	0.44	0.10	0	0.32	0
2	01064300	9.88	0	0	.01	.28	0	0		0	.01	0	0	0	0
3	01064400	4.32	.18	.18	0	0	0	0		.005	0	0	0	0	0
4	01064800	5.25	0	0	.07	.11	0	0		0	0	0	0	0	0
5	01069700	1.12	0	7.91	.05	0	.05	.73		0	.12	0	0	.03	0
6	01073000	9.73	0	.81	.18	.01	.36	.92		.57	.05	.09	.16	0	.01
7	01075500	49.89	.70	.82	1.62	2.89	0	.03		.17	.03	0	.11	.02	0
8	01078000	71.62	.13	6.32	1.73	3.19	.29	2.01		.56	.55	1.48	.29	.19	.03
9	01084500	49.87	0	3.46	.57	.63	.15	.45		1.93	.42	.24	.86	.07	0
10	01085800	5.25	0	.09	.36	.10	0	0		.02	.02	0	.01	0	0
11	01087000	102.90	.17	15.06	2.42	3.55	.33	3.56		1.37	2.84	.98	1.29	.55	.027
12	01093800	3.42	0	.04	.03	.11	0	0		0	0	0	0	0	0
13	01094000	127.86	.57	27.51	4.86	8.26	.81	.62		2.15	2.65	.06	.44	.57	.02
14	01096000	48.27	.01	13.22	.39	1.97	0	.03		1.20	1.15	.00	.16	.23	0
15	01097300	5.25	0	7.06	0	0	0	0		.12	1.49	0	0	.056	0
16	01101000	10.92	0	8.77	1.58	0	0	.047		.18	2.94	.023	.008	.41	0
17	01105876	0	0	15.10	0	0	0	0		0	.42	0	0	.95	0
19	01106000	7.22	.02	.69	0	.05	0	0		1.00	.23	0	.01	0	0
20	01107400	2.28	0	6.92	0	.023	0	.096		.046	1.53	.026	0	.55	0
21	01111300	11.70	0	3.98	.03	.29	0	0		.63	.29	0	0	.08	0

Table 9. Areal extent of surficial geologic units, swamps, and lakes--Continued

Site number (fig. 1)	Station number	Surficial geologic units								Swamps and lakes					
			Coarse stratified drift							Swamps, underlain by			Lakes, underlain by		
											Stratified drift			Stratified drift	
		Till	Constructional topography	Coarse normal	Coarse perched	Alluvium	Coarse cap	Fine stratified drift		Till	Coarse	Fine	Till	Coarse	Fine
22	01115630	5.51	0	1.56	0.27	0.011	0	0.84		0.007	0.05	0.25	0	0.013	0.004
23	01117468	6.69	0	2.16	.02	0	0	0		.22	.49	0	.039	.035	0
24	01117800	25.35	0	9.57	.06	.10	0	.008		.94	2.08	0	.022	.46	0
25	01118000	53.68	0	18.87	.17	.32	0	.008		2.67	2.85	0	.83	.73	0
26	01126200	4.26	0	.61	.14	.006	.13	.37		.26	.15	.15	.012	.01	0
27	01127880	5.94	0	0	0	.05	0	0		.20	0	0	.06	0	0
28	01137500	75.68	0	5.63	2.93	2.76	.32	.088		0	.32	.042	.001	.035	.006
29	01139800	8.69	.02	0	0	.15	0	0		.01	0	0	.01	0	0
30	01142500	28.39	0	.28	.02	.82	.62	.39		.03	.02	.03	.03	0	0
31	01150800	3.36	0	0	0	.04	0	0		.01	0	0	.02	0	0
32	01153500	91.96	0	3.41	1.39	4.34	0	0		.21	.22	0	.08	.02	0
33	01154000	67.74	0	1.50	.73	2.31	0	0		.32	0	0	.04	.01	0
34	01162500	17.85	.01	1.00	.03	.43	0	.004		1.37	.24	0	.21	.27	0
35	01169900	21.06	0	1.49	.84	0.70	0	0		.18	.038	0	.014	.063	0
36	01170100	40.40	0	.30	.07	1.01	0	0		.04	0	0	.14	0	0
37	01171500	44.50	0	3.86	3.06	1.73	0	.81		.74	.40	.003	.29	.19	0
38	01171800	3.64	0	1.58	.088	0	0	.15		.016	.14	0	.002	.015	0
39	01174000	3.32	0	.065	0	0	0	0		.022	0	0	.001	0	0
40	01174900	2.83	0	.015	0	.005	0	0		.015	0	0	0	0	0
41	01175670	7.48	0	.98	.029	.19	0	0		.30	.19	0	.005	.18	0

Table 9. Areal extent of surficial geologic units, swamps, and lakes--Continued

Site number (fig. 1)	Station number	Surficial geologic units: Till	Coarse stratified drift: Constructional topography	Coarse stratified drift: Coarse normal	Coarse stratified drift: Coarse perched	Coarse stratified drift: Alluvium	Coarse stratified drift: Coarse cap	Fine stratified drift	Swamps, underlain by: Till	Swamps, underlain by: Stratified drift: Coarse	Swamps, underlain by: Stratified drift: Fine	Lakes, underlain by: Till	Lakes, underlain by: Stratified drift: Coarse	Lakes, underlain by: Stratified drift: Fine
42	01176000	118.00	0	30.00	0.24	1.44	0.14	0.27	4.71	5.32	0	1.27	3.09	0
43	01180500	51.36	0	1.12	0	.26	0	0	.64	.036	0	.038	0	0
45	01198000	44.95	0	3.68	.13	2.25	0	0	.26	.15	0	.28	.036	0
46	01332000	37.20	.86	.91	.60	1.35	.01	0	.11	.03	0	.09	.01	0
47	01333000	38.89	.15	.63	.63	1.88	0	.45	.01	0	0	.017	.02	0
48	04287000	69.48	0	.30	.27	.71	.59	2.66	.19	.01	.02	.12	.01	0
49	04292100	4.04	0	.02	.04	.06	0	.13	.06	0	0	0	0	0
50	04292700	3.62	0	0	0	.04	2.69	2.16	.06	0	.15	0	0	0
51	04293000	115.49	0	4.76	3.01	3.98	1.85	2.86	.66	.01	0	.01	0	0