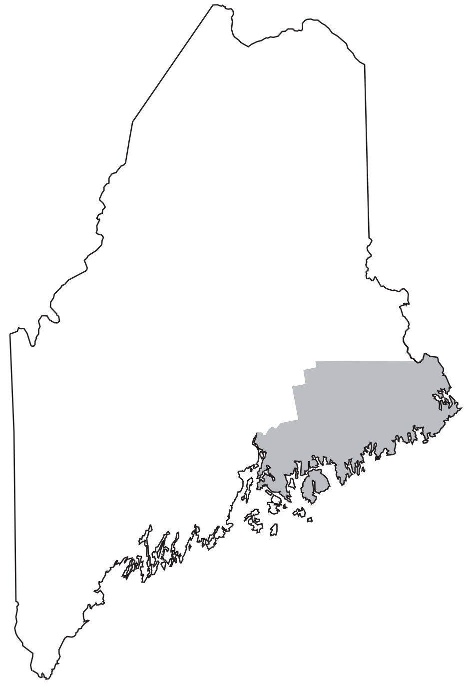
In cooperation with the
Maine Geological Survey,
Department of Environmental Protection,
Maine State Planning Office,
Maine Department of Agriculture,
Maine Department of Transportation

August Median Streamflow on Ungaged Streams in Eastern Coastal Maine



Scientific Investigations Report 2004-5157

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

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U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
inch (in.)	2.54	centimeter (cm)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

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

$$°C = (°F - 32) / 1.8$$

August Median Streamflow on Ungaged Streams in Eastern Coastal Maine

by Pamela J. Lombard

Abstract

Methods for estimating August median streamflow were developed for ungaged, unregulated streams in eastern coastal Maine. The methods apply to streams with drainage areas ranging in size from 0.04 to 73.2 square miles and fraction of basin underlain by a sand and gravel aquifer ranging from 0 to 71 percent. The equations were developed with data from three long-term (greater than or equal to 10 years of record) continuous-record streamflow-gaging stations, 23 partial-record streamflow-gaging stations, and 5 short-term (less than 10 years of record) continuous-record streamflow-gaging stations. A mathematical technique for estimating a standard low-flow statistic, August median streamflow, at partial-record streamflow-gaging stations and short-term continuous-record streamflow-gaging stations was applied by relating base-flow measurements at these stations to concurrent daily streamflows at nearby long-term continuous-record streamflow-gaging stations (index stations). Generalized least-squares regression analysis (GLS) was used to relate estimates of August median streamflow at streamflow-gaging stations to basin characteristics at these same stations to develop equations that can be applied to estimate August median streamflow on ungaged streams. GLS accounts for different periods of record at the gaging stations and the cross correlation of concurrent streamflows among gaging stations. Thirty-one stations were used for the final regression equations.

Two basin characteristics—drainage area and fraction of basin underlain by a sand and gravel aquifer—are used in the calculated regression equation to estimate August median streamflow for ungaged streams. The equation has an average standard error of prediction from -27 to 38 percent. A one-variable equation uses only drainage area to estimate August median streamflow when less accuracy is acceptable. This equation has an average standard error of prediction from -30 to 43 percent. Model error is larger than sampling error for both equations, indicating that additional or improved estimates of basin characteristics could be important to improved estimates of low-flow statistics.

Weighted estimates of August median streamflow at partial-record or continuous-record gaging stations range from 0.003 to 31.0 cubic feet per second or from 0.1 to 0.6 cubic feet per second per square mile. Estimates of August median streamflow on ungaged streams in eastern coastal Maine, within the range of acceptable explanatory variables, range from 0.003 to 45 cubic feet per second or 0.1 to 0.6 cubic feet per second per square mile. Estimates of August median streamflow per square mile of drainage area generally increase as drainage area and fraction of basin underlain by a sand and gravel aquifer increase.

Introduction

The need for information to describe low-flow characteristics of streams in Maine by Federal, State, and local agencies, consulting engineers, commercial enterprises, and natural resource conservation groups is increasing. Low-flow characteristics are used to determine the adequacy of streamflow for development of water supplies, disposal of wastes, generation of electricity, irrigation of agricultural land, maintenance and restoration of aquatic habitat, and conservation of watersheds. Currently (2004), few streamflow-gaging stations on small streams (streams with drainage areas less than 100 mi^2) in eastern coastal Maine have a sufficient period of record (10 years) to estimate low-flow statistics in this region. New England-wide equations used to estimate August median streamflows on ungaged streams with large drainage areas may not apply to small streams in eastern coastal Maine. Management and effective utilization of water resources could improve with low-flow estimation techniques developed specifically for small streams in this region.

The New England Aquatic Base-Flow (ABF) policy was developed by the U.S. Fish and Wildlife Service (USFWS) (1981) to manage low streamflows for aquatic organisms while still allowing water withdrawals for human consumption. The ABF policy recommends that water not be withdrawn from streams when streamflow is below the August median streamflow. The USFWS estimated the August median streamflow per square mile of drainage area by using the median of the annual series of August monthly mean streamflows from 48 streamflow-gaging stations in New England (U.S. Fish and

Wildlife Service, 1981). In the absence of adequate streamflow data, the policy recommends that an ABF of 0.5 $(ft^3/s)/mi^2$ (cubic feet per second per square mile) of drainage area can be used to approximate August median flow.

The definition of August median streamflow has varied in previous investigations; thus, the resulting values of August median streamflow per square mile of drainage area also have varied. In cases where a central value of a distribution is preferable to one that may be skewed by a few extreme observations, the median of the monthly medians or the median of the daily flows is preferable to a central measure such as the mean or the median of the mean monthly streamflows (Helsel and Hirsch, 1992). Charles Ritzi and Associates (1987) and Kulik (1990) calculated the August median streamflow at streamflow-gaging stations in New England as the median of all of the daily mean streamflows measured in August during the period of record. Charles Ritzi and Associates (1987) estimated the August median to be from 0.33 to 0.38 $(ft^3/s)/ mi^2$. Kulik (1990) determined that the August median varied by region and estimated it as 0.6 $(ft^3/s)/mi^2$ for mountain windward regions and 0.3 $(ft^3/s)/mi^2$ for non-mountain windward regions in New England.

County and statewide policies and regulations regarding water withdrawals and (or) instream water use are being developed with limited information on streamflows in Maine. The State of Maine recently adopted legislation to ensure water-withdrawal reporting (Maine State Legislature, 2002). This legislation directs the Board of Environmental Protection to establish water-use standards for maintaining instream flows by 2005. Standards will be based on the natural variation of flows and water levels. Adequate equations to estimate low-flow statistics, including August median streamflows, are a critical first step in establishing these standards. Additionally, one of the goals of the Atlantic Salmon Conservation Plan is “to ensure water withdrawal or impoundment does not adversely affect Atlantic salmon during high, medium, or low water periods” (Maine Atlantic Salmon Task Force, 1997). Part of this plan is to obtain reliable and accurate flow information for the Narraguagus, Pleasant, and Machias Rivers in eastern coastal Maine. To develop regression equations that could be used to better estimate the August median streamflow on ungaged, unregulated streams in eastern coastal Maine, the U.S. Geological Survey (USGS) began a 5-year cooperative study with the Maine Geological Survey in 2000. Additional support for the project was provided by Maine Department of Environmental Protection, Maine State Planning Office, Maine Department of Agriculture, and Maine Department of Transportation.

Purpose and Scope

This report presents equations to estimate August median streamflow on streams in Washington and Hancock Counties in eastern coastal Maine (Fig.1), as well as an estimate of the accuracy of these equations. The report describes (1) how instantaneous streamflow measurements at partial-record streamflow-gaging stations and short-term continuous-record streamflow-gaging stations were correlated to daily mean streamflows at long-term continuous-record streamflow-gaging stations to estimate August median streamflows at the partial-record stations and short-term continuous-record stations; (2) how regression equations to estimate August median streamflow on small, ungaged streams were developed; and (3) how weighted estimates of August median streamflow at partial-record stations and continuous-record stations in the study area were calculated.

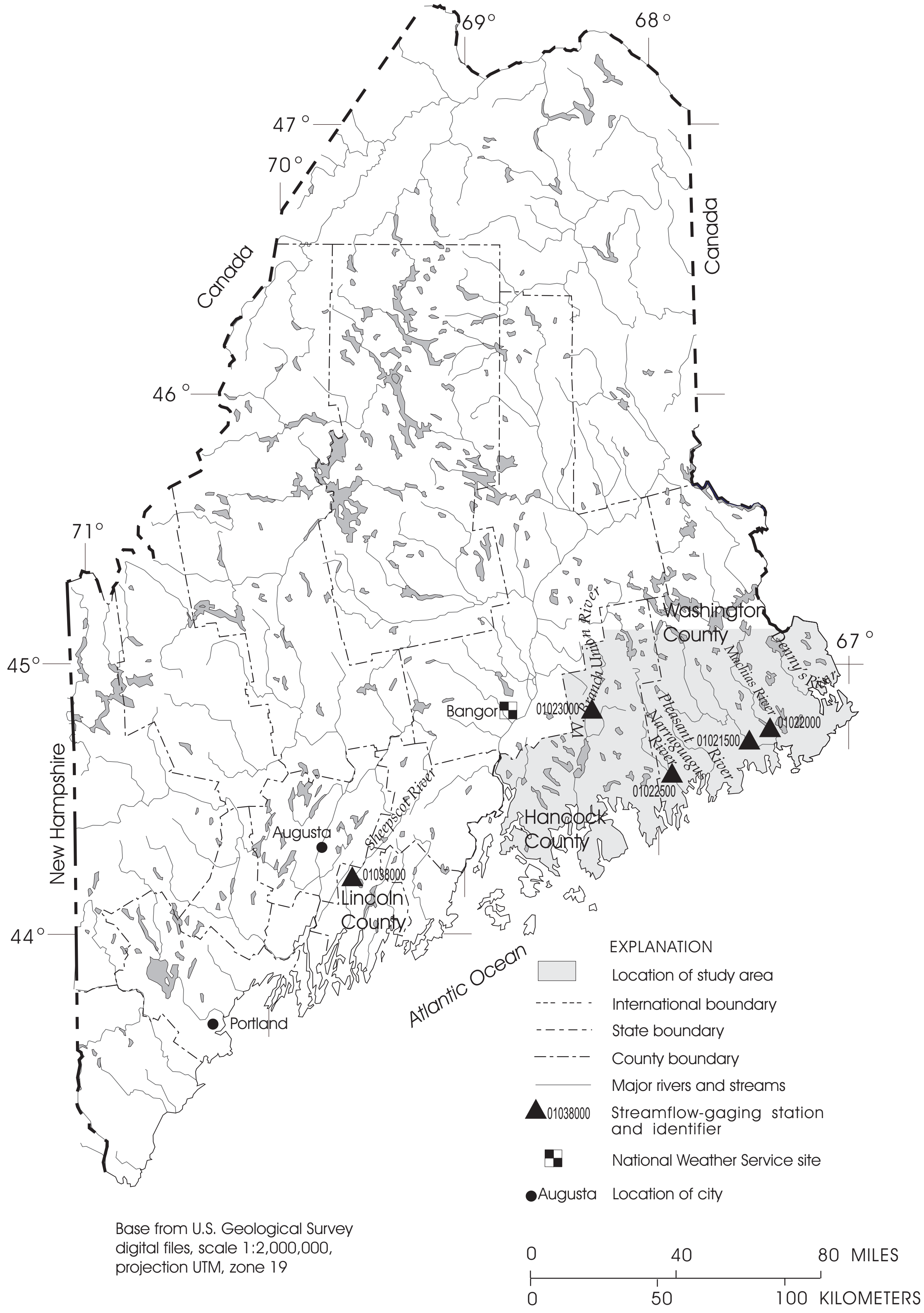
Previous Studies

A previous study of August median streamflow on ungaged streams was conducted in eastern Aroostook County, Maine (Lombard and others, 2003). Mean basin elevation and drainage area were used to estimate August median streamflow on basins with drainage areas from 0.38 to 43 mi^2 in northern Maine. Additionally, statewide low-flow equations for basins ranging in size from 10 to 1,400 mi^2 were recently developed for Maine (Dudley, 2004). These statewide low-flow equations use drainage area and fraction of basin underlain by a sand and gravel aquifer to estimate the annual 7-day low flow with a 10-year recurrence interval (7Q10), and summer mean monthly and median monthly flows in Maine.

Methods for estimating low-flow statistics at partial-record stations on the basis of correlations between daily mean discharges at the partial-record streamflow-gaging stations and concurrent daily mean discharges at nearby continuous-record streamflow-gaging stations are presented by Riggs (1972). Riggs also outlined a technique of regionalizing low-flow characteristics of rivers by multiple regression on basin characteristics, such as drainage area and surficial geology. Numerous investigators have applied this technique of regionalization to develop low-flow regression models, using basin characteristics as independent variables to predict low-flow statistics on ungaged streams in New England (Johnson, 1970; Cervionne and others, 1993; Risley, 1994; Wandle and Randall, 1994; Ries, 1994a, 1994b, 1997). Ries (1997) developed equations specifically for estimating August median streamflow in Massachusetts. These investigators all found low-flow statistics to be highly correlated to drainage area, and in most cases, the relation was specific to a geographic region of the State. Other variables that commonly were correlated with low-flow statistics were a measure of the basin relief or slope (Risley, 1994; Ries, 1994a, 1994b, 1997) and a measure of the surficial geology (Cervione and others, 1993; Wandle and Randall, 1994; Ries, 1994a, 1994b, 1997).

Description of Study Area

Hancock and Washington Counties are in the coastal part of eastern Maine (fig. 1), encompass 1,522 mi^2 and 2,528 mi^2, respectively, and had populations of 51,791 and 33,941 in 2000



Base from U.S. Geological Survey digital files, scale 1:2,000,000, projection UTM, zone 19

Figure 1. Location of study area and continuous-record streamflow-gaging stations used as index stations, eastern coastal Maine.

Maine Register, 2004). This sparsely populated region is characterized by low-relief rolling topography, and is made up primarily of forest and blueberry barrens. The surficial geologic materials in the basins are predominantly glacial till, and fine and coarse-grained glaciomarine deposits with some ice-contact glaciofluvial deposits, eskers, and bedrock (Thompson and Borns, 1985).

Cold winters and cool summers typify the climate of eastern coastal Maine. The normal annual temperature based on the 30-year period from 1971 to 2000 in Bangor is 44.7° F, with mean monthly temperatures ranging from 18° F in January to 69° F in July. The mean annual precipitation is 40 in. in Bangor (National Weather Service, http://www.erh.noaa.gov/er/car/climate.htm). High flows typically occur in early spring and late fall, and low flows generally occur in the summer and early fall. During the summer months, streamflow comes from ground water discharged from aquifers (base flow), and rainfall from summer storms.

Data Collection and Analysis

A continuous-record streamflow-gaging station (continuous-record station) is a station at which data are collected with sufficient frequency to define daily mean values and variations within a day (Stewart and others, 2003). A partial-record streamflow-gaging station (partial-record station) is a station at which discrete measurements are obtained over a period of time without continuous data being recorded or computed (Stewart and others, 2003). For the purposes of this report, continuous-record stations are divided into continuous-record stations with less than 10 years of record (short-term continuous-record stations), and continuous-record stations with equal to or more than 10 years of record (long-term continuous-record stations). Index stations are long-term continuous-record stations with daily streamflow measurements that correlate well with base-flow measurements at a partial-record station or short-term continuous-record station.

Ideally, equations to estimate August median streamflow on small, ungaged streams in eastern coastal Maine would be developed from long-term continuous-record data from small streams in the same region. Because only three stations on small streams in eastern coastal Maine have long-term continuous records with August median streamflows greater than zero, short-term continuous-record stations and partial-record stations also were used to develop the equations. Low-flow statistics at long-term continuous-record stations were calculated directly from the data. Records from index stations were used to estimate August median streamflow at partial-record stations and short-term continuous-record stations. All but one of the index stations used in this study are in the eastern part of Maine near the coast in Hancock and Washington Counties. The remaining index station is in Lincoln County (fig. 1).

Station Selection and Streamflow Measurements

Twenty-six partial-record stations and one short-term continuous-record station were established for this project. In addition, nine existing short-term continuous-record stations and four existing long-term continuous-record stations were tested for possible inclusion in the regression analysis. Of these 40 potential stations, nine were eliminated for the following reasons: two partial-record stations were eliminated because they each had two outlets, making their drainage areas difficult to define; one partial-record station, one short-term continuous-record station and one long-term continuous-record station were eliminated because they had August median streamflows estimated at 0.0 ft^3/s (cubic feet per second); two short-term continuous-record stations were eliminated because they did not correlate well with any of the index stations tested; and two short-term continuous-record stations were eliminated because most of their measurements were rated as poor (Stewart and others, 2003). The 31 remaining stations were used in the regression analysis to develop an equation to estimate August median flow on ungaged streams (fig. 2, table 1). All stations used in the regression analysis are in Hancock and Washington Counties, have relatively small drainage areas (from 0.04 mi^2 to 73 mi^2), are unregulated, and as a group are considered representative of eastern coastal Maine.

In addition to the stations described above, 10 long-term continuous-record stations were tested for use as index stations. Ideally, index stations would be close to partial-record stations geographically and have drainage areas in the same range as the drainage areas of the partial-record stations (less than 100 mi^2). Because few long-term continuous-record stations in the region meet these criteria, stations with drainage basins larger than 100 mi^2 also were tested for use as index stations. The 10 stations tested include the 4 long-term continuous-record stations tested for use in the regression analysis (only 3 of which were used in the final regression analysis), and 6 long-term continuous-record stations that were not tested for use in the regression analysis because their drainage areas are greater than 100 mi^2. Five long-term stations were chosen as index stations on the basis of their correlations with at least one partial-record station or one short-term continuous-record station (table 2). Three of the index stations are in Washington County, one is in Hancock County, and one is in Lincoln County (fig. 1). Although two of the stations (USGS streamflow-gaging stations 01022000 and 01023000) are no longer active continuous-record gaging-stations, base-flow measurements were made at these stations on the same day that the measurements were made at the partial-record stations in order to correlate flows at the partial-record stations with flows at the index stations. Selected index stations have been gaged by the USGS from 18 to 64 years. All streamflow data can be found in the series of USGS annual water-data reports and predecessor Water-Supply Papers (Stewart and others, 2003).

Standard USGS methods as described by Rantz and others (1982) were used to make all streamflow measurements at the partial-record stations. Measurements were made by wading

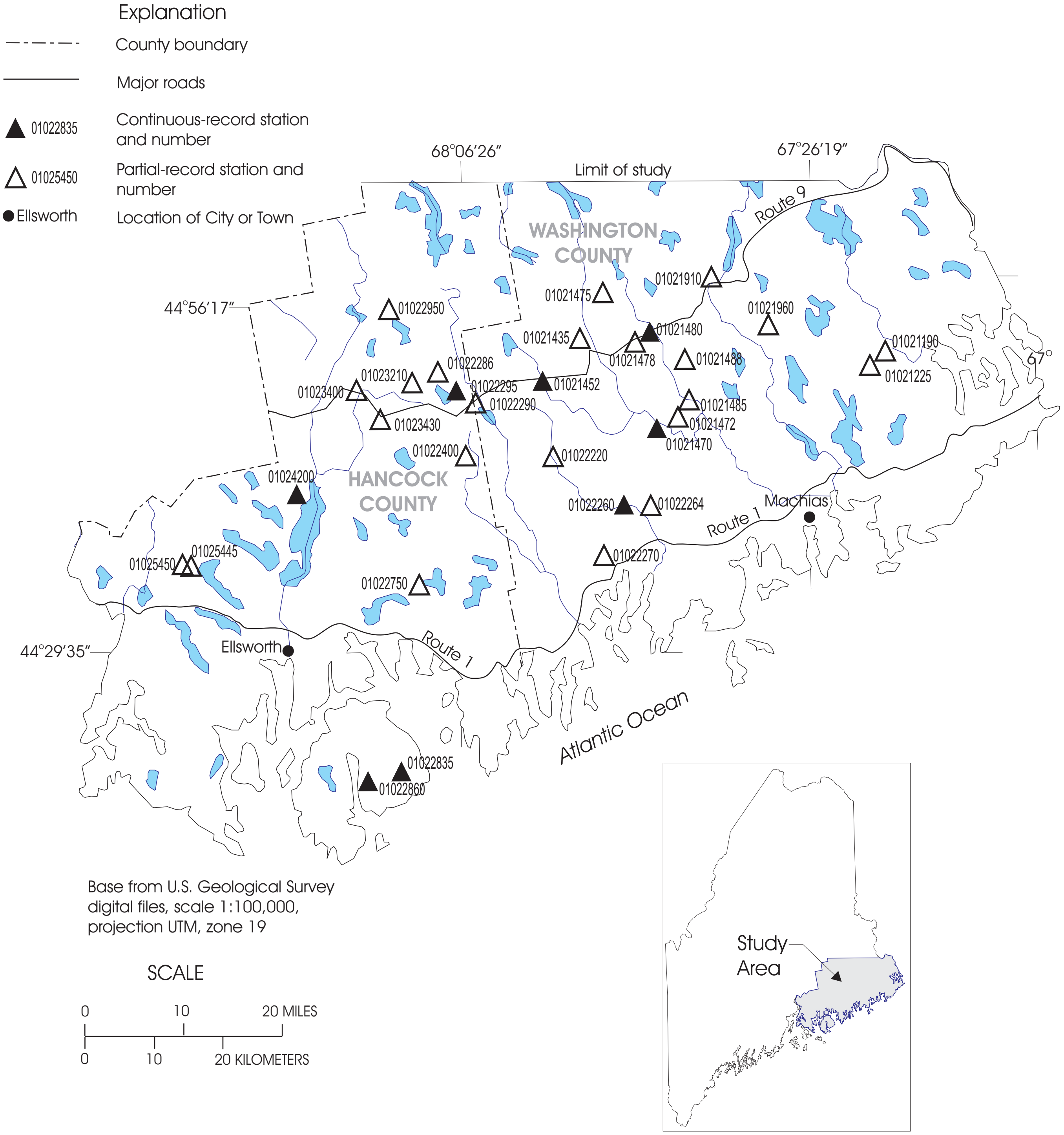


Figure 2. Location of partial-record and continuous-record streamflow-gaging stations used in regression analyses in eastern coastal Maine.

Table 1. Partial-record and continuous-record stations and selected basin characteristics used in regression analyses, eastern coastal Maine.

[USGS, U.S. Geological Survey; mi^2, square miles; o ‘ “, degrees, minutes and seconds].

USGS station number (Fig. 2)	Latitude o ‘ “	Longitude o ‘ “	Station name and location	Number of base-flow measurements*	Index station number	Drainage area (mi^2)	Fraction of basin underlain by a sand and gravel aquifer
			Partial-record stations				
01021190	44 54 14	67 17 15	Venture Brook near Dennysville, Maine	10	01022000	3.13	0
01021225	44 53 07	67 19 02	Cathance Stream at Marion, Maine	10	01022000	27	0
01021435	44 55 41	67 52 09	Crooked River near Beddington, Maine	10	01022500	17.5	0.278
01021472	44 49 12	67 41 04	Holmes Brook near Northfield, Maine	10	01038000	5.43	0.283
01021475	44 59 24	67 49 24	Dead Stream near Wesley, Maine	10	01038000	0.996	0
01021478	44 55 22	67 45 50	Honeymoon Brook near Wesley, Maine	10	01022500	0.416	0
01021485	44 50 35	67 39 47	Old Stream near Northfield, Maine	10	01022500	73.2	0.229
01021488	44 53 52	67 40 09	New Stream near Wesley, Maine	11	01021500	10.3	0
01021910	45 00 32	67 36 58	Harmon Brook near Crawford, Maine	10	01021500	3.24	0
01021960	44 56 33	67 30 32	Northern Stream near Cooper, Maine	10	01022000	24	0.037
01022220	44 46 08	67 55 23	Pleasant River near Crebo Flat, Maine	10	01022500	25.5	0.693
01022264	44 41 53	67 44 16	Little River near Columbia Falls, Maine	10	01022500	5.25	0.118
01022270	44 38 04	67 49 46	Harrington River near Harrington, Maine	10	01022500	6.53	0.239
01022286	44 53 06	68 08 24	Humpback Brook near Beddington, Maine	10	01022500	3.2	0
01022290	44 50 34	68 04 10	Narraguagus River near Beddington, Maine	10	01022500	67.8	0.105
01022400	44 46 17	68 05 20	Pork Brook near Lower Beddington, Maine	10	01022500	2.1	0.289
01022750	44 35 48	68 10 46	Card Mill Stream near Franklin, Maine	10	01022000	15.2	0
01022950	44 58 14	68 13 59	Alligator Stream near Great Pond, Maine	10	01022000	7.83	0.020
01023210	44 52 16	68 11 23	Unnamed Trib. to Lower Lead Mtn Pond near Beddington, Maine	10	01022500	1.79	0
01023400	44 51 42	68 17 43	Middle Branch Union River near Aurora, Maine	8	01022500	28.1	0.033
01023430	44 49 18	68 14 59	Leighton Brook near Aurora, Maine	10	01023000	2.14	0.310
01025445	44 37 37	68 37 42	Unnamed tributary to Winkumpaug Brook near Ellsworth, Maine	10	01021500	0.253	0
01025450	44 37 37	68 37 42	Winkumpaug Brook near Ellsworth, Maine	12	01021500	1.98	0

Table 1. Partial-record and continuous-record stations, and selected basin characteristics used in regression analyses, eastern coastal Maine--Continued

[USGS, U.S. Geological Survey; mi^2, square miles; o ‘ “, degrees, minutes and seconds].

USGS station number (Fig. 2)	Latitude o ‘ “	Longitude o ‘ “	Station name and location	Period of continuous record (water years**)	Index station number	Drainage area (mi^2)	Fraction of basin underlain by a sand and gravel aquifer
			Continuous-record stations				
01021452	44 52 16	67 56 27	Mopang Stream near Beddington, Maine	2001-03	01021500	18.8	0.051
01021470	44 48 03	67 43 31	Libby Brook near Northfield, Maine	2002-03	01038000	7.79	0.706
01021480	44 56 09	67 44 08	Old Stream near Wesley, Maine	1998-03	01022500	29.1	0.210
01022260	44 41 52	67 47 16	Pleasant River near Epping, Maine	1980-91, 2000-03	NA***	60.6	0.340
01022295	44 51 34	68 06 23	West Bear Brook near Beddington, Maine	1988-03	NA***	.04	0
01022835	44 20 41	68 13 02	Cadillac Brook near Bar Harbor, Maine	1999-2003	01038000	.123	0
01022860	44 19 54	68 16 48	Hadlock Brook near Northeast Harbor, Maine	1999-2003	01038000	.182	0
01024200	44 43 17	68 24 40	Garland Brook near Mariaville, Maine	1964-82	NA***	9.79	0.096

* All base-flow measurements made between 2000 and 2003.

** The water year is the 12-month period from October 1 through September 30.

*** August median flow can be calculated at stations with 10 or more years of continuous record, thus, these stations do not need an index station for record extension.

Table 2. Long-term continuous-record streamflow-gaging stations in Maine used as index stations.

[USGS, U.S. Geological Survey; o ‘ “, degrees, minutes and seconds; ft^3/s, cubic feet per second; mi^2, square miles].

USGS station number (Fig. 1)	Latitude o ‘ “	Longitude o ‘ “	Station name	Period of continuous record (water years*)	Drainage area (mi^2)	August median streamflow (ft^3/s)
			Continuous-record stations used as index stations			
01021500	44 43 23	67 31 15	Machias River at Whitneyville, Maine	1905-1921, 1929-1976, 2001-2003	458	219
01022000	44 46 05	67 24 30	East Machias River near East Machias, Maine	1927-1958	251	81
01022500	44 36 29	67 56 10	Narraguagus River at Cherryfield, Maine	1948-2003	227	84
01023000	44 50 25	68 22 22	West Branch Union River at Amherst, Maine	1910-1919, 1929-1979	148	27
01038000	44 13 23	69 35 38	Sheepscot River at North Whitefield, Maine	1938-2003	145	30.5

*The water year is the 12-month period October 1 through September 30.

current-meter methods, portable Parshall flume methods, and volumetric methods. Streamflows at the partial-record stations were measured during independent base flows that were separated by storms. A range of flows throughout the summer months was sought, and flows that changed rapidly or flows that could be attributed directly to rain runoff were avoided. Measurements of low flow were made within a 30-hour period at all stations for each independent base flow event. All flow records are published in the series of USGS annual water-data reports (Stewart and others, 2003).

Basin Characteristics

Topographic, climatic, and geologic basin characteristics, which potentially could be linked to the low-flow statistic August median streamflow, were delineated and calculated using a geographic information system (GIS). Calculated basin characteristics include drainage area, minimum, maximum and mean elevation, elevation range, mean basin slope, percent of basin underlain by a sand and gravel aquifer, percent wetlands, percent ponds, percent total storage, and annual precipitation at the basin centroids. The base-10 logarithmic transformation of each basin characteristic also was calculated.

Basin delineation was done by hand using contours on 1:24,000-scale USGS quadrangle maps. Basin characteristics including drainage area were calculated for each basin after the basin boundary was digitized using GIS. Minimum, maximum, and mean elevation, elevation range, and mean basin slope were computed from a 30-meter-resolution USGS digital elevation model (DEM). Slope for each pixel was determined using a 9-pixel moving average of the DEM. Mean basin slope was computed as the mean of all pixel slopes in the basin. Pond areas were calculated from the digital line graphs of 1:24,000-scale 7.5 minute USGS topographic quadrangle maps. Fraction of basin underlain by a sand and gravel aquifer were calculated from drainage maps compiled by Maine Geological Survey. Wetland, pond, and total storage areas were calculated from digital National Wetland Inventory maps produced by USFWS at a scale of 1:24,000. Mean annual precipitation for each basin was computed using Parameter-elevation Regressions on Independent Slopes Model (PRISM) output grids (Daly and Neilson, 1992; Daly and others, 1997). The NRCS PRISM Internet site below serves non-proprietary versions of annual and monthly PRISM precipitation data (http://www.ftw.nrcs.usda.gov/prism/prismdata_state.html).

August Median Streamflows at Streamflow-Gaging Stations

August median streamflows were estimated at all partial-record and continuous-record stations including index stations. August median streamflows for the partial-record stations and short-term continuous-record stations were estimated by correlating the low streamflow measurements made at the stations to daily mean streamflows on the same days at index stations. This method is described by Riggs (1972) and follows the USGS guidelines for regional low-flow analyses where appropriate (U.S. Geological Survey, 2003). Weighted estimates of the August median streamflows at all stations used in the regression analyses are presented near the end of this report.

Computation of August Median Streamflow at Long-Term Continuous-Record Stations including Index Stations

August median streamflows were calculated at all long-term continuous-record stations including index stations. Initially, the series of annual August medians was calculated at each long-term continuous-record station. The Mann Kendall trend test (Helsel and Hirsch, 1992) indicated that there was no trend with time in the annual series of August medians at any of the long-term continuous-record stations. The expected August median streamflow was estimated by computing the median of the observed annual August medians. This method of computing the August median streamflow closely approximates the method of taking the August daily mean streamflow that is exceeded 50 percent of the time during the period of all August daily streamflows for the period of record, but is preferable because it allows for the calculation of the variance around the median. This estimate of variance is essential for the generalized least-squares regression analyses, providing an estimate of error for the final regression equations.

Collection of daily mean streamflow data was discontinued at the East Machias River near East Machias, Maine (USGS station 01022000) in 1958 and the West Branch of the Union River at Amherst (USGS station 01023000) in 1979. These stations were still used as index stations because they had sufficient periods of record to calculate August median streamflows; base-flow measurements were collected from 2000 to 2003 to correspond with base-flow measurements at the partial-record stations. Machias River at Whitneyville (USGS station 01021500) was discontinued in 1976, but restarted in 2001. Base-flow measurements were collected in 2000 at this station to correspond with base-flow measurements at the partial-record stations.

Estimation of August Median Streamflows at Partial-Record Stations and Short-Term Continuous-Record Stations

August median streamflows for the partial-record stations and short-term continuous-record stations were estimated by relating the low streamflow measurements made at the stations to daily mean streamflows on the same days at index stations. Stedinger and Thomas (1985) developed a technique to estimate the mean and standard deviation of an annual event such as the d-day T-year low flow, which is the annual, minimum d-day consecutive low flow that will be exceeded, on average, every T years. Using this technique to calculate the August median at a partial-record station, as opposed to the d-day T-year low flow, is appropriate if the logarithms of the monthly medians at the index station are approximately normally distributed (G.D. Tasker, U.S. Geological Survey, oral commun., 2003). Estimates are made on the basis of the relation between base-flow measurements at the partial-record station and concurrent daily streamflows at an index station. This relation is defined by use of least-squares-regression analysis of the logarithms of the flows. The regression analysis and the low-flow statistic at the index station are used to estimate the desired flow characteristics at the partial-record station. The Stedinger-Thomas technique was used to calculate the August median streamflow and the variance of the August median streamflow at partial-record stations and short-term continuous-record stations. This technique fits a least-squares regression to the data after the user determines whether the base-flow measurements have an adequate linear relation with the concurrent daily streamflows at the index station.

In order to estimate an August median and standard deviation of the August median at partial-record and short-term continuous-record stations, the logarithm of the measured streamflows must have a linear correlation with the logarithm of the concurrent daily mean streamflows at an index station. An example of the correlation between concurrent measurements at a partial-record station and an index station is shown in figure 3. All the partial-record stations and short-term continuous-record stations used in the analysis had a correlation coefficient of 0.70 or greater with an index station. If measurements at a partial-record station correlated well (coefficient greater than 0.70) with measurements from more than one index station, then the index station with the higher correlation coefficient was used. If the correlation coefficient was similar for two index stations, then the index station was chosen on the basis of a visual observation of the graphical relation between the two stations. Base-flow measurements at the partial-record station, the corresponding daily mean streamflows at an index station, total number of years of record at the index station, and the median and standard deviation of the base-10 logarithms of the August median streamflows at the index station were used to compute the base-10 logarithms of the median streamflow and its variance at the partial-record station.

The Stedinger-Thomas technique was used to estimate the August median streamflow at all partial-record stations and short-term continuous-record stations except when the station had one or more measurements of zero streamflow. Two partial-record stations (USGS stations 01022400 and 01025445) and two short-term continuous-record stations (USGS stations 01022835 and 01022860) had at least one measurement of zero streamflow. Ordinary least-squares regression is based on the assumption that the residuals from the regression equation are approximately normally distributed. A logarithmic transformation of streamflow is generally required to achieve approximate

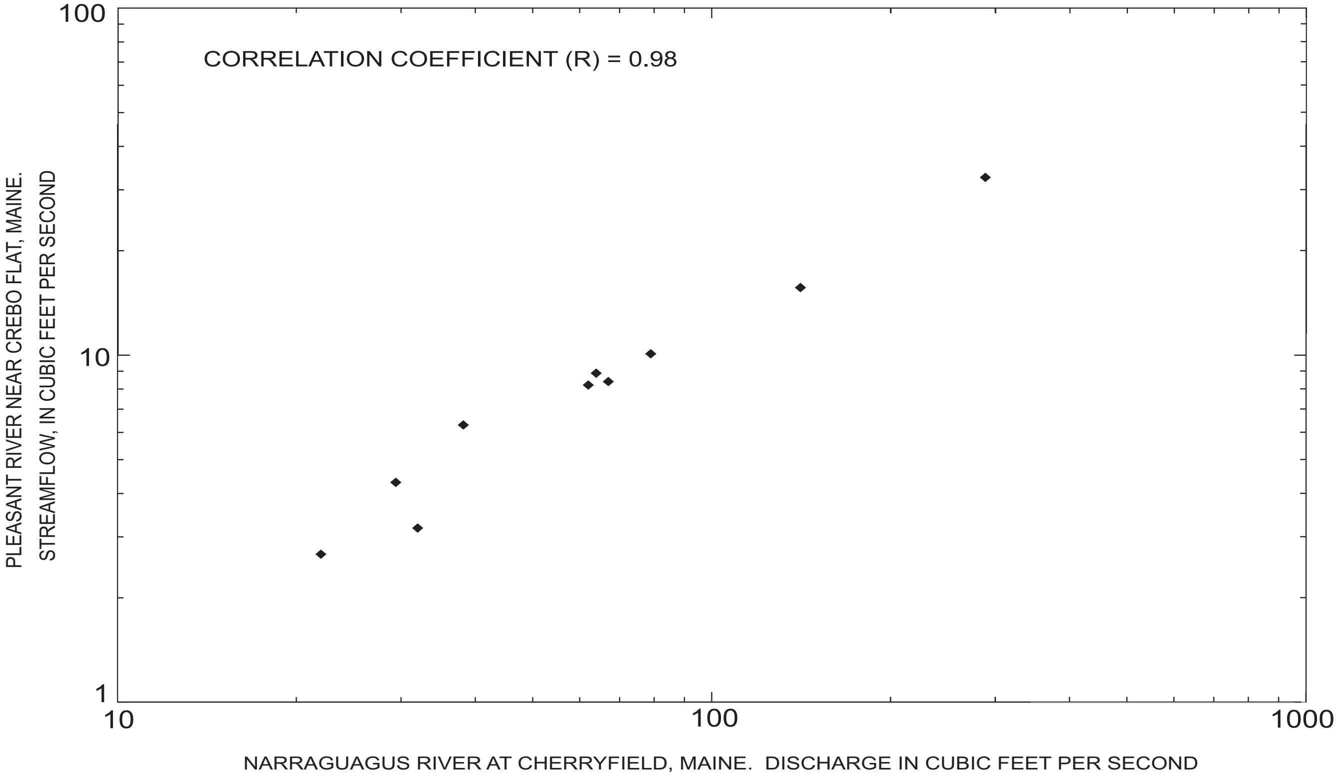


Figure 3. Relation of base-flow measurements at partial-record station, Pleasant River near Crebo Flat, Maine, and concurrent daily mean flow measurements at index station, Narraguagus River at Cherryfield, Maine, 2000-2003.

normality; however, the occurrence of zero flows makes the logarithmic transformation difficult to apply. Therefore, streamflow values below a small threshold (0.01 ft^3/s) were treated as censored values (less than 0.01 ft^3/s) and Tobit regression (Judge and others, 1985) was used to estimate the regression coefficients. A similar approach was used Perry and others (2002) in Kansas to estimate median streamflows in the presence of zero values. In these cases, the Tobit regression was computed including the zero observations, but the standard error of the residuals was computed using only the residuals from the non-zero observations (A.V.Vechia, U.S. Geological Survey, oral commun., 2004).

Estimation of August Median Streamflow on Ungaged Streams

Multiple-linear regression analyses were used to develop equations to estimate August median streamflow on ungaged streams. August median streamflow at the 31 partial- and continuous-record stations were related statistically to physical and climatic characteristics of the drainage basins of these stations. The independent variables drainage area and percent of basin underlain by a sand and gravel aquifer best explain the variability in the dependent variable, August median streamflow, and are included in the final regression equation. This equation can be used to estimate August median streamflow on a river in the absence of streamflow data if these basin characteristics can be calculated.

Statistical Methods

Initially, variations in the median August streamflow were related to variations in the drainage-basin characteristics through ordinary least-squares regression analysis (OLS) (Helsel and Hirsch, 1992). A regression of all possible subsets in OLS was used to reduce the number of drainage-basin characteristics and determine the best combination of independent variables to use in the final equation. Generalized least-squares (GLS) regression techniques were used to develop the final equations and estimates of accuracy presented in this report. Stedinger and Tasker (1985) showed that GLS regression techniques are more appropriate than OLS or weighted least-squares (WLS) for regionalizing streamflow statistics where the streamflow records at the index stations are of varying lengths and concurrent streamflows at different stations are cross-correlated. Although WLS can adjust for records of varying lengths, it does not adjust for the cross-correlation of concurrent streamflows at sites. The cross-correlation can be especially problematic when working with partial-record stations where two or more partial-record stations are correlated with the same index station. Another benefit of GLS over OLS and WLS is that the prediction error of the resulting equations in GLS can be separated into model error and sampling error.

Ordinary Least-Squares Regression

OLS equations were developed in a regression of all possible subsets. To establish linearity, logarithmic transformations of the response variable (August median streamflow) and one of the explanatory variables (drainage area) were performed. The equations with the strongest relations between the explanatory variables and the response variables were chosen on the basis of three values: the p-values of the T-statistic, the adjusted R^2, and Mallow's Cp statistic (Helsel and Hirsch, 1992). The p-values of the T-statistic indicate the significance of the individual explanatory variables, the adjusted R^2 value indicates the amount of variance in the response variable explained by the explanatory variable(s), and Mallow's Cp statistic is a compromise between maximizing the explained variance by including all relevant variables and minimizing the standard error by keeping the number of variables as small as possible (Helsel and Hirsch, 1992). Partial residual plots and residuals against predicted plots were examined. The best one- and two-variable models were tested for regression assumptions including linearity, homoscedasticity (constant variance in the response variable over the range of explanatory variables), and normality.

The best one- and two- variable models that satisfied the above-mentioned criteria had the following combinations of explanatory variables: the logarithm of the drainage area; the logarithm of the drainage area and the fraction of basin underlain by a sand and gravel aquifer.

Generalized Least-Squares Regression

Final one-, and two-variable models and their coefficients and estimates of error were selected with GLS. A model that estimated August median streamflow using the explanatory variables drainage area and fraction of basin underlain by a sand and gravel aquifer minimized the standard error and maximized the explained variance. A second model only using drainage area was selected for cases where reduced accuracy was acceptable. The GLS regression was adjusted for records of different lengths and the cross correlation of concurrent streamflows among partial-record stations, especially those correlated with the same index stations. Residuals were mapped for each partial-record station, and no spatial patterns were found. A computer program was developed for performing GLS regression in situations where the majority of stations being used to develop an equation for August median streamflow are partial-record stations. A more detailed statistical analysis and rationale for the use of GLS can be found in Lombard and others (2003).

Equations for Estimating August Median Streamflow on Ungaged Streams

Two-Variable Model

The final equation using fraction of basin underlain by a sand and gravel aquifer (Aq) and drainage area (DA) in square miles to predict August median streamflow at ungaged stations on ungaged streams (Qi) is

$$Qi = 0.148\ (DA)^{1.18466}\ \ 10^{0.409(Aq)}\ . \qquad (1)$$

Drainage area and fraction of basin underlain by a sand and gravel aquifer are both significant (p-values equal to 0.0001 and 0.0104, respectively). The average standard error of prediction (ASEP) is from -27 to 38 percent. The ASEP is a measure of how well the regression equation estimates the response variable when it is applied to ungaged drainage basins that were not used to develop the equation. There is a 68-percent probability that the true value of a median flow at a station will be within the range of the standard error of prediction.

The equation listed above is appropriate for predicting August median streamflows at unregulated drainage basins on ungaged streams in the coastal part of Hancock and Washington Counties within the two-dimensional range of variables shown by the shaded area in figure 4. If the equations are used with explanatory variables outside the two-dimensional range shown in figure 4, or if the explanatory variables are calculated with methods other than those outlined earlier, then the resulting estimates of August median streamflow will be of unknown accuracy.

Estimates of August median streamflow on ungaged streams range from 0.003 to 45 ft^3/s within the appropriate range of explanatory variables. If estimates are divided by the drainage area, these estimates range from 0.1 to 0.6 (ft^3/s)/mi^2, and these values generally increase as fraction of basin underlain by a sand and gravel aquifer and drainage area increase.

The GLS analysis results in an error that can be divided into sampling-error variance and model-error variance. The model-error variance is a measure of error resulting from an

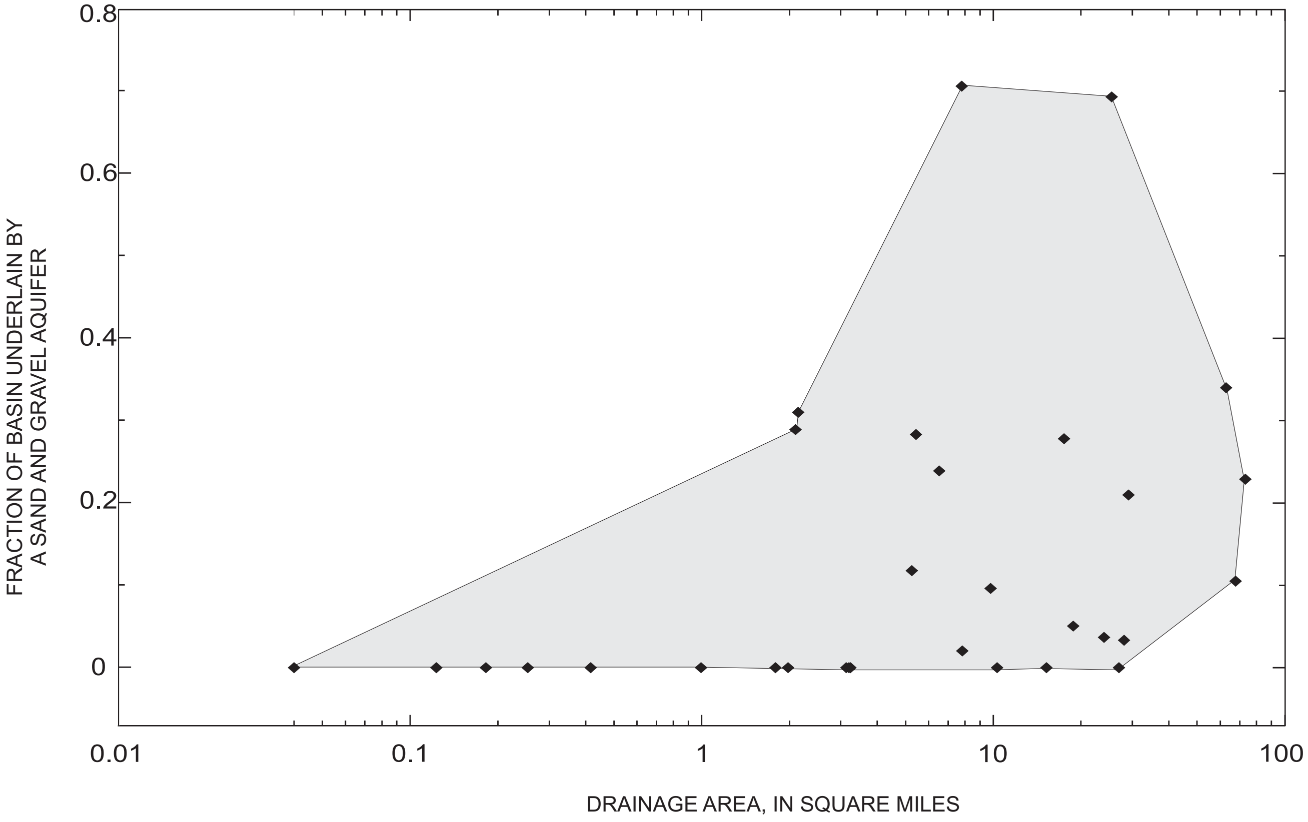


Figure 4. Two-dimensional range of explanatory variables used in regression equation for predicting August median streamflows on ungaged streams in eastern coastal Maine [shaded area shows range].

incomplete model, one that does not include all the variables that would be necessary to completely explain the variability in the entire population of the dependent variable. Sampling-error variance is a measure of the error resulting from only being able to sample a subset of the complete population (both in time and in space). The average model-error variance in the above model is 0.0149 (base-10 logs), and the average sampling-error variance is 0.0044 (base-10 logs). The model error is more than three times as great as the sampling error. This result indicates that future research on ungaged streams in Maine should focus on improving the model by developing new basin characteristics rather than by collecting additional data at present partial-record stations or by establishing new partial-record stations to reduce the error in the regression equation.

The statewide study in Maine for larger basins (Dudley, 2004) and low-flow studies in other northeastern States (Cervione and others, 1993; Wandle and Randall, 1994; Ries, 1994a, 1994b, 1997) indicate that surficial geology can be important in explaining the variability of low flows. More detailed mapping of the sand and gravel aquifers in Maine, as well as more index stations on small streams in the region of interest may increase the accuracy of future low-flow equations.

One-Variable Model

A simplified technique using only drainage area (DA) in square miles to estimate August median streamflow on ungaged streams (Qi) is presented in the equation below. This technique is quicker and easier to apply than the two-variable model, but should be used only when estimates of less accuracy are acceptable.

$$Qi = 0.167\,(DA)^{1.2236} \qquad (2)$$

Drainage area is highly significant (p-value < 0.0001). The average standard error of prediction is from -30 to 43 percent. This error is made up of an average model-error variance of 0.0197 (base-10 logs) and an average sampling-error variance of 0.0042 (base-10 logs). Estimates of August median streamflow range from 0.003 to 31 ft^3/s within the appropriate range of drainage areas. If these estimates are divided by the drainage area, they range from 0.1 to 0.6 $(ft^3/s)/mi^2$, and these values increase as drainage area increases. The estimates of August median streamflow on the small streams analysed in this report are lower than estimates of August median streamflow in previous investigations that had few or no stations less than 10 mi^2.

Weighted Estimates of August Median Streamflow at Partial- and Short-Term Continuous- Record Streamflow-Gaging Stations

It is appropriate to use weighted estimates of August median streamflow at partial-record and short-term continuous-record stations where available. If two independent estimates are weighted inversely proportional to their variance, the variance of the weighted average is less than the variance of either estimate (Interagency Advisory Committee on Water Data, 1982). Weighted estimates are made up of 1) measurements collected at the station and 2) the estimate for the August median streamflow at the station from the equation for ungaged stations. The weights for this estimate are based on the variance of the base-10 logs of the respective estimates (Lombard and others, 2003).

Weighted estimates of August median streamflow for the partial-record and short-term continuous-record stations used in this report are presented in table 3. The weighted estimates of August median streamflow range from 0.003 to 31 ft^3/s or from 0.1 to 0.6 $(ft^3/s)/mi^2$.

Summary and Conclusions

August median streamflows in eastern coastal Maine were studied by the U.S. Geological Survey in cooperation with the Maine Geological Survey, with additional support from the Maine Department of Environmental Protection, the Maine State Planning Office, the Maine Department of Agriculture, and the Maine Department of Transportation. This report presents equations that can be used to estimate August median streamflow on any unregulated stream in eastern coastal Maine that has a drainage area ranging in size from 0.04 to 73.2 mi^2 and a fraction of basin underlain by a sand and gravel aquifer ranging from 0 to 71 percent. August median streamflows were estimated at 3 long-term continuous-record stations (with records greater than or equal to 10 years), 23 partial-record stations, and 5 short-term continuous-record stations (records less than 10 years) to develop equations for estimating August median streamflow on ungaged streams. Each estimate of August median streamflow at a partial-record station or short-term continuous-record station was based on the stations's relation with one of five index stations in coastal Maine.

Table 3. Weighted August median streamflows at partial-record and short-term continuous-record streamflow-gaging stations, eastern coastal Maine.

[USGS, U.S. Geological Survey; ft^3/s, cubic feet per second; $ft^3/s/mi^2$, cubic feet per second per square mile].

USGS station number (Figs. 1 and 2)	Station name and location	Weighted August median flow (ft^3/s)	Weighted August median flow ($ft^3/s/mi^2$)
	Partial-record stations		
01021190	Venture Brook near Dennysville, Maine	0.53	0.17
01021225	Cathance Stream at Marion, Maine	7.61	0.28
01021435	Crooked River near Beddington, Maine	6.28	0.36
01021472	Holmes Brook near Northfield, Maine	1.05	0.19
01021475	Dead Stream near Wesley, Maine	0.12	0.12
01021478	Honeymoon Brook near Wesley, Maine	0.05	0.12
01021485	Old Stream near Northfield, Maine	21.8	0.30
01021488	New Stream near Wesley, Maine	1.66	0.16
01021910	Harmon Brook near Crawford, Maine	0.65	0.20
01021960	Northern Stream near Cooper, Maine	5.12	0.21
01022220	Pleasant River near Crebo Flat, Maine	10.69	0.42
01022264	Little River near Columbia Falls, Maine	1.61	0.31
01022270	Harrington River near Harrington, Maine	1.48	0.23
01022286	Humpback Brook near Beddington, Maine	0.50	0.16
01022290	Narraguagus River near Beddington, Maine	20.7	0.31
01022400	Pork Brook near Lower Beddington, Maine	0.45	0.21
01022750	Card Mill Stream near Franklin, Maine	4.06	0.27
01022950	Alligator Stream near Great Pond, Maine	2.48	0.32
01023210	Unnamed Tributary to Lower Lead Mountain Pond near Beddington, Maine	0.30	0.17
01023400	Middle Branch Union River near Aurora, Maine	8.03	0.29
01023430	Leighton Brook near Aurora, Maine	0.36	0.17
01025445	Unnamed tributary to Winkumpaug Brook near Ellsworth, Maine	0.03	0.12
01025450	Winkumpaug Brook near Ellsworth, Maine	0.34	0.17
	Continuous-record stations		
01021452	Mopang Stream near Beddington, Maine	8.55	0.45
01021470	Libby Brook near Northfield, Maine	4.68	0.60
01021480	Old Stream near Wesley, Maine	8.26	0.28
01022260	Pleasant River near Epping, Maine	31.0	0.51
01022295	West Bear Brook near Beddington, Maine	0.003	0.08
01022835	Cadillac Brook near Bar Harbor, Maine	0.01	0.09
01022860	Hadlock Brook near Northeast Harbor, Maine	0.02	0.11
01024200	Garland Brook near Mariaville, Maine	2.32	0.24

Generalized least-squares regression analyses resulted in a two-variable regression equation to estimate August median streamflow on ungaged streams using two drainage-basin characteristics, drainage area and fraction of basin underlain by a sand and gravel aquifer. An average standard error of prediction from 27 to 38 percent reflects the high degree of variability often demonstrated by small drainage basins. Within this estimate of error, the model error was more than three times as great as the sampling error, indicating that future research should focus on improving the model by developing new basin characteristics rather than by establishing new partial-record stations or col-lecting additional data at established stations. A one-variable regression equation using only drainage area to estimate August median streamflow on an ungaged stream also was developed along with an estimate of its accuracy. The equation should be used only when reduced accuracy is acceptable. The generalized least-squares regression accounted for records of different lengths as well as cross correlation between the stations in both the one- and two-variable models.

Weighted estimates of August median streamflow should be used at the partial-record stations and short-term continuous-record stations, because they combine regional regression equation estimates with specific estimates based on base-flow measurements for each station. The weighted estimates of August median streamflow range from 0.003 to 31 ft^3/s or from 0.1 to 0.6 $(ft^3/s)/mi^2$. Estimates of August median streamflow on ungaged streams range from 0.003 to 45 ft^3/s or from 0.1 to 0.6 $(ft^3/s)/mi^2$ when the equation is applied within the range of acceptable explanatory variables. Estimates generally increase as fraction of basin underlain by a sand and gravel aquifer and drainage area increase.

Estimates of August median streamflow per square mile of drainage area at ungaged stations vary with drainage basin size, and for the smaller streams, are lower than estimates in previous investigations. Previously, 0.5 $(ft^3/s)/mi^2$ was used on basins of all sizes to estimate August median streamflow. Differences in estimates are partially a result of the method of calculating the median streamflow. The median of the monthly median streamflow generally will be lower than the median of the mean monthly streamflow because mean streamflow data are skewed towards the higher flow events. Smaller August median values calculated in this report may also be a result of the smaller drainage basins used in this analysis. Previous investigations usually had few or no stations less than 10 mi^2 in drainage area. This investigation indicates that August median streamflow per square mile of drainage area increases as the basin size increases.

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