Prepared in cooperation with the
NORTH CAROLINA DEPARTMENT OF ENVIRONMENT,
HEALTH, AND NATURAL RESOURCES

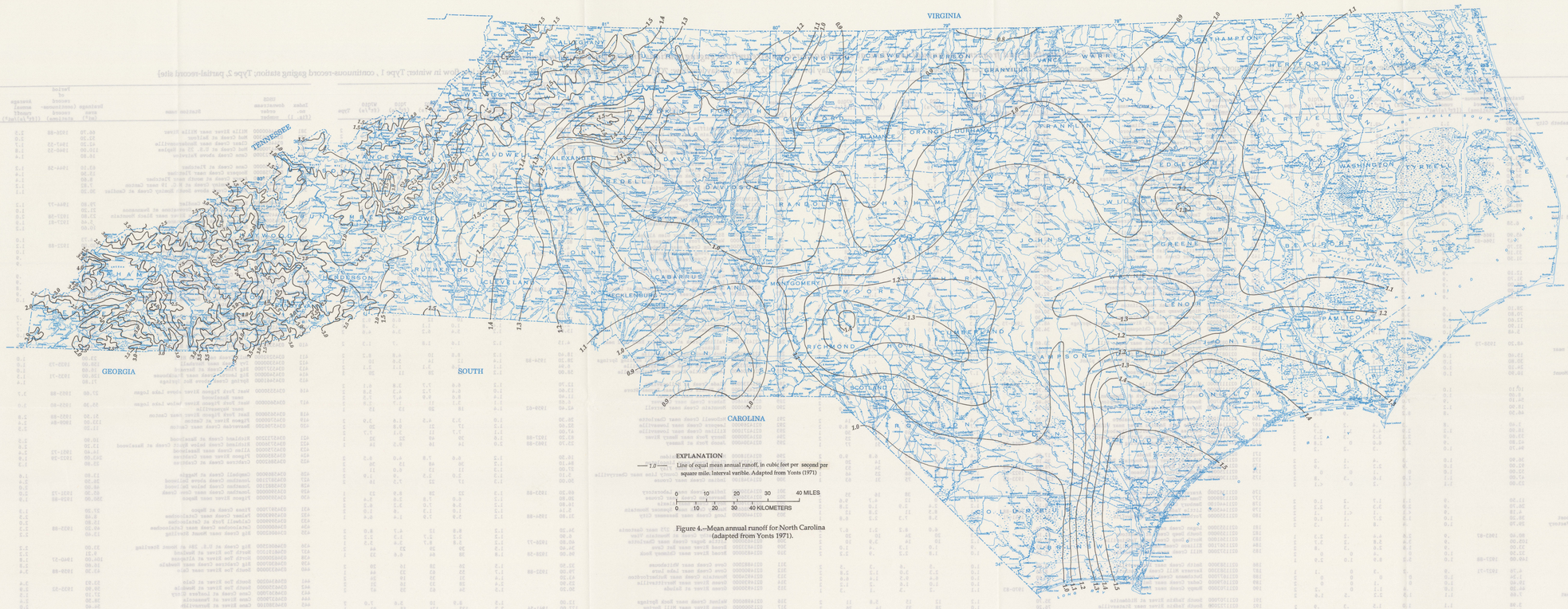

Figure 4.--Mean annual runoff for North Carolina (adapted from Yonts 1971).

REGIONAL LOW-FLOW FREQUENCY REGRESSION EQUATIONS

Multiple regression analysis was used in developing equations for estimating low-flow characteristics of streams. The assumed form of the regression equations was:

$$Y = B_0(X_1^{B_1})(X_2^{B_2})(X_3^{B_3})\ldots \qquad (1)$$

where

Y = the low-flow characteristic of interest (7Q10, W7Q10, 3Q02, or 7Q2),

B_0 = the regression constant,

B_1, B_2, B_3 = regression coefficients,

and

X_1, X_2, X_3 = explanatory variables related to low-flow characteristics.

Equation 1 is similar in form to that adopted in other studies, such as those by Carpenter (1983) and Barnes (1986). To assure linearity and constancy of the error variance, equation 1 was log-transformed to:

$$\log Y = \log B_0 + B_1 \log X_1 + B_2 \log X_2 + B_3 \log X_3 \ldots \qquad (2)$$

Preliminary multiple regression analysis was performed on a selected data set consisting of 74 continuous-record stations having a record of 30 years or more and 7 stations with records extended to 30 years or more through correlation techniques. A number of basin characteristics were also available for these stations, including drainage area, stream length, channel slope, percentage of basin forested, soil infiltration index, mean annual precipitation, the 2-year 24-hour rainfall intensity, mean January and July temperatures, Lane's variability index (Lane and Lai, 1950), and streamflow recession indices. In this and subsequent regression analyses, stations for which low-flow characteristics were zero were excluded because zero values cannot be log-transformed. On a statewide basis, drainage area proved to be the most significant of the above variables; in most regression analyses, mean annual precipitation was the second most significant variable.

Subsequent regression analyses, based on 120 continuous-record and 403 partial-record stations having drainage areas less than 400 mi^2, were used to examine fewer variables--drainage area, mean annual runoff, and average well yield by hydrologic area. Mean annual runoff, not tested with the preliminary 74-station data set, was used instead of precipitation because mean annual runoff more accurately reflects areal differences in annual evapotranspiration and infiltration than does precipitation. On an annual basis, for example, more of the precipitation that falls in the western Piedmont and mountains (HA10) eventually becomes streamflow because of the shorter growing season there as compared with other areas of the State.

In statewide regressions, drainage area, mean annual runoff, and well yield by hydrologic area were all significant at the 1-percent level. A 1-percent level of significance indicates that there is a 99-percent chance that there is a relation between the dependent and the explanatory variable. However, when regressions were performed on separate hydrologic areas or groups of similar hydrologic areas, use of the well-yield factor did not substantially improve the equations. Also, mean annual runoff resulted in distinct improvements only in the western Piedmont and mountains hydrologic area (HA10).

Residuals from statewide regressions based on drainage area alone and on drainage area and mean annual runoff together as explanatory variables were examined for areal bias. These examinations, along with Student's T-tests and analysis of variance by ranks of low-flow characteristics, indicated that the closely spaced Raleigh Belt hydrologic area (HA5) and the Charlotte Belt and Milton Belt hydrologic area (HA9) could be combined for purposes of regression analysis. Conversely, the residuals analysis and other tests of low-flow characteristics (primarily T-tests) indicated that separate regressions were more accurate for the Sand Hills hydrologic area (HA3) and the western Piedmont and mountains hydrologic area (HA10) than a single regression for the two hydrologic areas, particularly in the case of W7Q10 values, which were lower in the western Piedmont and mountains hydrologic area (HA10) than in the Sand Hills hydrologic area (HA3). The significant differences in the W7Q10 values are likely due to the fact that much of the precipitation that falls in the winter months in the western part of the State remains frozen and is unavailable to percolate into the ground-water system to sustain base flow to streams during the winter.

Tests indicated that a few combinations of the remaining hydrologic areas were justifiable for regression purposes, but the large percentage standard error of estimates of regression for these combinations were unacceptable. Therefore, these combinations were not used in this report. Despite some statistical homogeneity, such hydrologic areas maintain separate identities in table 1 for one or more of the following reasons: (1) physical separation, (2) lack of statistical homogeneity in one or more low-flow characteristics, and (3) clearly different topographic, geologic, or climatologic characteristics.

Final regression equations (3-10) for the Sand Hills hydrologic area (HA3) and the combined Raleigh Belt (HA5) and the Charlotte Belt and Milton Belt hydrologic areas (HA9) are listed in table 2; these equations incorporate drainage area (DA) as the only explanatory variable. Also given in table 2 are regression equations (11-16) for the western Piedmont and mountains hydrologic area (HA10); these equations incorporate mean annual flow (MAF) as the explanatory variable. MAF is a component variable obtained by multiplying drainage area (DA) by mean annual runoff (MAR) as obtained from figure 4. Equations (3-16) listed in table 2 are useful for estimating low-flow characteristics in streams in an area that covers 20,600 mi^2, or about 40 percent of the State. Standard error of estimates for these regression equations, which are for drainage basins greater than the lower drainage area limit given in table 1 but less than 400 mi^2, ranged from 31 percent for the 3Q02 equation (6) for the Sand Hills hydrologic area (HA3) to 92 percent for the 7Q10 equation (7) for the combined hydrologic areas HA5 and HA9. Regression equations developed for the remainder of the State are not presented in the report because standard error of estimates were too high (192 percent or larger) to provide reliable equations. For hydrologic areas where no equations were developed, refer to table 1 for the percentile distributions of computed low-flow characteristics.

Table 2.--*Low-flow frequency regression equations for selected hydrologic areas*[1]

[nQm flow, the minimum n-consecutive-day discharge, in cubic feet per second, with a probability of 1/m of occurring in any one climatic year; W7Q10 flow takes into account only the months of November through March; R^2, coefficient of determination; DA, drainage area in square miles; MAF, mean annual flow in cubic feet per second]

Hydrologic area name and number	Number of sites	Regression equation for nQm flow	R^2	Standard error of estimate (percent)	Equation number
Sand Hills (HA3)	24	$7Q10 = 0.431\ DA^{0.90}$	0.86	55	3
		$W7Q10 = 0.789\ DA^{0.91}$	.94	34	4
		$7Q2 = 0.653\ DA^{0.91}$	.93	37	5
		$3Q02 = 0.830\ DA^{0.91}$	.95	31	6
Raleigh and Charlotte and Milton Belts (HA5 and HA9, combined)	60	$7Q10 = 0.196\ DA^{0.93}$	.35	92	7
		$W7Q10 = 0.270\ DA^{0.78}$	.67	65	8
		$7Q2 = 0.253\ DA^{0.78}$	.69	61	9
		$3Q02 = 0.316\ DA^{0.83}$	.78	49	10
Western Piedmont and mountains (HA10)	299	$7Q10 = 0.155\ MAF^{1.01}$	.87	50	11
		$W7Q10 = 0.252\ MAF^{0.99}$	.90	40	12
		$7Q2 = 0.281\ MAF^{1.00}$	.92	37	13
		$3Q02 = 0.344\ MAF^{1.00}$	.93	33	14

[1]See table 1 for drainage area limits below which indicated low-flow statistics are generally zero. Equations should not be used for drainage areas less than these limits or for drainage areas greater than 400 square miles. Number of sites may differ slightly from those shown in table 1 because sites with zero values for flow characteristics were not used to develop regression equations.

A point of particular interest is that all of the exponents for the four equations for the western Piedmont and mountains hydrologic area (HA10) are about 1.0. This indicates that the low-flow characteristics for unregulated streams in this hydrologic area are directly related to mean annual flow by a proportionality constant. Fundamentally, any such relation is probably driven by precipitation and precipitation variability, of which streamflow and streamflow variability are largely reflective.

ESTIMATING LOW-FLOW FREQUENCY CHARACTERISTICS

A hierarchy of procedures is used in estimating low-flow frequency characteristics of streams. The most reliable estimates are generated from multi-year continuous records of streamflow at the site of interest. Other reliable estimates are those made from a series of five or more base-flow measurements at a site, which are then correlated with concurrent streamflow at one or more nearby long-term continuous-record stations for which low-flow characteristics are available. Procedures for these two cases are described by Riggs (1972).

For ungaged sites on gaged or measured streams, low-flow characteristics may be estimated by using a weighted average of estimates from the gaged site and regressions given in table 2. The weight of the estimate from the gaging station is 100 percent at the gage, diminishing to 0 percent at distance upstream and downstream corresponding to one-fourth and four-times the drainage area at the gage. The weight of the estimate from regression equations would be 100 percent minus the weight of the estimates from the gaged site. Outside the one-fourth and four-times drainage area limits, regional relations could be given full weight.

In hydrologic areas HA3, HA5, HA9, and HA10, regression equations 3-14 in table 2 can be used where applicable for estimation purposes, provided the drainage area at the site is greater than the indicated lower drainage area limit in table 1 and less than 400 mi^2. Where the drainage area is less than the indicated lower limit in table 1, examination of low-flow frequency characteristics of nearby streams should be the basis for estimates at the ungaged site. Preferably, however, a series of base-flow measurements could be made at the ungaged site, using discharge measurements, such as previously described, could be used for estimating low-flow characteristics. The latter approach is particularly appropriate for small drainage areas because of higher variability in per-square-mile values of low-flow statistics for small drainage areas.

The appropriate equation for the hydrologic area in which the site is located can be obtained from table 2. To use the regression equations, first determine the drainage area of the site of interest in square miles. Then, if the site is located in the western Piedmont and mountains hydrologic area (HA10), determine the mean annual runoff for the basin, in $(ft^3/s)/mi^2$, using figure 4.

For example, assume the site of interest is in the western Piedmont and mountains hydrologic area (HA10). The drainage area is 3.5 mi^2, the mean annual runoff is 1.2 $(ft^3/s)/mi^2$; and the low-flow characteristic of interest is the 7Q10 low flow. Then:

$$MAF = (MAR)\ (DA) \qquad (15)$$

and substituting above values:

$$1.2\ ft^3/s = (1.2\ (ft^3/s)/mi^2)\ (3.5\ mi^2)$$

From equation 11, table 2:

$$7Q10 = 0.155\ MAF^{1.01},$$

by substitution,

$$7Q10 = (0.155)\ (4.2^{1.01});$$

or,

$$7Q10 = 0.66\ ft^3/s \text{ (standard error 50 percent).}$$

No regional relations are provided for hydrologic areas HA1, HA2, HA4, HA6, HA7, and HA8 because of the high percentage standard error of estimates of the regression equations. However, the information in table 1 may be used to estimate the probable range in unit low-flow characteristics for ungaged, unmeasured sites in these areas. For example, the low-flow 7Q10 values in HA1 range from 0 to 0.019 $(ft^3/s)/mi^2$, and the median value is 0. The drainage area below which a zero value is likely for a low-flow characteristic is also given in table 1 for most hydrologic areas.

Where a drainage area is located in more than one hydrologic area, the preferred procedure is to make separate estimates for the parts of the drainage basin that lie in each hydrologic area using the techniques previously described, then add the results. However, this additive approach should not be used when one or more of the downstream hydrologic areas is in an area having a zero or near-zero median value for the particular low-flow characteristic of interest. For example, evidence from measurements indicates that some streams flowing out of the high-yielding Sand Hills hydrologic area (HA3) into the Coastal Plain clay soils hydrologic area (HA1) may actually lose water instead of gaining or maintaining base-flow contributions from the Sand Hills. Such losses could be due to a combination of a lack of positive contribution to streamflow from the clay soils and actual loss of streamflow by direct evaporation from the stream surface and by transpiration from streambank vegetation.

Streamflow data or low-flow characteristics for North Carolina streams to be used in place of, or in conjunction with, the characteristics estimated by regression equations or information in table 1 are contained in table 3 on the reverse of plate 2; in annual water-resources data reports of the U.S. Geological Survey, and in Yonts (1971). Measurement-based estimates of low-flow frequency characteristics of other North Carolina streams are contained in Goddard (1963) and in U.S. Geological Survey files in Raleigh, North Carolina.

There is, however, a lack of sufficient low-flow data with which to develop low-flow frequency estimates in some areas. There is a paucity of low-flow data for streams in the Coastal Plain and, to a lesser degree, for streams in those parts of the eastern and central Piedmont hydrologic area identified on sheet 1 as having low potential to sustain base flow of streams. The present (1991) inability to develop reliable, predictive regression equations for these parts of the State is partly attributable to the lack of sufficient data for natural base flow in these areas but is also partly due to a lack of complete understanding of the hydrology of low flows.

The need for greater understanding of low-flow hydrology is most acute in those areas where regression equations for the low-flow characteristic values are not shown because the percentage errors of estimate are too large (HA1, HA2, HA4, HA6, HA7, and HA8). Not coincidentally, these are the areas where the magnitudes of low-flow characteristics are smallest; this leads to unacceptably large percentage errors when what might normally be judged to be small-magnitude errors in terms of cubic feet per second are expressed as a percentage of the magnitude of the low-flow characteristic itself. Thus, for such areas, a more complete qualitative and quantitative understanding of the low-flow hydrology is necessary to achieve regression estimates of acceptably low percentage error for most uses.

In addition to the need for more data on and better understanding of the natural low-flow regime, there is a need for better definitions of the places and patterns of streamflow regulation and diversions, many of which may be unknown to public officials. Such definitions are necessary both to ensure the integrity of the data base for natural conditions and to allow estimates of low-flow characteristics for regulated sites.

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LOW-FLOW CHARACTERISTICS OF STREAMS IN NORTH CAROLINA

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