Streamflow Characteristics of the Waccamaw River at Freeland, North Carolina, 1940-94

By Jerad D. Bales and Benjamin F. Pope

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ABSTRACT

Streamflow characteristics of the Waccamaw River at Freeland, North Carolina, for the period 1940-94 were described and compared to streamflows in the adjacent Lumber River Basin. Precipitation in the two basins was about equal for the study period. During 1940-63, streamflows in the Waccamaw and Lumber Rivers were essentially identical relative to average conditions. The flow regime from the late 1950's to the early 1980's was distinctly wetter than the flow regimes which immediately preceded and followed this period. Following 1963, droughts in the Waccamaw Basin seem to have been less severe than in the Lumber Basin, and the annual 1-, 7-, and 30-day low flows exhibited a slightly increasing trend in the Waccamaw River. Mean daily flow in the Waccamaw River at the 90 percent exceedance level (low flows) during 1985-94, a relatively dry period, was very nearly equal to flows at the same exceedance level for 1970-79, the wettest 10-year period between 1940 and 1994. Prior to the 1980's, flows per unit drainage area in the Waccamaw Basin were generally less than those in the Lumber Basin, but after 1980, the opposite was true. There is an increasing trend in the difference between Waccamaw River and Lumber River high flows, primarily as a result of increases in Waccamaw River high flows. On average, streamflow in the Waccamaw River consisted of 53.3 percent base flow, but base flow accounted for 70.6 percent of the total flow in the Lumber River, which is more typical of Coastal Plain streams. The ratio of base flow to runoff in the Waccamaw River may have changed relative to that in the Lumber River in the late 1970's. There was greater variability in Waccamaw River streamflow than in Lumber River flow, and flow variability in the Waccamaw River may have increased slightly during 1985-94.

INTRODUCTON

The Waccamaw River, which originates at Lake Waccamaw, drains an area of 1,257 mi^2 (square miles) in extreme southeastern North Carolina (fig. 1). In 1990, 63 percent of the basin was covered with forest, 27 percent was cropland, and 2.3 percent was urban or developed (North Carolina Division of Environmental Management, 1993). The 1990 population of the basin was 48,586, compared to 42,691 in 1970 (North Carolina Division of Environmental Management, 1993). A U.S. Geological Survey stream gage has been in continuous operation on the Waccamaw River at Freeland (fig. 1) since August 1939.

Citizens in Brunswick and Columbus Counties have expressed concerns about the Waccamaw River, including changes in streamflow characteristics, effects of land-use activities on nonpoint-source pollutants entering the river, and generally poor water-quality and biological conditions in the river. As one of a series of studies funded by the North Carolina General Assembly to address these concerns, the U.S. Geological Survey, in cooperation with the North Carolina Department of Environment, Health, and Natural Resources, Division of Water Resources, initiated an investigation in 1994 of the streamflow characteristics of the Waccamaw River. The objectives of the investigation were to (1) characterize streamflow in the Waccamaw River at Freeland for the period 1940-94, and (2) compare Waccamaw River flow characteristics to flow characteristics of nearby streams.

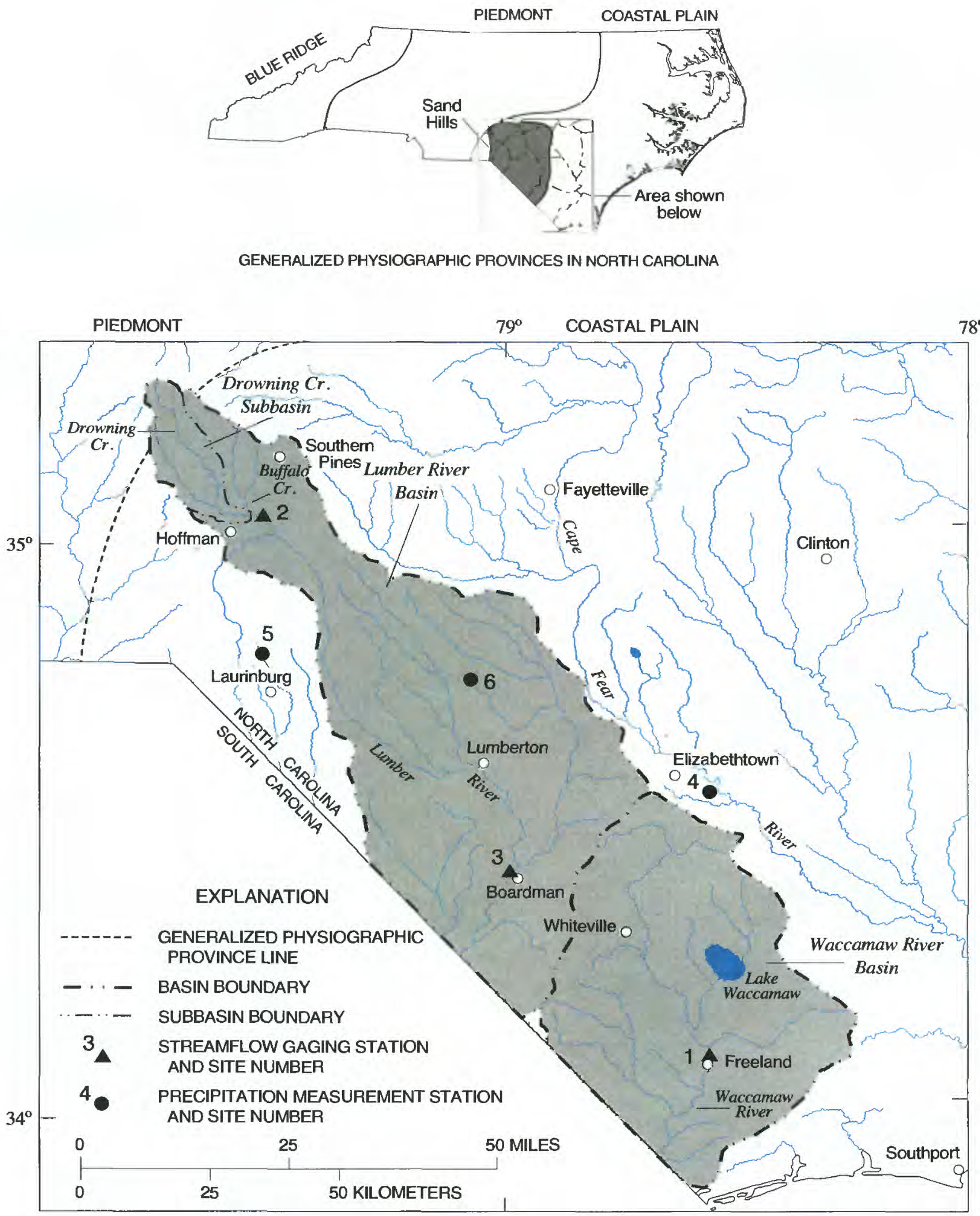

Figure 1. Locations of streamflow and precipitation stations in the Waccamaw River study area, North Carolina.

Purpose and Scope

The purpose of this report is to describe the streamflow characteristics of the Waccamaw River at Freeland, North Carolina, for the period 1940-94. Flows in the Waccamaw River are compared to those in the Lumber River at Boardman and Drowning Creek near Hoffman for the same period. Precipitation for the study period is characterized and is used in the interpretation of flow characteristics. Monthly streamflow statistics, including departures from normal (or average) conditions, distributions of flows, and trends are presented. Flow durations, flood frequencies, low-flow statistics, and base-flow conditions are evaluated. Differences among Waccamaw River, Lumber River, and Drowning Creek flow characteristics are identified and changes in flow conditions are noted. The relation between changes or trends in Waccamaw River flow characteristics identified in this study and human activities is very difficult to determine because of the absence of quantitative information on changes in basin land use, irrigation, and drainage practices during 1940-94.

Study Area and Available Data

The Lumber and Waccamaw River Basins are similar in many respects. However, population in the entire Lumber River Basin (drainage area of 1,630 mi^2 at the South Carolina State line) increased from 124,219 in 1970 to 181,064 in 1990 (North Carolina Division of Environmental Management, 1993), which is a 45-percent increase compared to a 14-percent increase in the Waccamaw River Basin during the same period. Most of the growth in the Lumber River Basin occurred in the Drowning Creek subbasin (fig. 1).

Current land use in the Lumber River Basin is similar to that in the Waccamaw Basin—50 percent of the basin is forest, 36 percent is cropland, and 4 percent is urban or developed areas. Historical land-use information generally is not available for either basin. Some ditching and draining associated with silviculture and agriculture has occurred in the Waccamaw Basin, but there is no quantitative information on the extent of these practices nor on changes over time. Flows in the Waccamaw River (fig. 1, site 1), Drowning Creek (site 2), and the Lumber River (site 3) are not significantly affected by regulation; the town of Southern Pines withdrew an average of 2.9 ft^3/s (cubic feet per second) from Drowning Creek in 1994. It is likely that there are a number of unmonitored withdrawals for irrigation in both basins.

The primary difference between the two basins is that the Waccamaw River lies entirely in the Coastal Plain Province, but the Lumber River drains both the Sand Hills region and the Coastal Plain Province. The boundary between the Sand Hills and Coastal Plain is near the origin of the Lumber River, at the confluence of Drowning Creek and Buffalo Creek.

Lake Waccamaw, from which the Waccamaw River originates, receives drainage from an area of 103 mi^2, or about 15 percent of the drainage area of the Waccamaw River at Freeland. The lake has a surface area of 8,950 acres and a volume of about 44,000 acre-feet (North Carolina Department of Environment, Health, and Natural Resources, 1992). Releases of water from the lake into the Waccamaw River are controlled by an outlet structure; configuration of the structure has been changed from time to time, but these changes are generally undocumented.

Local topographic gradients in the Coastal Plain are less than about 2 ft/mi (foot per mile). As a consequence, hydraulic gradients also are low, resulting in less potential to move water from the land to streams than in areas with greater relief. In contrast, topographic gradients in the Sand Hills range from 50 to 200 ft/mi. Low flows are generally much greater in the Sand Hills than in other parts of the Coastal Plain having similar soils (Giese and Mason, 1993).

Low-flow hydrologic areas (HA) for North Carolina were identified by Giese and Mason (1993). Most of the Waccamaw Basin upstream from site 1 (fig. 1) lies in HA1, which is in the Coastal Plain and is characterized by clay soils. The median 7Q10 (the annual minimum 7-day consecutive low flow that, on average, occurs once every 10 years) for streams in HA1 is 0.0 $(ft^3/s)/mi^2$ (cubic foot per second per square mile) of drainage area (Giese and Mason, 1993). The Drowning Creek subbasin lies entirely in HA3 (Sand Hills region, sandy soils). Most of the Lumber Basin upstream from site 3 is in either HA2 (Coastal Plain, sandy soils) or HA3, and is underlain by sandy soils with a small percentage of clay-sand mix and clay soils in the lower part of the basin. Median 7Q10 for HA2 streams is 0.006 $(ft^3/s)/mi^2$ and is 0.318 $(ft^3/s)/mi^2$ for streams in HA3 (Giese and Mason, 1993). In general, a higher percentage of precipitation on high-permeability sandy soils is

Table 1. Streamflow gaging stations used in data analysis
[USGS, U.S. Geological Survey; mi^2, square miles]

Site number (fig. 1)	USGS station number	Station name	Latitude	Longitude	Drainage area (mi^2)	Period of record
1	02109500	Waccamaw River at Freeland	34°05′55″	78°32′55″	680	1939-94
2	02133500	Drowning Creek near Hoffman	35°03′38″	79°29′39″	183	1939-94
3	02134500	Lumber River at Boardman	34°26′32″	78°57′38″	1,228	1929-94

Table 2. Precipitation measurement stations used in data analysis

Site number (fig. 1)	Station location	Year installed	Latitude	Longi-tude
4	Elizabethtown	1911	34°38′	78°35′
5	Laurinburg	1941	34°45′	79°27′
6	Lumberton	1898	34°42′	79°04′

stored in the shallow ground-water system than on low-permeability clay soils, resulting in more sustained low flows, as the stored water is released during periods of low rainfall.

Records from three streamflow gaging stations (table 1; fig. 1) and three precipitation measurement stations (table 2; fig. 1) were compiled and analyzed. Concurrent records from two nearby gages in the Lumber River Basin were analyzed to determine if streamflow characteristics at the Waccamaw site (site 1) were localized or were consistent with regional variations.

At least 11 precipitation stations are located in, or very near, the Lumber and Waccamaw River Basins. Of the 11 stations, six have records which predate 1950, and three have records prior to 1939. Records from stations at Elizabethtown (site 4), Laurinburg (site 5), and Lumberton (site 6) were selected for analysis because these stations provide good geographic coverage of the basins, and the stations have long periods of record with little missing data.

Approach

Although collection of records at the Lumber River site (site 3) began prior to the measurement of streamflow on the Waccamaw River in August 1939, only concurrent data collected after October 1939 were included in this analysis. Specific steps in the analysis were as follows:

• *Comparison of precipitation distributions*—The distribution of annual precipitation amounts from the three long-term rainfall sites (table 2; fig. 1) were compared to determine if data from the rainfall sites are statistically different. Because annual precipitation amounts typically are not normally distributed, a non-parametric test (the Mann-Whitney test) was used. Differences in precipitation distributions, if they exist, may explain differences in streamflow characteristics at the three streamflow sites.

• *Evaluation of precipitation characteristics and trends at the rainfall sites*—Trends in precipitation at each of the three rainfall sites were evaluated by using 5- and 10-year moving averages and the LOWESS-smoothing procedure, which is a weighted local regression filter (Cleveland, 1979). LOWESS, which uses an iteratively weighted least-squares technique, is useful in identifying trends in highly variable time-series data. The degree of smoothing can be controlled by altering the value of the smoothness factor, f. The factor is chosen somewhat subjectively and reflects the size of the window used to compute a value on the LOWESS curve (Helsel and Hirsch, 1992). The smoothness factor can range from 0.01 to 0.99, with higher values resulting in greater smoothing because of a larger window size. Greater smoothing also can be interpreted as representing longer-term trends relative to lower values of the smoothness factor. Differences between annual rainfall amounts at Elizabethtown (site 4) near the headwaters of the Waccamaw River Basin and at the other two rainfall sites in the Lumber Basin were evaluated.

• *Determination of annual yields*—The annual ratio of streamflow to precipitation (yield) was determined for the Waccamaw and Lumber River Basins. Trends in annual yield were identified.

• *Evaluation of monthly streamflow characteristics*—A linear regression of logarithmically transformed flow versus time was developed for the Waccamaw and Lumber River flows, and the slopes of the regressions were evaluated. The residuals (difference between predicted and actual flows) were analyzed to determine if there was a trend with time.

The rescaled cumulative departures of the monthly mean streamflow at each streamflow site were plotted and interpreted. The rescaled cumulative departures of the monthly mean streamflow were computed as the cumulative sum of the differences between the monthly value and the monthly mean for the period of record, divided by the monthly standard deviation for the period of record (Garbrecht and Fernandez, 1994); the values are dimensionless. This procedure allows fluctuations and trends in flow to be visualized and was used to identify extended wet and dry periods and to compare general trends among the streamflow sites. Extended periods of greater-than-average and less-than-average streamflow and trends in streamflow were identified.

Periods of negative slope (sloping downward from left to right) indicate time spans of monthly streamflow which are less than the mean; periods of positive slope indicate greater-than-average streamflow conditions. The steepness of the slope indicates the magnitude of the deviations from average conditions. Periods of relatively small changes in the rescaled cumulative departures, whether the actual values are positive or negative, indicate periods of near-average flows. Changes or trends near the beginning and end of the record are difficult to identify from plots of the rescaled cumulative departures. A unidirectional trend in streamflow would appear as a parabolic trend in a plot of the rescaled cumulative departures against time.

Streamflow departures were compared with precipitation departures. This analysis provided preliminary information on trends in streamflow at streamflow sites, the relation of the streamflow trend to precipitation, and the regional variability of the trend.

The LOWESS technique was used to smooth the monthly flows and to further evaluate possible trends. The distributions of the monthly mean flows from each of the streamflow sites were compared to determine if the distributions are statistically different. The nonparametric Wilcoxon rank sum test was applied to the data. A double mass curve of monthly streamflow in cubic feet per second per square mile was constructed as another method to compare streamflow in the Waccamaw and Lumber Rivers.

• *Computation of routine flow statistics*—The following information was determined from each of the three sets of streamflow records: (1) flow duration, (2) low-flow statistics, and (3) high-flow statistics (including flood frequencies). Low-flow statistics included the 7Q10, 7Q2, and 30Q2. These statistics were computed using the standard log-Pearson Type III distribution (Riggs, 1973). Flood frequencies were computed using methods described by the Interagency Advisory Committee on Water Data (1982). Flows were converted to cubic feet per second per square mile for these computations. The statistics were computed for the period 1939-94, and for 10-year periods at 5-year intervals (for example, 1940-49, 1945-54, 1950-59, and so on), and for other selected 10-year periods.

• *Evaluation of annual series of low and high flows*—The annual series of 1-day, 7-day, and 30-day (n-day) low and high flows were determined. The n-day low/high flow is the n-consecutive day period with the lowest/highest mean flow during the year. The data were smoothed using the LOWESS technique. The Mann-Kendall test (Helsel and Hirsch, 1992) was used to determine whether a statistically significant monotonic trend was present in each of the annual series of n-day flows. The test was applied to the full 1940-94 period. General trends in annual n-day low and high flows identified from LOWESS-smoothed plots were evaluated and compared among streamflow sites.

• *Separation of base flow from runoff and analysis of each separately*—In some cases, changes in the hydrologic regime can be more clearly manifested as changes in the runoff component of streamflow. Base flow was separated from runoff using the method of the Institute of Hydrology (1980a, 1980b). Base flow and runoff were then analyzed separately. Time series of the base flow and runoff and the ratio of base flow to runoff were plotted. The LOWESS technique was applied to each of the three (base flow, runoff, and base flow to runoff ratio) data series. Regressions of log-transformed base flow and runoff against time were computed and analyzed.

• *Evaluation of flow variability*—Twelve-month and 10-day moving range values were determined (Barringer and others, 1994) as a measure of flow variability. The range is defined as the difference between the highest and the lowest flow within a period. The 12-month moving range for a given month, analogous to the moving average, is computed for the month of interest and the 11 successive months following. Likewise, the 10-day moving range is computed for the daily mean flow on the day of interest and the 9 successive days. Ranges for total streamflow, base flow, and runoff were determined. Values were smoothed using the LOWESS technique.

STREAMFLOW CHARACTERISTICS OF THE WACCAMAW RIVER

Long-term precipitation characteristics of the Waccamaw River at Freeland for the period 1940-94 are first described to provide a context for the characterization of streamflow conditions. Flow durations, flood-frequency distributions, low-flow statistics, and base-flow characteristics are then presented for the Waccamaw River. Streamflow characteristics of the Waccamaw River are compared with those at the Lumber River at Boardman (site 3) and Drowning Creek near Hoffman (site 2).

Precipitation

Long-term mean and median precipitation amounts were generally the same at sites 4, 5, and 6 (table 3). The driest year on record at each site was 1951, but the wettest year was different for each rainfall site. High annual precipitation amounts were generally the result of excessive rainfall in the summer or early fall months. Rainfall amounts during these months can vary greatly over short distances, which may account for the different years of maximum precipitation at the three rainfall sites. The distributions of annual rainfall totals were not normally distributed for any of the three sites for 1940-94. The nonparametric Mann-Whitney signed rank test indicated that the distribution of annual rainfall at Elizabethtown was not statistically different from the distributions at Lumberton and Laurinburg.

Periods of four or more consecutive years of less-than-average precipitation at Elizabethtown occurred four times during 1940-94 (fig. 2): 1940-43, 1951-54, 1965-68, and 1978-81. The greatest multi-year precipitation deficit occurred during 1951-54. Periods of four or more years of greater-than-average precipitation occurred during 1955-60 and 1991-94 (fig. 2).

Five and 10-year moving averages of the annual rainfall totals suggest a slight increase in annual rainfall amounts at Elizabethtown for the period 1940-94 (fig. 3). Precipitation amounts were generally quite low between 1940 and 1954. These low annual totals affect the moving averages and partially cause the appearance of an increasing trend.

During any given year, annual rainfall amounts at the three rainfall sites could differ significantly (fig. 4). Annual differences between site 4 (Elizabethtown) and site 5 (Laurinburg) ranged from -18.20 in. (inches) (site 5 rainfall exceeded that at site 4) in 1985 to 15.42 in. in 1977. In 1947, rainfall at Laurinburg exceeded that at Elizabethtown by 13.32 in. Differences between sites 4 and 6 ranged from -14.40 in. (1947) to 10.54 in. (1950). The comparably large differences between site 4, Elizabethtown, and the

Table 3. Monthly and annual precipitation statistics for selected sites in the study area

Site (fig. 1)	Period of record	Monthly mean, in inches: January	February	March	April	May	June	July	August	September	October	November	December	Annual mean, in inches	Annual median, in inches	Maximum annual, in inches (year)	Minimum annual, in inches (year)
Elizabeth-town (site 4)	1940-94	3.42	3.28	4.16	2.88	3.49	4.51	6.10	5.74	4.25	2.97	2.73	3.05	46.70	46.58	60.26 (1974)	31.64 (1951)
Laurinburg (site 5)	1947-94	3.77	3.63	4.50	3.09	3.55	5.05	5.91	4.94	4.15	3.27	3.12	3.19	47.99	47.60	61.32 (1959)	30.76 (1951)
Lumberton (site 6)	1940-89, 1992-94	3.42	3.37	4.14	3.08	3.58	4.84	5.85	5.25	4.09	2.84	2.81	3.09	46.39	46.37	62.25 (1945)	28.41 (1951)

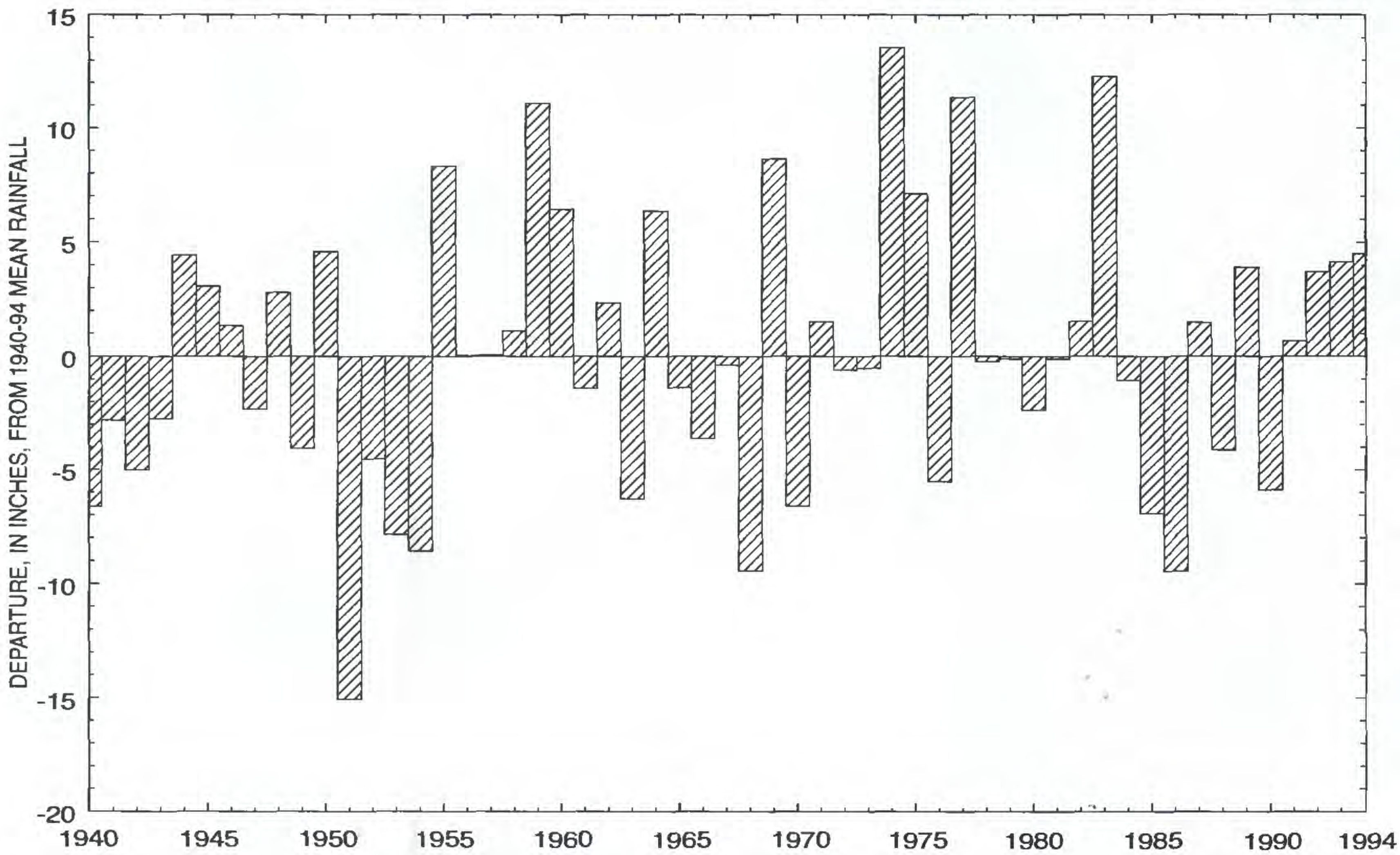

Figure 2. Annual departures from 1940-94 mean rainfall at Elizabethtown, N.C.

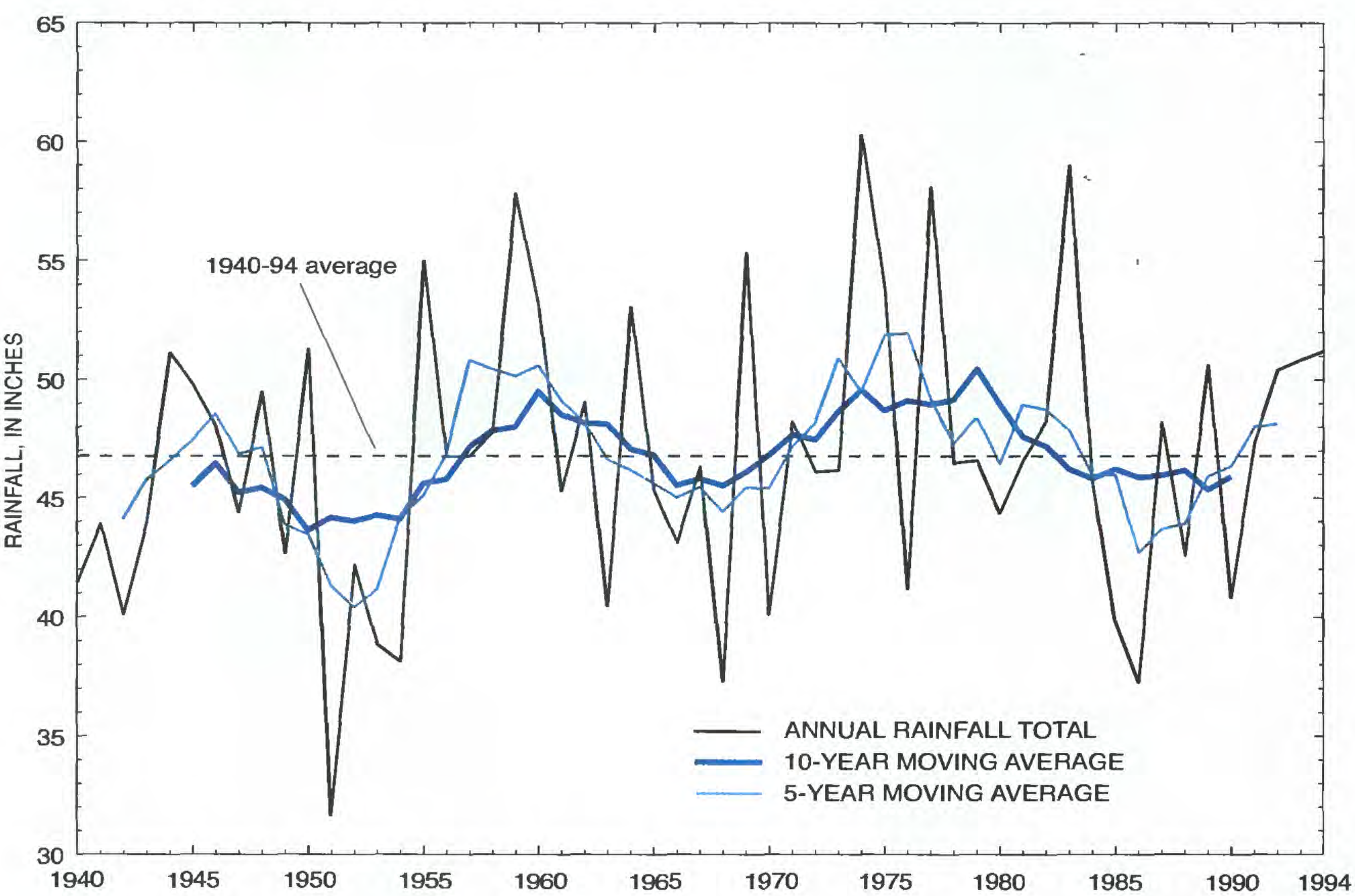

Figure 3. Five- and 10-year moving averages of annual rainfall amounts at Elizabethtown, N.C., 1940-94.

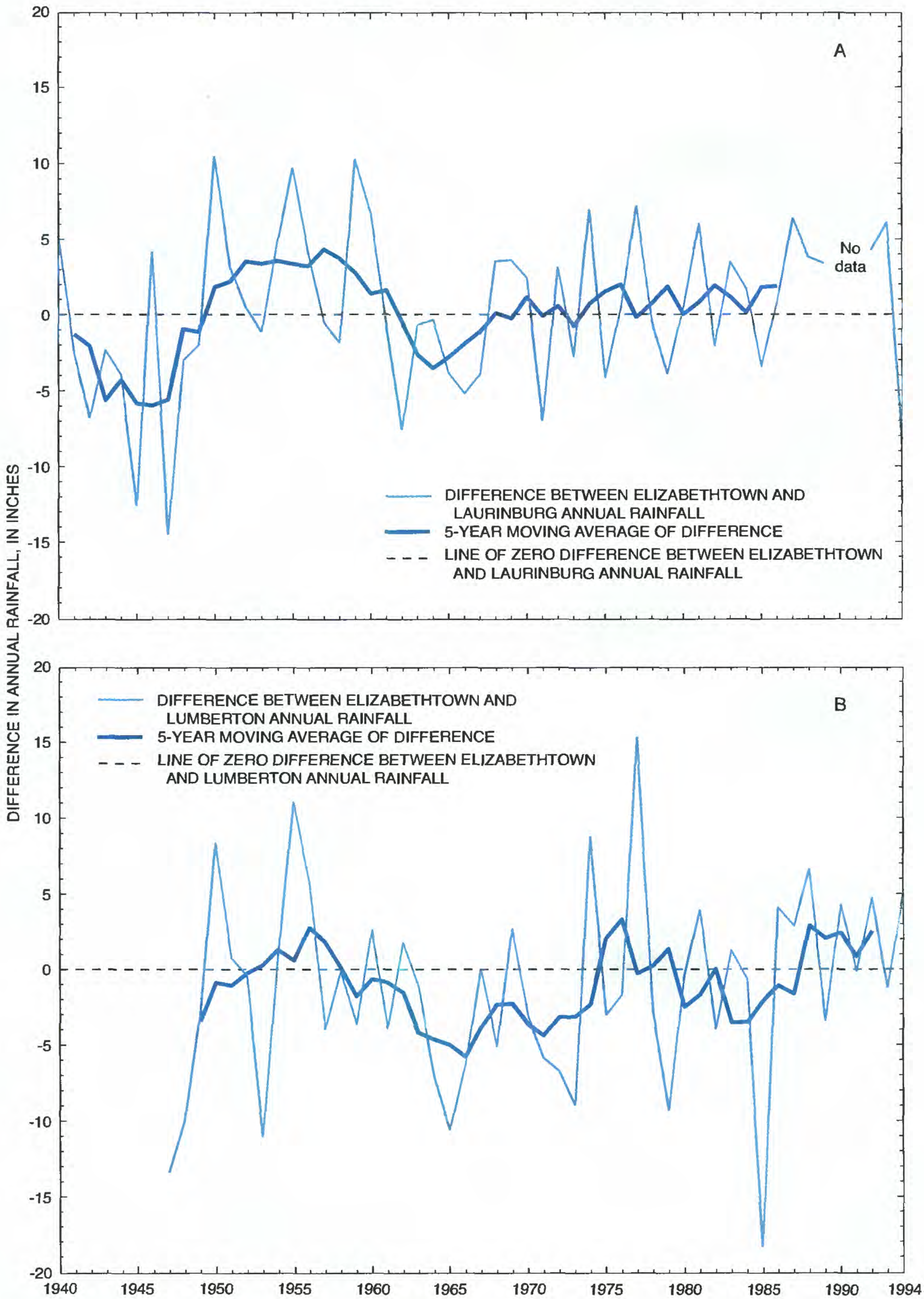

Figure 4. Differences between annual rainfall amounts and 5-year moving average of differences at (A) Elizabethtown and Laurinburg, and (B) Elizabethtown and Lumberton.

other sites for 1947 suggest that rainfall for site 4 may have been under-reported. Precipitation amounts for other rainfall sites in the region support this conclusion. Total annual precipitation for 1947 at Whiteville (Columbus County), Willard (Pender County), Clinton (Sampson County), and Southport (Brunswick County) was 61.79 in., 60.57 in., 53.20 in., and 69.58 in., respectively, compared to the reported 44.39 in. at Elizabethtown.

The 5-year moving average of the differences between annual rainfall amounts at Elizabethtown (site 4) and the other two sites shows an increasing trend from generally negative differences (site 4 rainfall is less than rainfall at other sites) to near-zero or slightly positive differences (fig. 4). These trends support the conclusion of a general increase in reported rainfall amounts at site 4 during the period 1940-94. However, neither 5- and 10-year moving averages nor LOWESS-smoothed plots (not shown) indicated a trend in annual rainfall amounts at sites 5 and 6 (fig. 1). Consequently, the apparent trend in reported rainfall amounts at site 4 is likely associated with the under-reporting of rainfall in 1947, and possibly other years, rather than changes in rainfall patterns.

Annual Yields

The mean ratios of annual streamflow to annual rainfall (yield) for the Waccamaw River and the Lumber River were the same for the period 1940-93 (fig. 5). In both basins, 30 percent of the rainfall, on average, passed the respective gaging stations as streamflow.

The same general patterns in the streamflow-rainfall ratio existed at both sites except during the late 1940's. The high streamflow-rainfall ratios for the Waccamaw River in 1947 and 1948 (fig. 5) are likely a result of under-reported rainfall at Elizabethtown

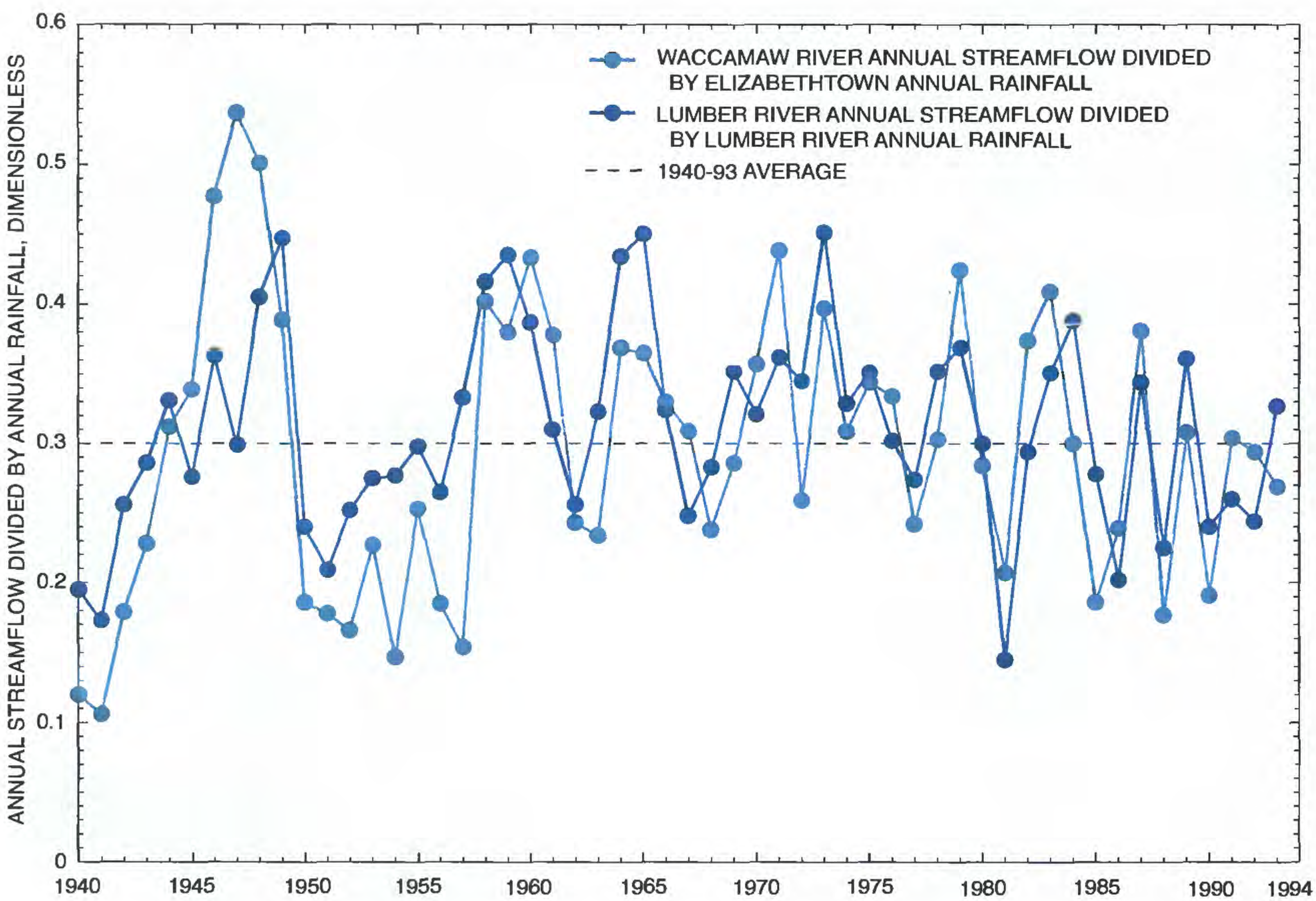

Figure 5. Ratio of annual streamflow to annual rainfall at the Waccamaw and Lumber Rivers, 1940-94.

during those years (fig. 4). Following 1950, there is no trend in the difference between the Waccamaw and Lumber streamflow-rainfall ratios. However, during 1950-93, the Waccamaw ratio was less than the Lumber ratio about two-thirds of the time. This is probably explained by the fact that the Lumber River drains part of the Sand Hills region, where yields are higher than in other parts of the Coastal Plain. For example, Drowning Creek, which is located in the Sand Hills, has a long-term average (1940-94) streamflow of 1.38 $(ft^3/s)/mi^2$, whereas the long-term average streamflow for the Waccamaw River during the same period was 1.03 $(ft^3/s)/mi^2$.

During 1958-83, the streamflow-rainfall ratio was 0.331 for the Waccamaw Basin and 0.339 for the Lumber Basin, or about 10 percent greater than the long-term average of 0.3. Rainfall at Elizabethtown during this period was about 4 percent greater than average. During 1984-93, however, the streamflow-rainfall ratio was 0.261 for the Waccamaw Basin and 0.276 for the Lumber Basin, and rainfall at Elizabethtown was about 3 percent less than average. Hence, although 1984-93 was not a period of prolonged, severe drought, the percentage of precipitation which became streamflow in the Waccamaw and Lumber Basins was significantly lower than average, and much lower than the previous 26 years. In fact, annual precipitation at Elizabethtown was higher than average during much of 1984-93 (fig. 2). Higher-than-average summer temperatures during the period (table 4) probably were partially responsible for lower yields during this time despite the higher-than-average rainfall.

Table 4. Difference between measured temperatures at Whiteville, 1984-93, and 1951-80 average temperatures

[Positive value indicates mean for period was greater than long-term mean temperature; negative value indicates mean for period was less than long-term temperature; --, not available]

Year	Month					Annual
	May	June	July	Aug.	Sept.	
1984	0.2	1.3	-1.0	0.3	-2.5	0.7
1985	1.2	1.3	.6	-.4	.5	1.9
1986	1.4	2.6	3.4	-.5	.7	2.2
1987	.6	2.0	.9	2.4	1.7	.1
1988	-.4	-2.1	.5	2.5	-1.9	-.2
1989	-1.7	3.7	.9	-.9	--	--
1990	--	--	--	--	--	--
1991	4.3	1.6	--	1.0	.3	-.2
1992	-3.0	-1.2	4.3	-.2	1.4	1.0
1993	2.6	2.6	5.0	.8	2.1	1.3

Monthly Streamflow Characteristics

Monthly mean flow in the Waccamaw River is, on average, greatest during March (fig. 6). More than half (57 percent) of the total annual flow occurs during the four months of January to April. Conversely, the four months with the greatest precipitation at Elizabethtown are June to September, when 44 percent of the total annual precipitation occurs. Despite the higher rainfall amounts, streamflow is lower during June to September than during January to March because evapotranspiration is greater during the summer months than during winter months.

Four major droughts occurred in North Carolina between 1940 and 1988 (Zembrzuski and others, 1991). The 1950-57 drought, which had a recurrence interval of greater than 25 years throughout most of the State, was the most persistent drought on record in North Carolina. The drought was, however, briefly interrupted in the fall of 1954 and summer of 1955 by rains from the passage of four hurricanes, with two of the hurricanes having some effect on the Waccamaw Basin. Hurricane Hazel (October 15, 1954) passed directly over the Waccamaw Basin, and Hurricane Diane (August 17, 1955) passed just to the north and east of the basin. Hurricane Hazel had little effect on precipitation and flow in the Waccamaw Basin (figs. 2 and 7). Rainfall associated with Hurricane Diane resulted in the second highest recorded monthly mean streamflow in the Waccamaw River at Freeland (fig. 8). During the remainder of 1955, however, flows in the Waccamaw remained quite low. Other droughts identified by Zembrzuski and others (1991), all of which had recurrence intervals of between 10 and 25 years, occurred during 1966-71, 1980-82, and 1985-88.

Monthly mean flows for the Waccamaw and Lumber Rivers were logarithmically transformed and regressions of the log-transformed flows against time were computed. The slope of the regression line for the Waccamaw River was statistically different from 0 at the 90 percent confidence level, indicating that there is a 90 percent chance the Waccamaw River monthly mean flows exhibited a change (or slight trend) over the period of record. The slope of the Lumber River regression was not statistically different from zero. Residuals from the two regressions were computed (difference between actual and predicted values), untransformed, corrected for logarithmic bias, and plotted against time. There was no trend in the

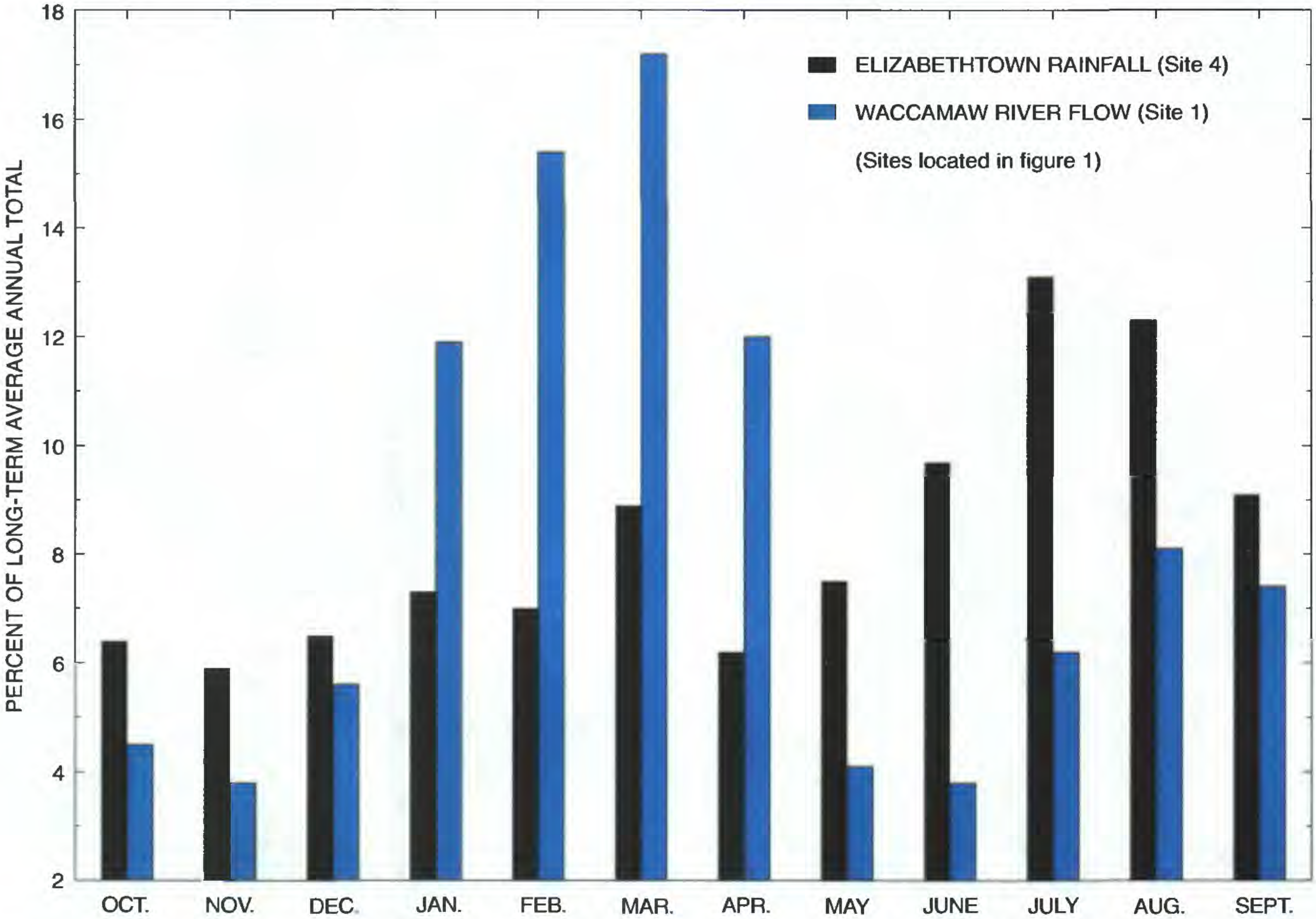

Figure 6. Mean monthly percentage of 1940-94 mean precipitation at Elizabethtown and 1940-94 mean streamflow at the Waccamaw River at Freeland.

residuals for either river, and the residuals were normally distributed.

Five-year moving averages of monthly mean streamflow (fig. 7) are similar for the Waccamaw and Lumber Rivers. Periods of sustained lower-than-average flows include the early 1940's, the early 1950's, and the mid-1980's through the mid-1990's. The period from the late 1950's through the early 1980's was one of generally greater-than-average flows in the Waccamaw and Lumber Rivers, as well as greater-than-average yields (fig. 5). During much of the latter period, however, Waccamaw Basin flows in cubic feet per second per square mile were lower than those from the Lumber Basin. Since about 1980, however, Waccamaw Basin flows in cubic feet per second per square mile usually exceeded those of the Lumber Basin. The general patterns seen in the monthly mean flows (fig. 8) and moving averages (fig. 7) are more clearly evident in the plots of rescaled cumulative departures.

Rescaled Cumulative Departures

The rescaled cumulative departures (RCD's) of monthly flows for the Waccamaw River, Lumber River, and Drowning Creek each exhibit the same general patterns for the period of record (fig. 9). In particular, the Lumber and Waccamaw Rivers have almost identical RCD's from 1940 through about mid-1964. Although the RCD's for Drowning Creek follow the same general trends as the other two sites, there was a slight difference—Drowning Creek is located in the Sand Hills region and drains a substantially smaller area than the other two sites. Consequently, most of the subsequent comparisons of flow conditions in this report will be between the Waccamaw and Lumber Rivers.

Although not identified by Zembrzuski and others (1991) as a significant drought, the period 1940-43 was one of less-than-average rainfall (fig. 2) and streamflow (fig. 9). In fact, this drought appears to

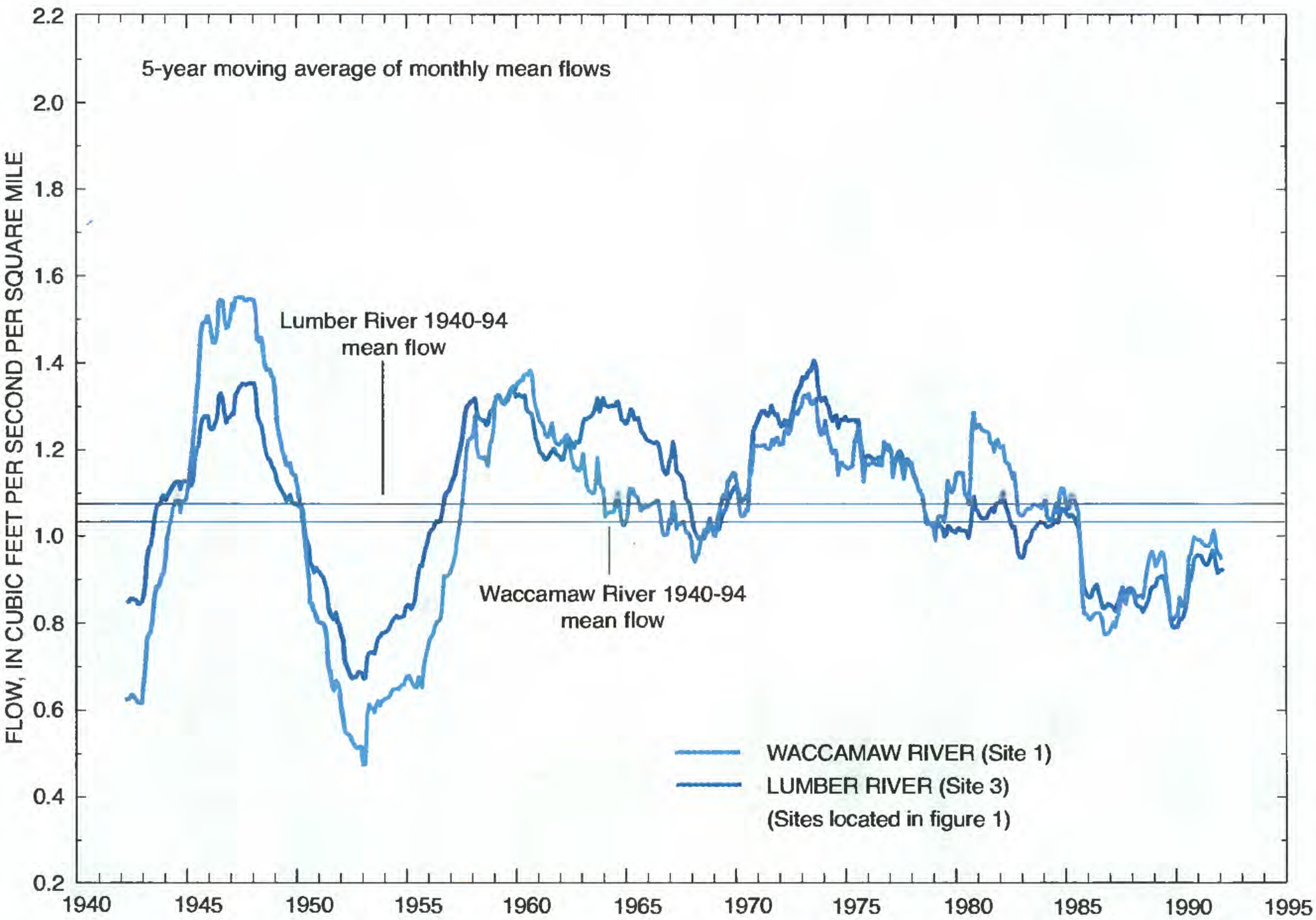

Figure 7. Five-year moving average of monthly mean streamflow at the Waccamaw River at Freeland and the Lumber River at Boardman, 1940-94.

have been the second or third most severe on record (1940-94) for this basin. However, from mid-1945 through late 1949, flows were significantly greater than average at all three sites.

The 1950-57 drought was the most severe on record. Rainfall was extremely low during 1951-54 (fig. 2), and was greater than average in 1955 only because of the high rainfall associated with Hurricane Diane (12.40 in. at Elizabethtown in August 1954). Extrapolating the trends from 1950-54 shown in figure 9, the 1950-57 drought would have been much more severe without the rainfall of Hurricane Diane and associated high flows. The effects of the hurricane on flows were substantially greater in the Waccamaw Basin than in the Lumber Basin (rainfall at Lumberton was 9.96 in. in August 1954).

Flows in the Waccamaw and Lumber Basin were average or greater than average during 1958-65. From September 1964 to June 1966, flows in the Lumber River (and Drowning Creek) were much greater than average (as indicated by the large positive slope in the RCD's, fig. 9), but were near or slightly greater than average in the Waccamaw River. Moreover, the 1966-71 drought identified by Zembrzuski and others (1991) was much less severe in the Waccamaw Basin than in the Lumber Basin. The drought appears to have actually ended in both basins in the spring of 1969.

Flows in the Waccamaw and Lumber Rivers were generally greater than average from the spring of 1969 through April 1980. The general patterns of the respective RCD's for the Waccamaw and Lumber Rivers were the same for the period. The slopes of the RCD lines for the two sites also were similar during the period; the RCD's at both sites increased about 30 standard deviations during the period.

The 1980-81 drought was much more severe and prolonged in the Lumber Basin than in the Waccamaw Basin. The RCD's for the Waccamaw River declined about 10 standard deviations during the

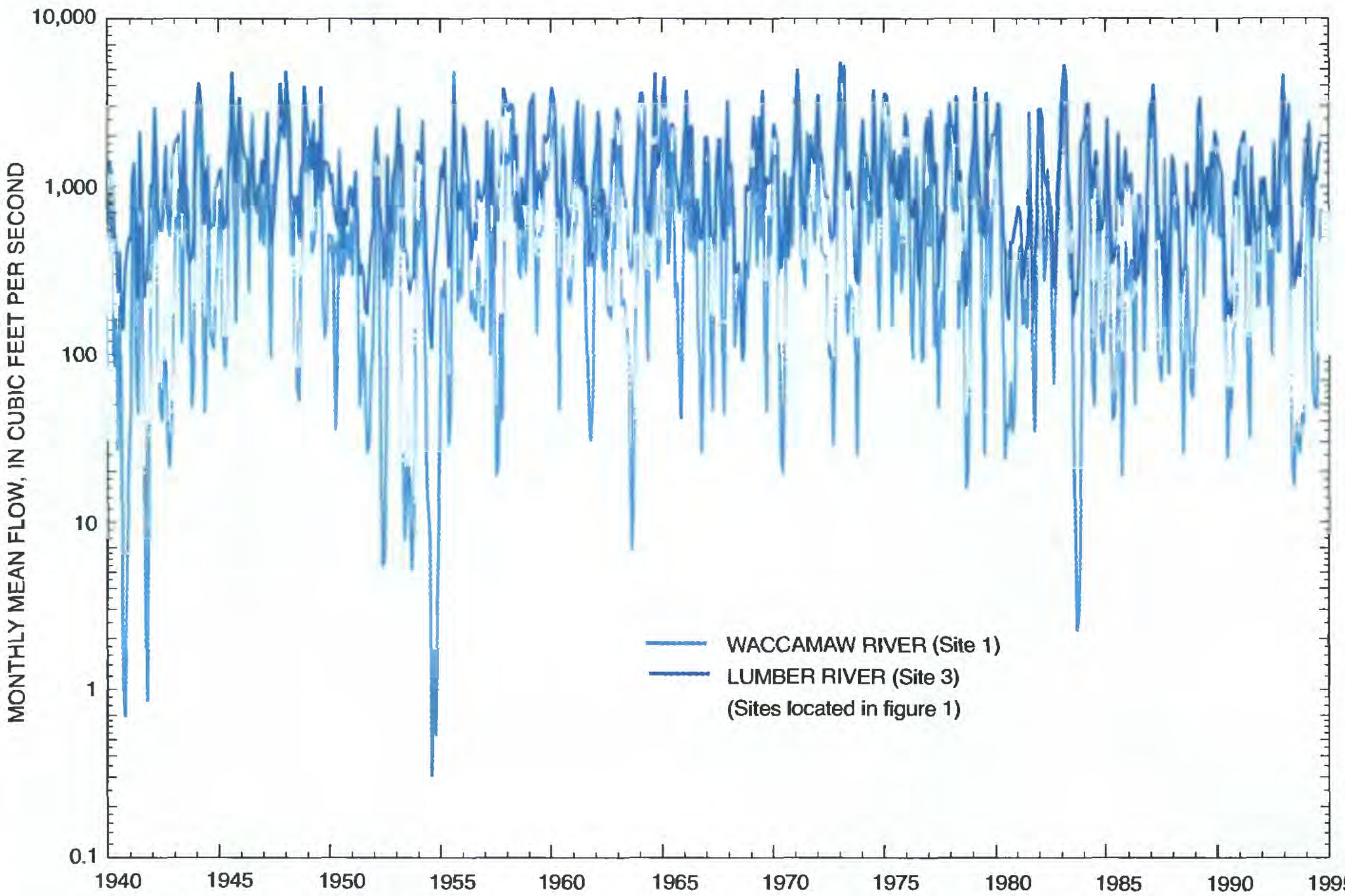

Figure 8. Monthly mean streamflow for the Waccamaw and Lumber Rivers, 1940-94.

period, but the decline in the Lumber River was about 16 standard deviations. In addition, flows in the Waccamaw River were greater relative to average conditions than in the Lumber River during 1982-83, as indicated by the larger increase in RCD for the Waccamaw River than for the Lumber River during the period.

The 1985-88 drought (Zembrzuski and others, 1991) appears to have actually begun in the Waccamaw Basin in mid-1983 and in the Lumber River (and Drowning Creek) Basin in mid-1984. As with the 1980-81 drought, the 1983-88 drought was more severe in the Lumber Basin than in the Waccamaw Basin. Flows were greater than average in 1989, but less-than-average flows resumed in 1990 and continued through 1992. Again, flows were lower relative to average conditions in the Lumber River than in the Waccamaw River during much of 1990-92.

Tree rings from living bald cypress trees were used by Stahle and others (1988) to reconstruct long-period climatic conditions in eastern North Carolina. Tree ring samples were collected from bald cypress trees along the Black River, which is a tributary to the Cape Fear River and is located about 60 miles north of Freeland. As an indication of climatic conditions, the Palmer drought severity index (PDSI) for June was reconstructed for a 1,614-year period from A.D. 372 to 1985. Reconstructed PDSI's for 1887 to 1985 compared favorably with observed PDSI values for the same period.

The reconstructed PDSI values indicate that statistically significant changes in average climatic conditions occur on an approximately 30-year time scale. The statistically different regimes averaged 34 years in length for the full analysis period and ranged in length from 21 to 63 years. In 1988, Stahle and others suggested that "the record June droughts in

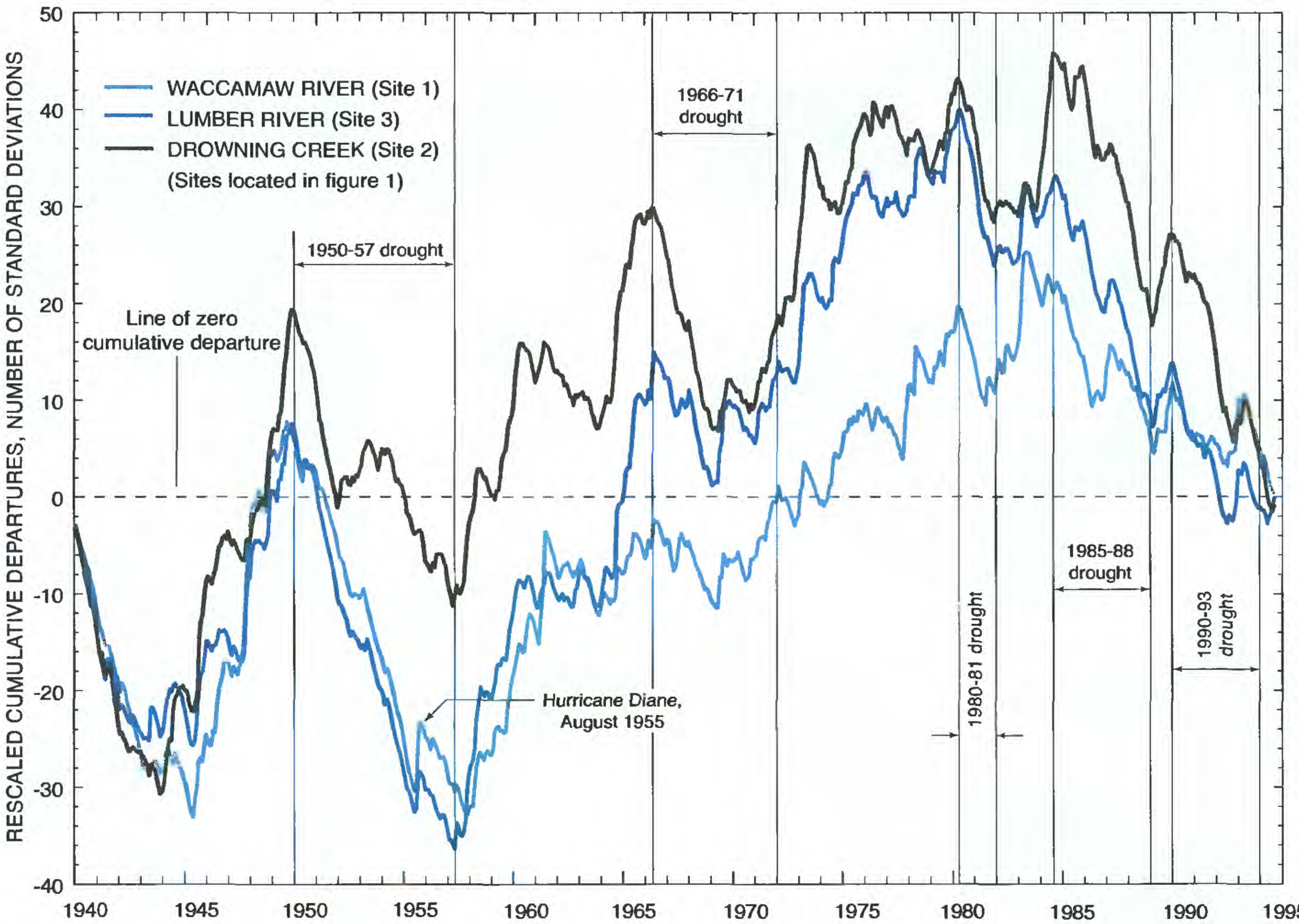

Figure 9. Rescaled cumulative departures (RCD's) of monthly mean streamflow for the Waccamaw and Lumber Rivers and Drowning Creek, 1940-94.

1985 and 1986, for example, could signal the end of the relatively wet regime that began in 1956, but this possibility remains highly speculative in the absence of a physical explanation for the changes."

The RCD's presented in figure 9 independently support and extend the conclusions drawn from the tree-ring data. Flows in the Waccamaw River generally were greater-than-average from 1957 to 1983 (fig. 9), a period of 27 years. And, as suggested by Stahle and others (1988), it appears that the "relatively wet regime" has indeed ended, because flow remained generally less than average from 1983 through 1994.

LOWESS-Smoothed Records

The 1940-94 records of monthly mean flows for the Waccamaw and Lumber Rivers were smoothed using the LOWESS technique to compare trends in monthly streamflows. Values of the smoothness factor *f* of 0.2 and 0.5 were used in this application (fig. 10).

For *f* = 0.5 (fig. 10A), trends in Waccamaw and Lumber River monthly flows appear to be very similar, with a generally increasing trend in flow from 1939 through about 1966 and a generally declining trend from 1966 through 1994. Except for the period from 1952 through about 1966, which included the severe 1950-57 drought, the LOWESS-smoothed curves for the Waccamaw and Lumber Rivers are generally parallel, indicating no long-term changes in flows at one site relative to the other. However, the difference between the two curves is greater (0.17 $(ft^3/s)/mi^2$ or more) prior to 1966 than after 1966, when the difference was about 0.11 $(ft^3/s)/mi^2$. As with the RCD's, the smoothed Drowning Creek

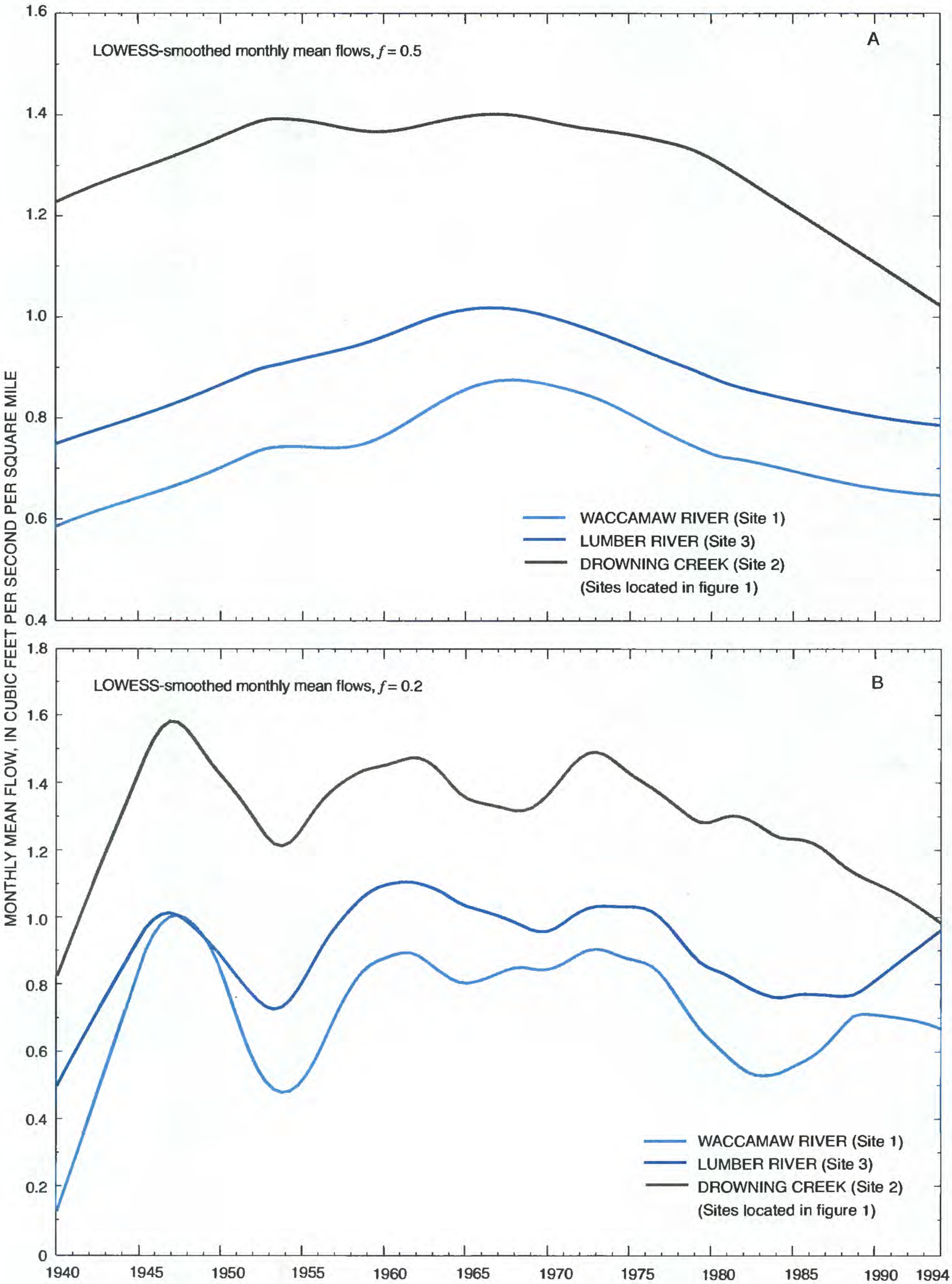

Figure 10. LOWESS-smoothed plots of monthly mean streamflow during 1940-94 for the Waccamaw and Lumber Rivers using smoothness factor *(f)* of (A) 0.5 and (B) 0.2.

flows are substantially different from the Waccamaw and Lumber River flows.

Short-term trends in monthly flows are depicted by using a smoothing factor of 0.2 (fig. 10B). As with $f = 0.5$, Lumber River flows in cubic feet per second per square mile are generally greater than those from the Waccamaw River, and the Waccamaw and Lumber River LOWESS-smoothed monthly flows have the same general trends, with the exception of the period 1979-94. During this period, and particularly following about 1983, the smoothed flows (including Drowning Creek) show distinctly different trends. These differences are investigated further using other techniques.

Flow Distributions

Waccamaw and Lumber monthly streamflow records were subdivided into five 10-year periods (table 5). The nonparametric Wilcoxon rank sum test was used to statistically compare distributions of monthly mean flow for the two sites. The *p*-statistic computed for this test indicates the probability that flows from two separate 10-year periods are from the same distribution. Values of *p* less than 0.1 were considered significant; in other words, if *p* was less than 0.1, then the two flow distributions were said to be statistically different.

According to the test, the distribution of monthly mean flows for the Waccamaw River during the period 1985-94 differed from those during the periods 1955-64, 1965-74, and 1975-84 (table 5). However, the distribution of monthly mean flows for 1985-94 was not statistically different from the 1945-54 distribution. This provides further support for the conclusion reached from the RCD analysis that the flow regime from the late 1950's to the early 1980's was distinctly wetter than the flow regimes which immediately preceded and followed this period. The distribution of monthly mean flows in the Waccamaw River exhibited less variability and a lower median during 1985-94 than during the four other 10-year periods (fig. 11). As previously shown, yields during 1984-93 were lower than average (fig. 5).

Similar results were observed for the five distributions of Lumber River monthly mean flows. The 1985-94 distribution of monthly flows was statistically different from the 1955-64, 1965-74, and 1975-84, as well as for the 1945-54 distribution (table 5). The *p*-statistics computed for the comparison of 1985-94 distribution with the other distributions were smaller for the Lumber River than for respective Waccamaw River comparisons. A smaller *p*-statistic indicates a greater probability that the distributions are different.

Table 5. Results of rank sum tests comparing distributions of monthly flow for the Waccamaw and Lumber Rivers during selected 10-year periods

[---, not applicable; bold values are those considered statistically significant, having a *p*-statistic less than 0.1]

10-year period	Waccamaw River *p*-statistic for 10-year period			
	1945-54	1955-64	1965-74	1975-84
1945-54	---	---	---	---
1955-64	0.377	---	---	---
1965-74	.134	0.187	---	---
1975-84	.351	.486	0.176	---
1985-94	.140	**.057**	**.006**	**0.069**
	Lumber River *p*-statistic for 10-year period			
1945-54	---	---	---	---
1955-64	**0.065**	---	---	---
1965-74	**.028**	0.331	---	---
1975-84	.274	.181	0.108	---
1985-94	**.078**	**.001**	**.001**	**0.035**

Double Mass Curve

A double mass curve was constructed to directly compare flows in the Waccamaw River with those in the Lumber River during 1940-94. The monthly mean arithmetic flows were transformed into logarithmic values because the monthly mean flows are approximately lognormally distributed. A simple linear regression model was used to determine a relation between the log-transformed Waccamaw River monthly mean flows and the log-transformed Lumber River flows. The relation had an r^2 value (coefficient of determination) of 0.6 (60 percent of the variance in the Waccamaw River monthly mean flows is described by Lumber River flows). The regression equation was used to predict Waccamaw River monthly mean flows for the period 1940-94 from the corresponding Lumber River flows. The predicted Waccamaw River flows, which were logarithmic values, were untransformed, correcting for logarithmic bias. The monthly residual flows, or difference between the predicted and observed monthly mean flows, were then computed and accumulated. The double mass curve is the plot of

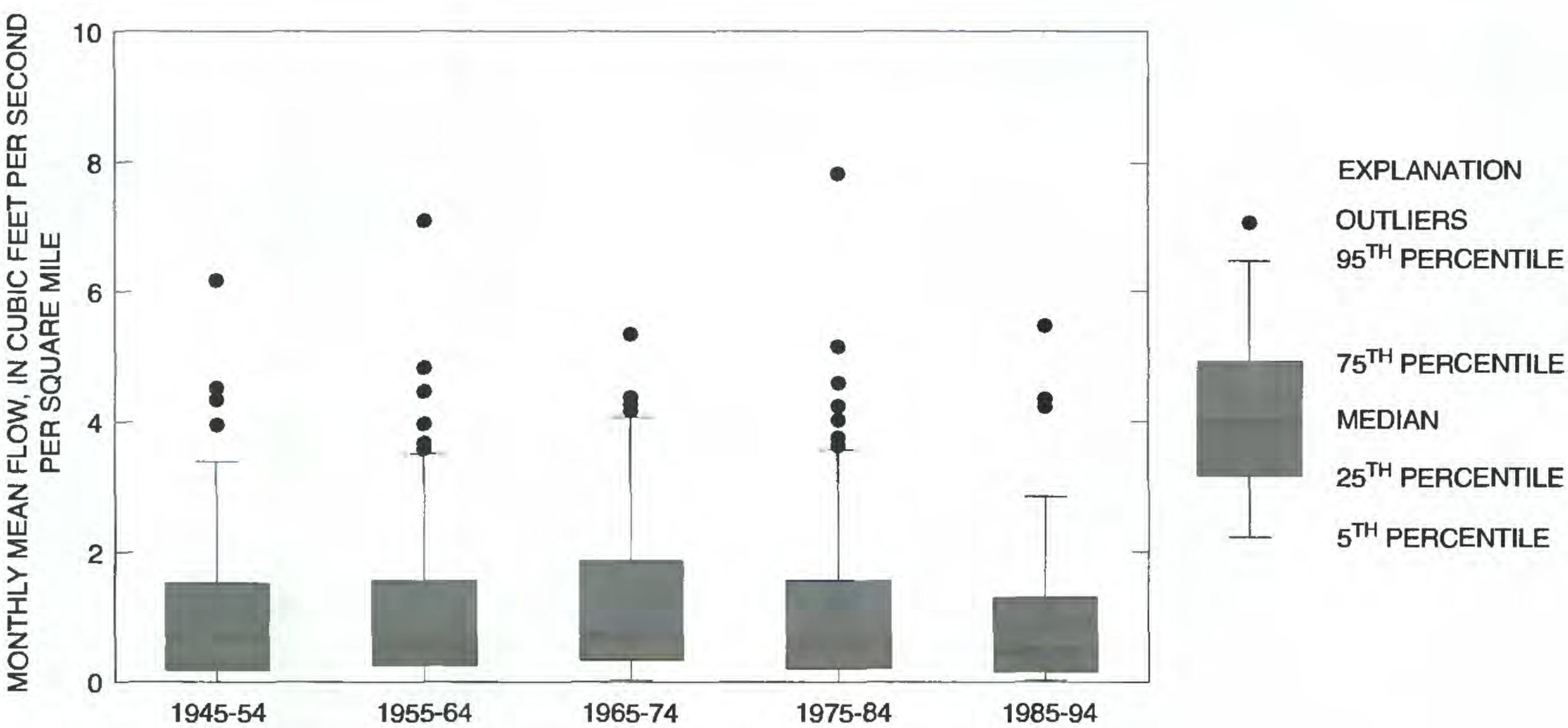

Figure 11. Boxplots of monthly distributions of flow in the Waccamaw River for five 10-year periods between 1945 and 1994.

accumulated monthly residual flows with time (fig. 12).

If the relation of Waccamaw River flows to Lumber River flows remains unchanged, the double mass curve plots, more or less, as a straight line. If the slope of the double mass curve increases relative to the slope of this line, then Waccamaw River flows are increasing relative to Lumber River flows. Short-term variations in the curve are the result of the imperfect relation between Lumber River and Waccamaw River flows.

From about 1940 through 1943 when a drought was occurring (fig. 9), Waccamaw River flows decreased relative to those in the Lumber River (the slope of the double mass curve decreased). As is explained in the following section, low flows in the Lumber River are more sustained, on a per drainage area basis, than those in the Waccamaw River. Hence, declines in Waccamaw River flows relative to Lumber River flows during droughts are not unexpected. Similar declines occurred between 1950 and 1957, 1967 and 1968, and from about the mid-1980's to the end of the record. The slope of the double mass curve during the period 1967-80, which was a period with generally greater-than-average flows, remained essentially unchanged with very few deviations. There is no indication from the double mass curve for the period prior to 1983 that there has been a major, sustained change in the relation between Waccamaw River and Lumber River monthly mean flows during the period 1940-94, but there have been fluctuations in the relation between flows in the two rivers. If earlier patterns persist, the slope of the double mass curve for the period after 1983 will return to the long-term mean slope after the period of lower-than-average flows has ended. However, if the relation between Waccamaw and Lumber River flows has changed, the slope of the double mass curve after 1983 reflects that new relation.

Daily Flow Durations

Flow duration curves of daily mean flow depict the percentage of time a given daily mean flow is equaled or exceeded during a selected time period. The shape of the flow duration curve is highly dependent on the period of record used to construct the curve. Flow duration curves were constructed from the Waccamaw and Lumber River daily mean flow data for the period 1940-94 (fig. 13). Differences between the curves at the higher flows is primarily a result of the difference in drainage area for the two basins. With a smaller drainage area, the Waccamaw Basin is more likely to be affected by intense rainfall events which cover the entire basin, resulting in higher flows per unit drainage area. The low-permeability clay soils predominant in the Waccamaw Basin also result in more rapid runoff of precipitation than the more permeable sandy soils of the Lumber Basin. The larger drainage area and sandy soils of the Lumber Basin provide greater storage than soils in the Waccamaw

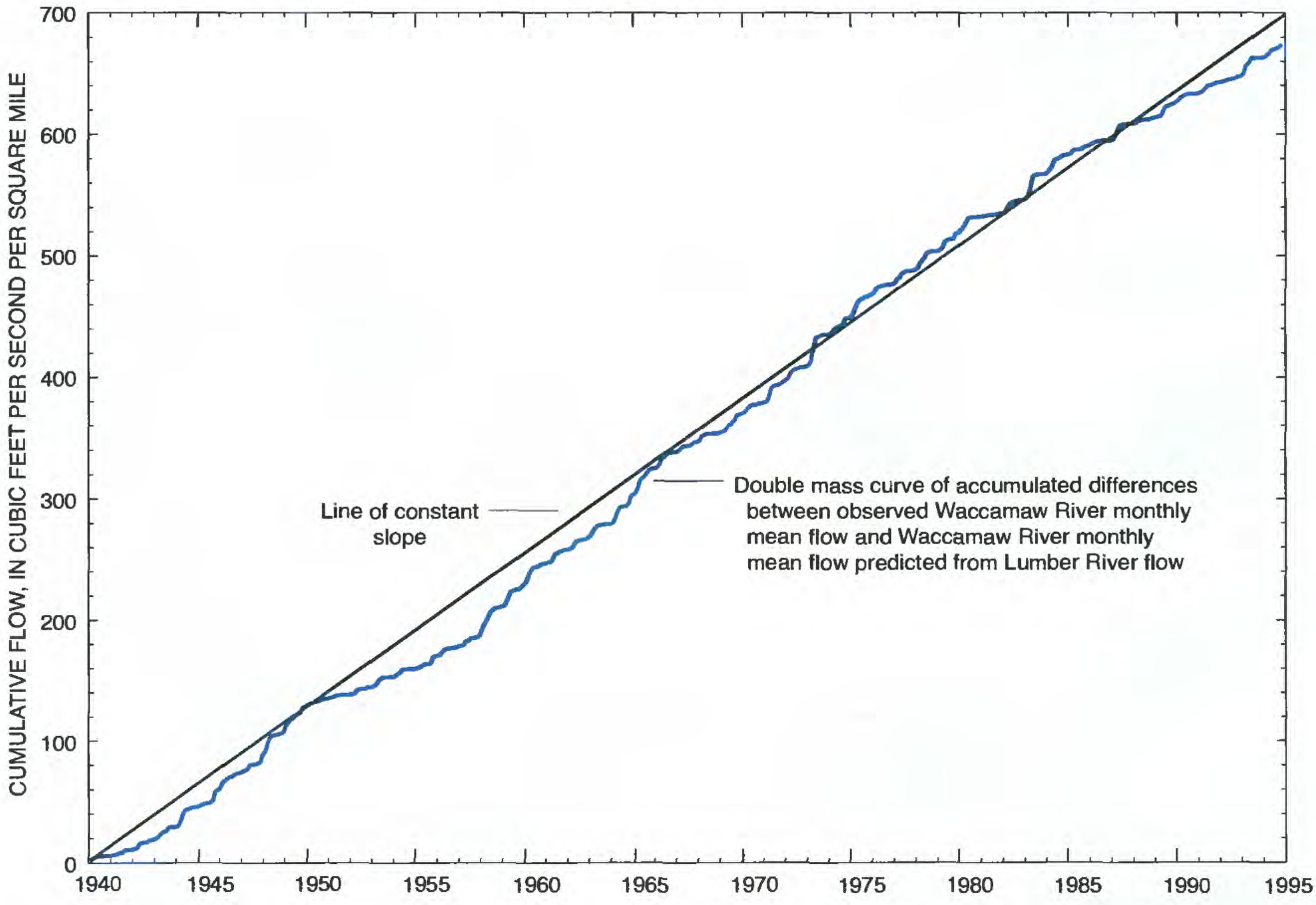

Figure 12. Double mass curve of accumulated differences between observed Waccamaw River monthly flows and Waccamaw River monthly flows predicted from Lumber River monthly flows, 1940-94.

River Basin, so that peak flows in the Lumber River are somewhat dampened (on a cubic foot per second per square mile basis) relative to those in the Waccamaw River. The greater storage in the Lumber Basin results in more sustained medium-to-low flows than in the Waccamaw River. Drainage from the Sand Hills part of the Lumber Basin likely further augments low flows, resulting in substantially greater yields than the Waccamaw Basin at exceedance values greater than 30 percent (fig. 13).

To examine possible changes in flow distributions during the study period, Waccamaw and Lumber River daily flow records were subdivided into the same five 10-year periods used in the monthly mean flow analysis. The lowest median daily flow for the five periods occurred during 1985-94 in the Waccamaw (fig. 11) and Lumber Rivers. The smallest interquartile range (difference between 25th and 75th percentile flows) of daily mean flows in both rivers also occurred during this 10-year period. In both rivers the greatest median daily flow of the five periods was during 1965-74, and the largest interquartile range was during 1975-84.

Flow duration curves for three 10-year periods were constructed for the Waccamaw River (fig. 14A) to compare 1985-94 flow durations with the relatively high-flow of 1975-84 and with the relatively low-flow of 1945-54. Daily mean flows at all exceed-ance levels that were less than about 80 percent were lower during 1985-94 than during 1945-54, which included about half of the 1951-57 drought, and 1975-84. However, the lowest 10 percent of the flows during 1975-84 were less than the lowest 10 percent of the flows during the relatively dry period of 1985-94. Hence, although flows were generally lower during 1985-94 than during 1975-84, the lowest flows during 1985-94 were more sustained than during the previous 10 years.

The lowest 10-year average flow (based on monthly means) was during 1949-58 (509 ft^3/s or

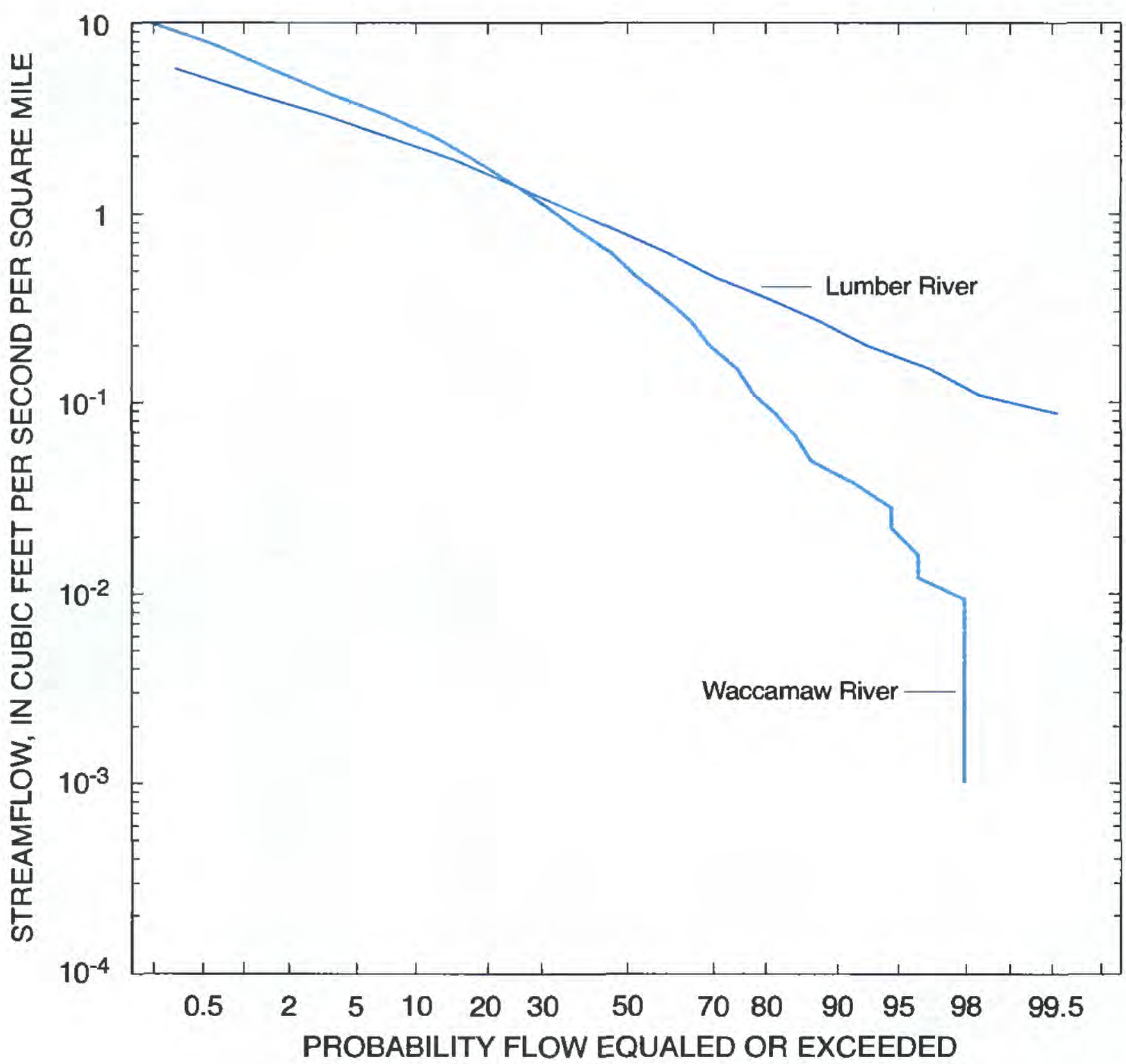

Figure 13. Daily flow duration curves for the Waccamaw and Lumber Rivers, 1940-94.

0.749 (ft^3/s)/mi^2), and the second lowest period that did not include any of the 1949-58 period was during 1985-94 (589 ft^3/s or 0.866 (ft^3/s)/mi^2). The highest 10-year average flow was during 1970-79, when the mean monthly flow for the period was 840 ft^3/s (1.24 (ft^3/s)/mi^2). Flow duration curves were constructed for these three periods to compare extreme dry and wet conditions with the most recent 10-year period (fig. 14B).

At exceedance levels less than about 60 percent, daily mean flows during 1985-94 were not greatly different from those during the 1949-58 dry period. However, flows equaled or exceeded about 80 percent of the time during 1985-94 were about double flows at the same exceedance level during 1949-58. At extreme low flows (exceedance levels greater than 90 percent) flows during 1985-94 approached those that occurred during 1970-79. Hence, during at least 60 percent of the time in 1985-94, flows were comparable to those that occurred during the extremely dry period of 1949-58. However, even during this relatively dry period, extremely low flows (exceedance levels of 90 percent or more) during 1985-94 were no less than half of those during the wet period of 1970-79 and were more than three times greater than those that occurred during 1949-58.

Low Flows

Low-flow statistics were computed for each of the three gaging stations (table 6). The low-flow statistics were computed for the period 1940-94, and for ten 10-year periods: 1940-49, 1945-54, 1950-59, and so on through 1985-94.

Although the Drowning Creek drainage area at site 2 is less than one-third of the Waccamaw River drainage area at site 1, low-flow statistics for Drowning Creek are substantially greater than those in the Waccamaw River—at least an order of magnitude greater. Low flow statistics per unit drainage area for

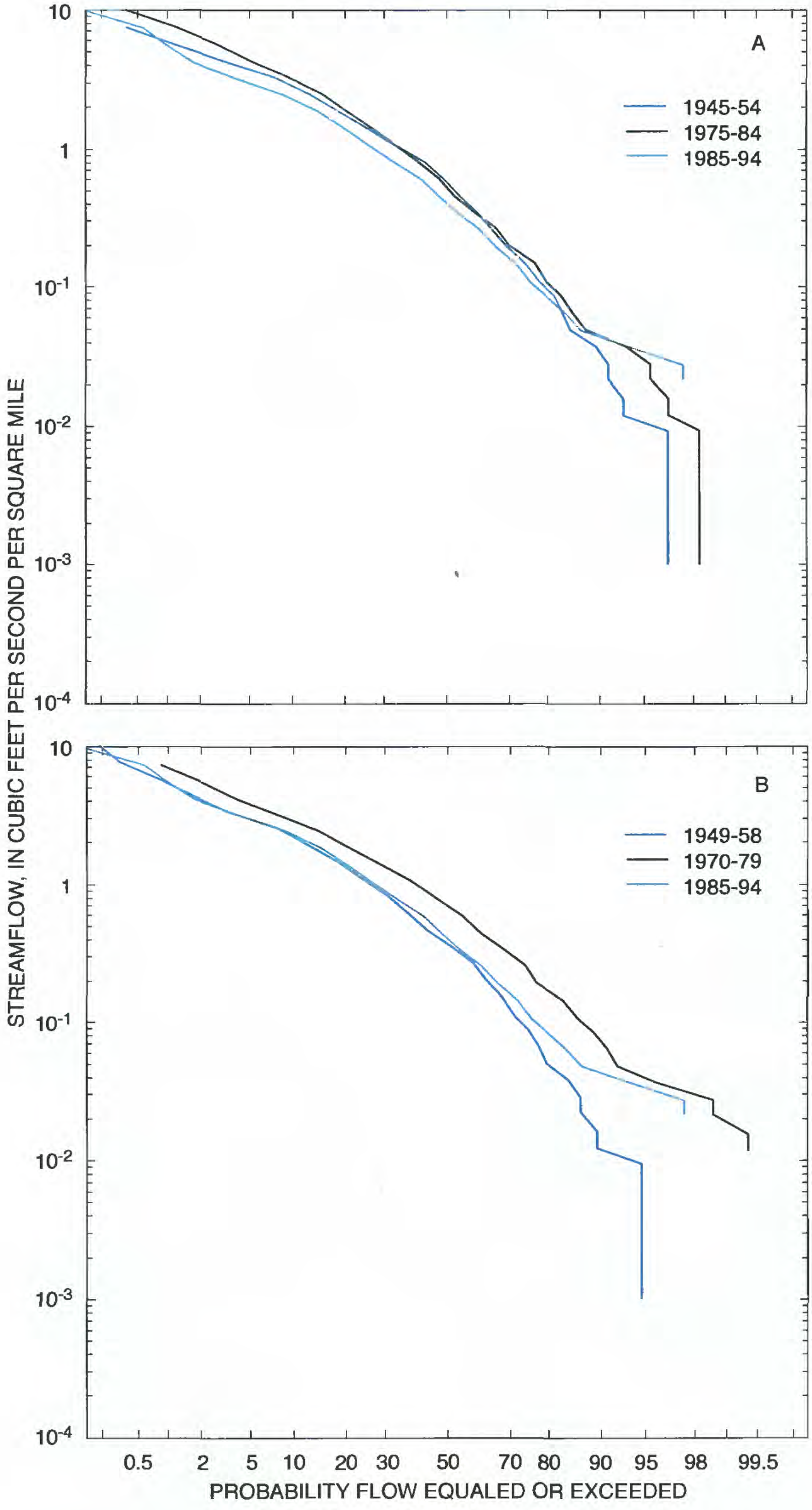

Figure 14. Daily flow duration curves for the Waccamaw River for the periods (A)1945-54, 1975-84, and 1985-94 and (B) 1949-58, 1970-79, and 1985-94.

Table 6. Selected low-flow statistics for the Waccamaw and Lumber Rivers and Drowning Creek, 1940-94

Site (fig. 1)	Station	Low flow, in cubic feet per second			Low flow, in cubic feet per second per square mile		
		7Q2	7Q10	30Q2	7Q2	7Q10	30Q2
1	Waccamaw River	22.0	2.06	33.4	0.032	0.003	0.049
2	Drowning Creek	66.1	35.2	87.5	.361	.192	.478
3	Lumber River	236	119	306	.192	.097	.249

the Lumber River also are several times greater than those for the Waccamaw River.

The lowest mean daily flow, 7-day low flow, and 30-day low flow were identified for each year during the period of record for each station. Values for each year were plotted (fig. 15), and data were smoothed using the LOWESS procedure with $f = 0.5$. Throughout the period of record, 1-day, 7-day, and 30-day low flows per unit drainage area in the Lumber River were always higher than corresponding flows in the Waccamaw River. Lumber River 1-day, 7-day, and 30-day low flows each exhibited the same general trend during 1940-94 (fig. 15), with an increase during the 1960's, a steep decline during the 1970's, and a more gradual decline in the 1980's and early 1990's. Drowning Creek annual low flows exhibited the same trends. The *n*-day low-flow trends for Drowning Creek and the Lumber River are similar to the trends in monthly mean flows (fig. 10A).

Waccamaw River annual low flows, however, were different from those observed in the Lumber River (fig. 15). In general, annual 1-, 7-, and 30-day low flows increased until about the mid-1960's, declined slightly until about 1980, and then increased through 1994. The strength of the increasing trend in the 1980's increased with the duration of the low-flow period (30-day low flows increased more than 1-day and 7-day). LOWESS-smoothed annual 7-day low flows in the Waccamaw increased at a rate of about 0.3 cubic feet per second per year during 1981-94, while the Lumber River experienced a decline of about 3 ft^3/s/year during the same period.

The Mann-Kendall trend test was used to determine if a statistically significant monotonic trend was present in the observed *n*-day low flows for the Waccamaw and Lumber Rivers. There was a statistically significant (95-percent confidence level) decrease in 1-day and 7-day low flows in the Lumber River during 1940-94. The decrease in 30-day low flows for the Lumber River was not statistically significant at the 95-percent level, but the *p*-statistic was 0.11. There was no statistically significant trend in Waccamaw River observed *n*-day low flows; *p*-statistics were between 0.21 and 0.37.

As was previously shown, monthly mean flows during 1981-94 (figs. 8 and 9), and particularly 1985-94 (fig. 14), were generally quite low compared to the entire period of record. Despite this, the lowest flows in the Waccamaw River were generally as great or greater than low flows during other times between 1940 and 1981. This is suggested by the LOWESS-smoothed curves in figure 15, and is evident from the flow duration curves (fig. 14B) in which flows greater than the 90-percent exceedance level for 1985-94 (a dry period) approached those for 1970-79 (a wet period). In fact, the 7Q10 for the Waccamaw River computed using 1985-94 flows was the second highest 7Q10 computed for the ten 10-year periods (table 7), with the highest being for the period 1965-74. However, the 7Q10 computed for the Lumber River

Table 7. 7Q10 low flows computed from data for selected 10-year periods

Site	7Q10 low flow, in cubic feet per second, for stated 10-year period									
	1940-49	1945-54	1950-59	1955-64	1960-69	1965-74	1970-79	1975-84	1980-89	1985-94
Waccamaw River	1.15	0.35	0.32	3.73	5.56	13.2	8.09	2.46	3.07	11.9
Lumber River	165	118	121	220	129	131	157	111	91.0	91.3

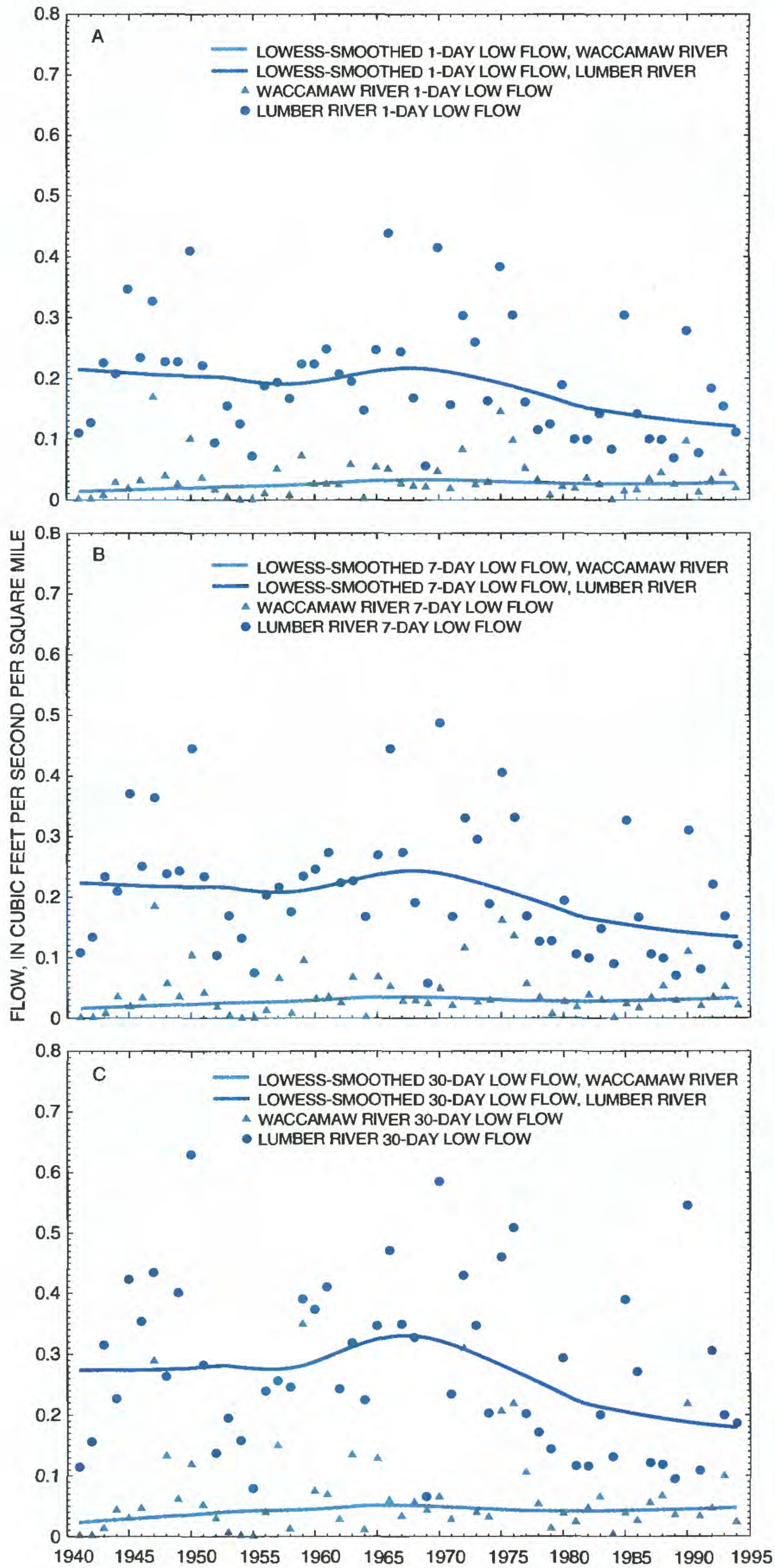

Figure 15. LOWESS-smoothed plots of annual 1-day, 7-day, and 30-day low flows for the Waccamaw and Lumber Rivers, 1940-94.

from 1985-94 flow records was the second lowest Lumber River 7Q10 computed for the 10 periods.

Channelization and artificial drainage in the Waccamaw Basin could be responsible for these apparent increases in low flows. It has been demonstrated that both channelization and artificial drainage lead to an increase in base, or low, flows. Mason and others (1990) found that channelization of a small stream in the central Coastal Plain of North Carolina increased base flow almost 10-fold over pre-channelization conditions. Heath (1975) reported similar results for channelization of a small stream in the northern Coastal Plain of North Carolina, and suggested that artificial drainage would have a similar effect.

High Flows

Peak flows having recurrence intervals of 2, 5, 10, 25, 50, and 100 years were computed from the 1940-94 series of annual peak flows (table 8). Although the Waccamaw River drainage area is only slightly more than half that of the Lumber River, Waccamaw peak flows for all recurrence intervals were very nearly equal to those for the Lumber River (table 8). As with the low flows, peak flows in cubic feet per second per square mile for Drowning Creek were much greater than those for the Waccamaw and Lumber Rivers.

The annual series of the greatest mean daily flow, 7-day high flow, and 30-day high flow were developed for the Waccamaw and Lumber Rivers for the period 1940-94 (fig. 16). With few exceptions, Waccamaw River 1-day, 7-day, and 30-day high flows in cubic feet per second per square mile exceeded corresponding values for the Lumber River (fig. 16). Differences were greatest for years having the higher flows (for example, 1983 and 1955, which had the two highest monthly mean flows on record for the Waccamaw River, fig. 8). All occurrences of Lumber River *n*-day high flows exceeding corresponding flows for the Waccamaw River were prior to 1970 (except the 30-day high flow for 1989). Results from the Mann-Kendall test performed on the observed *n*-day values indicated that there were no statistically significant trends in the *n*-day high flows for either the Waccamaw or the Lumber Rivers.

LOWESS-smoothed (with $f = 0.5$) curves of *n*-day high flows for the two rivers exhibited the same general trends, with an increase in *n*-day high flows until the early (Lumber) to mid (Waccamaw) 1970's, followed by a decline (fig. 16). This trend also is similar to the trend in smoothed monthly mean flows (fig. 10A). Differences between Waccamaw and Lumber River *n*-day high flows decreased as *n* increased (greater difference for 1-day than 30-day high flows). However, the difference between the two LOWESS-smoothed curves is not constant during the period, but shows a generally increasing difference throughout the period of record for the *n*-day high flows.

The annual series of differences between the Waccamaw 1-day and corresponding Lumber River 1-day high flows was plotted, and a 5-year moving average of the differences was calculated (fig. 17A).

Table 8. Selected peak-flow statistics for the Waccamaw and Lumber Rivers and Drowning Creek, 1940-94

Recurrence interval, in years	Flow, in cubic feet per second			Flow, in cubic feet per second per square mile		
	Waccamaw River	Lumber River	Drowning Creek	Waccamaw River	Lumber River	Drowning Creek
2	3,850	4,720	1,290	5.66	3.84	7.05
5	5,920	6,980	2,390	8.71	5.68	13.1
10	7,400	8,540	3,480	10.9	6.95	19.0
25	9,370	10,600	5,430	13.8	8.63	29.7
50	10,900	12,100	7,420	16.0	9.85	40.5
100	12,500	13,700	9,980	18.4	11.2	54.5

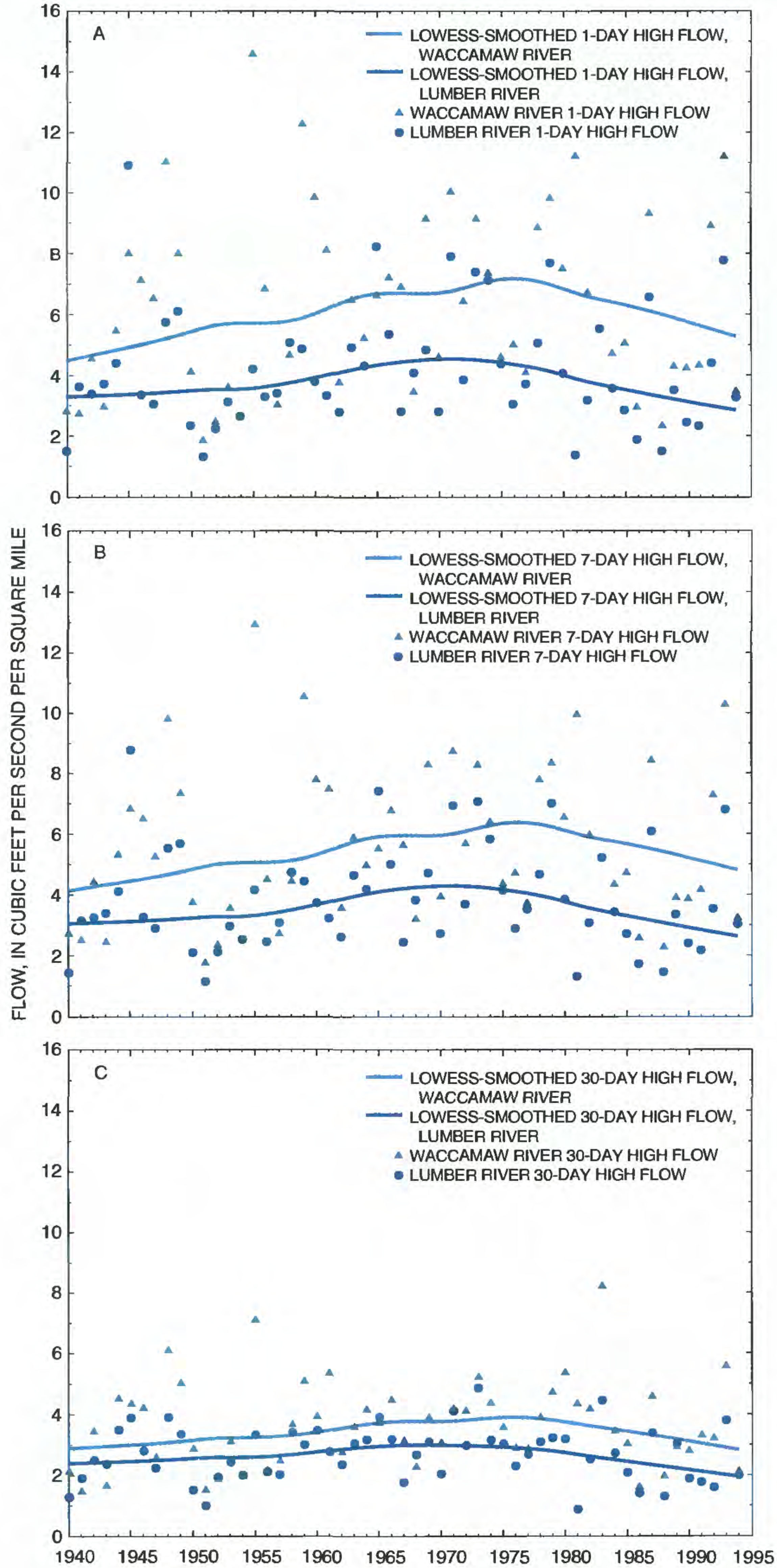

Figure 16. LOWESS-smoothed plots of annual 1-day, 7-day, and 30-day high flows for the Waccamaw and Lumber Rivers, 1940-94.

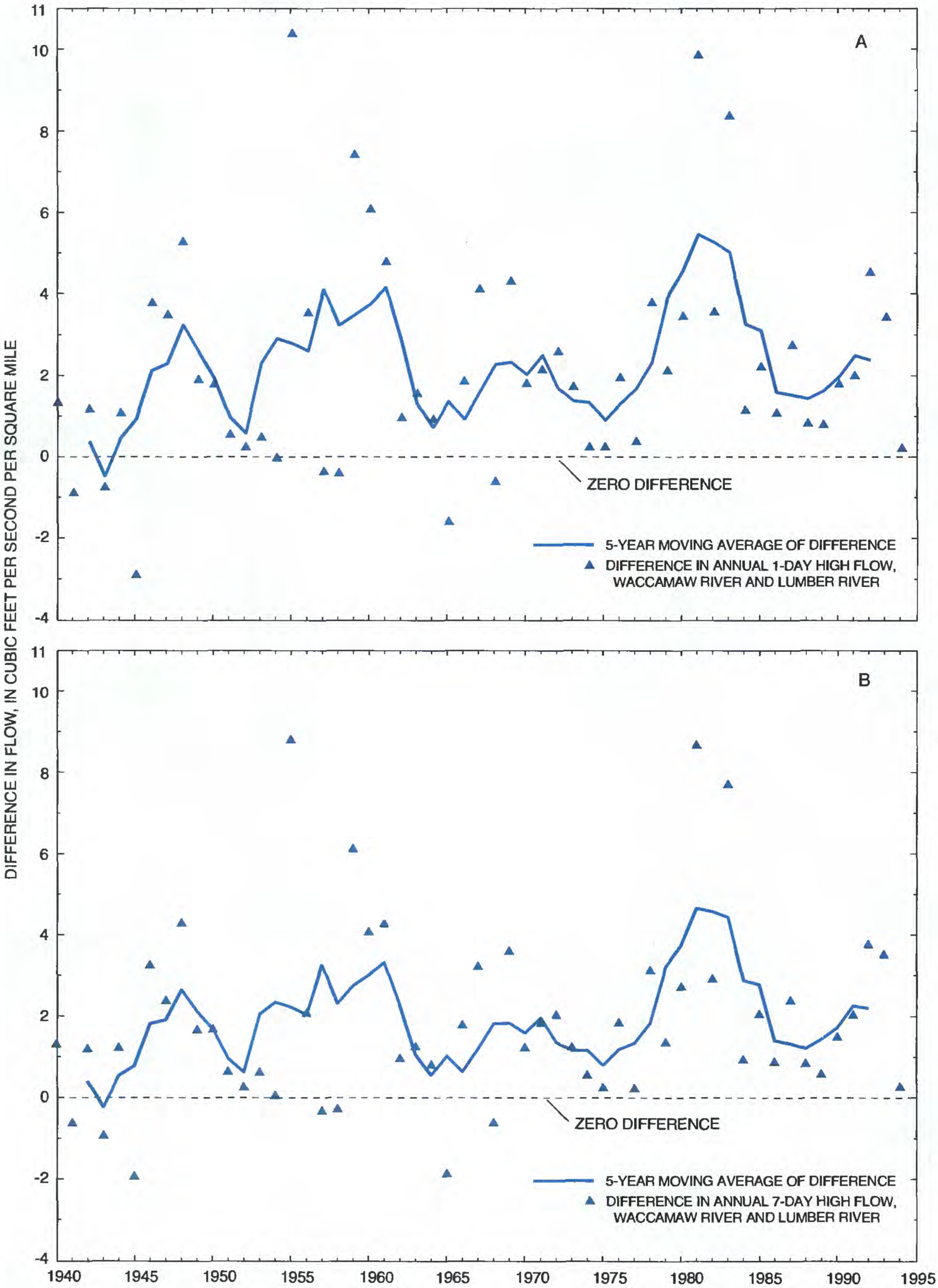

Figure 17. Difference between annual (A) 1-day and (B) 7-day high flows for the Waccamaw and Lumber Rivers.

The moving average shows a fairly clear increasing trend in the difference between Waccamaw River and Lumber River 1-day high flows, consistent with the trend in the difference between the LOWESS-smoothed curves (fig. 16A). A similar pattern is more evident in the 7-day high flows (fig. 17B). The analysis does not indicate whether the trend is the result of an increase in Waccamaw River high flows relative to Lumber River high flows, a decrease in Lumber River high flows relative to the Waccamaw River, or both.

Previously discussed analyses showed that the difference between Waccamaw River and Lumber River monthly mean flows per square mile decreased during the period of record, with most of the change occurring after 1966 (fig. 10A). Analyses of low flows indicated that *n*-day low flows for the Waccamaw River exhibited a slightly increasing trend and that Lumber River *n*-day low flows exhibited a statistically significant decreasing trend during the period of record. Heath (1975) concluded that channelization and artificial drainage leads to an increase in the magnitude of the highest flows because of increased drainage efficiency in the basin following channelization or ditching. These factors suggest that the increasing difference between Waccamaw and Lumber River *n*-day high flows may be the result of a general increase in Waccamaw River high flows relative to Lumber River high flows.

Base-Flow Separation

Streamflow can be divided into runoff and base flow. The distinction is primarily based on the time of arrival of water in the stream rather than the path followed to reach the stream. Runoff generally consists of overland flow and a substantial portion of interflow (water which moves laterally through the upper soil layer to the stream). Base flow is considered to be primarily ground water contributions to streamflow. On average, about two-thirds of the total streamflow volume in the Coastal Plain is base flow (Wilder and others, 1978).

Base Flows

The base-flow index (bfi) is defined as the ratio of the base-flow volume to the total streamflow volume. The annual bfi for the Lumber River exceeded the corresponding value for the Waccamaw River every year during 1940-94, with the exception of 1945, 1958, and 1977 (fig. 18). On average, streamflow in the Waccamaw River at site 1 (fig. 1) consisted of 53.3 percent base flow, with the annual percentage ranging from 28 percent (1942 and 1981) to 72 percent (1953 and 1958). In contrast, base flow in the Lumber River at site 3 (fig. 1) accounted for 70.6 percent of the streamflow during 1940-94, with annual bfi's ranging from 0.55 (1985) to 0.84 (1940 and 1956). As previously shown, *n*-day low flows for the Lumber River were significantly greater than those for the Waccamaw River (fig. 15; table 6), which is consistent with relatively low base flow in the Waccamaw.

The Waccamaw River annual mean bfi (0.53) is significantly less than the value of 0.67 reported by Wilder and others (1978) as the average for the North Carolina Coastal Plain, whereas the Lumber River bfi (0.706) is in good agreement with the Coastal Plain average. The Waccamaw River bfi values also exhibit greater annual variability than the Lumber River values (fig. 18). The lowest Waccamaw River bfi values were associated with dry years (1942, when annual streamflow was 51 percent of the long-term average; 1981, when annual flow was 67 percent of average; and 1985, when annual flow was 57 percent of average). There is, however, no clear relation between the annual bfi and the annual flow for either the Waccamaw River or the Lumber River (fig. 19).

Monthly mean base flows for the Waccamaw and Lumber Rivers were determined, and the time series was smoothed using LOWESS ($f = 0.5$) to identify trends in base flow. The two curves depicting monthly mean base flow (fig. 20) exhibit the same general trends—trends which are consistent with those seen in the monthly mean streamflow data (fig. 10A). Waccamaw River smoothed monthly mean base flows (fig. 20) were about 10 times greater than corresponding smoothed 7- and 30-day low flows (fig. 15B and C). This indicates that there is generally a large difference between the lowest 30-day mean flow during a year and the average base-flow condition during the same year in the Waccamaw Basin. In contrast, Lumber River base flows (fig. 20) were only about 2 to 3 times greater than corresponding 7- and 30-day low flows (fig. 15B and C).

Differences between the Lumber and Waccamaw River smoothed base flows increased in the mid- to late-1950's during and immediately following the

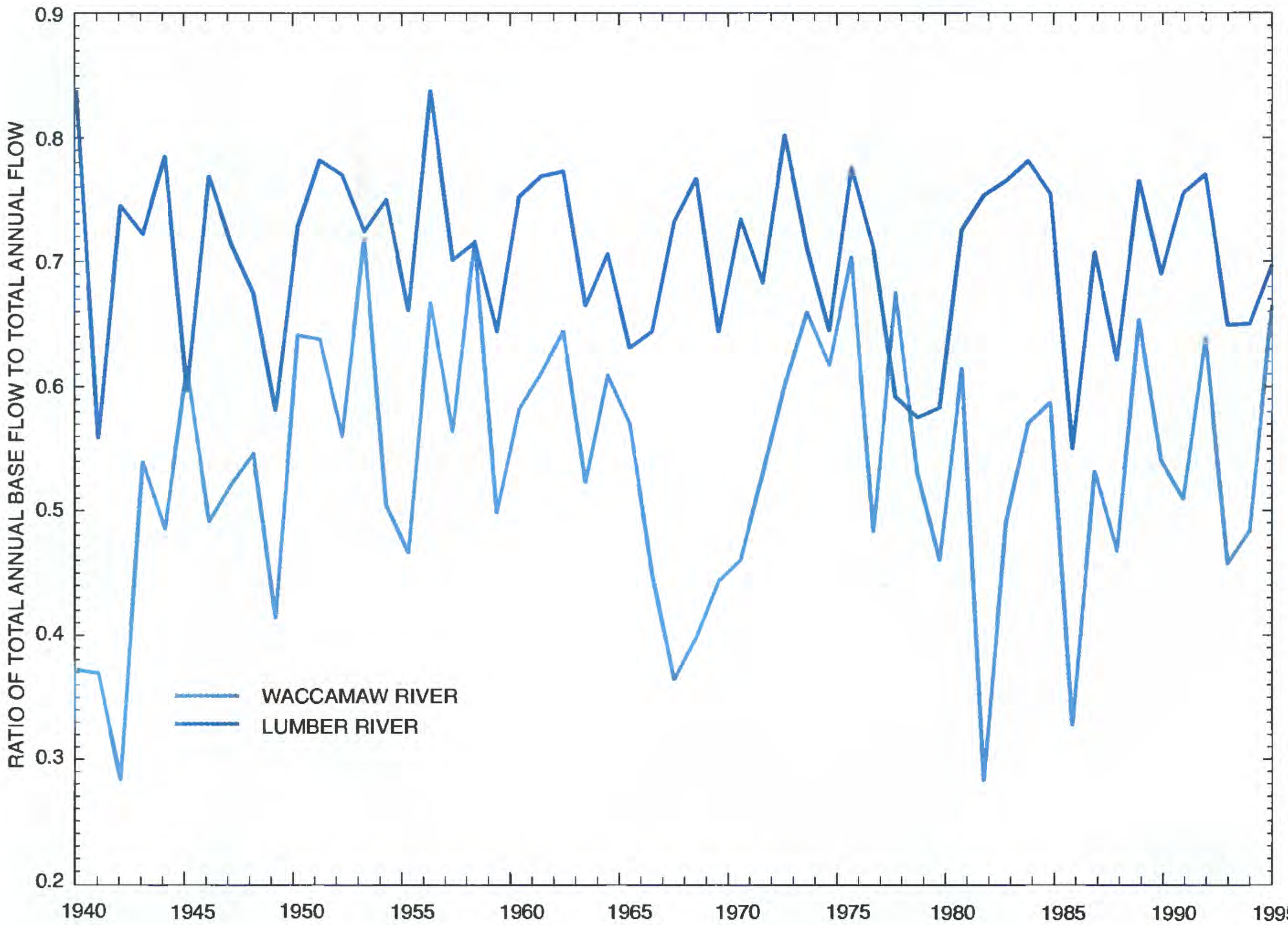

Figure 18. Ratio of total annual base flow to total annual flow for the Waccamaw and Lumber Rivers, 1940-94.

1950-57 drought (fig. 20). As previously shown, this drought was more severe in the Waccamaw Basin than in the Lumber Basin. Differences between Lumber and Waccamaw River smoothed monthly base flows declined in the 1970's, when streamflows were generally greater than average (fig. 20). Again, there was a pattern of increasing differences between Waccamaw and Lumber base flows during the 1980's and early 1990's, when flows were generally less than average.

As with the total flow (table 5), the Wilcoxon rank sum test was used to statistically compare distributions of monthly mean base flow for selected 10-year periods in the Waccamaw River and the Lumber River. The distribution of Waccamaw River base flows for 1985-94 was statistically different from the distributions for the previous four 10-year periods (table 9). However, the same was true for the Lumber River. The distribution of monthly mean base flows in the Waccamaw River for the other 10-year periods was not statistically different from one another, but some differences were noted in the Lumber River.

Runoff

Runoff per unit drainage area is greater in the Waccamaw Basin than in the Lumber Basin (fig. 20). LOWESS-smoothed monthly runoff curves for the two basins exhibit the same general trends (fig. 20), with about the same range in values. Trends in runoff are similar to trends in total flow (fig. 10A).

The difference between smoothed Waccamaw River and Lumber River runoff is approximately inversely related to the corresponding differences in base flow. When the difference between Waccamaw and Lumber River base flow decreases (1940's to mid-1950's), the difference between smoothed monthly runoff increases. Since 1980, the Waccamaw River runoff per unit drainage area appears to have increased relative to Lumber River runoff (fig. 20).

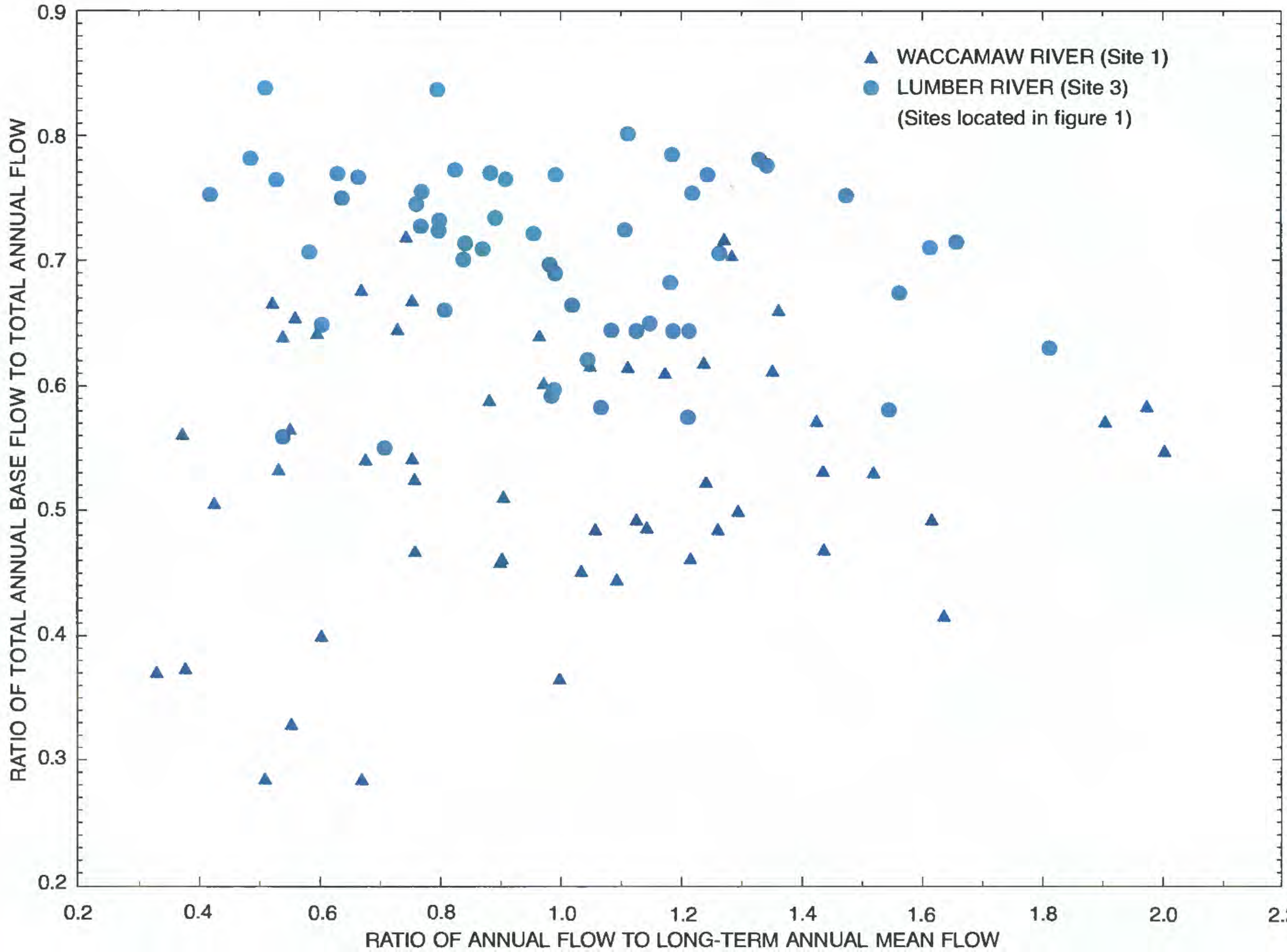

Figure 19. Relation of base-flow index to ratio of total annual base flow to annual mean flow for the Waccamaw and Lumber Rivers.

The ratios of monthly base flow to monthly runoff for the Waccamaw River ranged from 0.01 to 41.2, and from 0.15 to 82.3 for the Lumber River. The monthly ratios of base flow to runoff for the Waccamaw and Lumber Rivers were low in the late 1940's and increased to their highest values in the 1950's during the drought period, when runoff was low relative to total flow (fig. 21). During the drought in the early 1980's (fig. 9), the ratio for the Lumber River again increased as expected (fig. 21). However, the ratio of monthly base flow to runoff during this period decreased to extremely low values for the Waccamaw River indicating an increased proportion of runoff in the total flow, which also is suggested by the LOWESS-smoothed curves of monthly mean runoff (fig. 20). As shown earlier (fig. 9), the drought was less severe in the Waccamaw than in the Lumber Basin, but flows in the Waccamaw River were still less than average during this period. This increase in runoff relative to base flow is not consistent with patterns exhibited during previous periods having lower than average flow.

The distribution of monthly mean runoff in the Waccamaw River for 1985-94 was statistically different from those of the previous two 10-year periods (table 9). Likewise, the distribution for 1965-74 was statistically different from those of 1945-54 and 1955-64. Similar patterns were not evident in the monthly distributions of runoff for the Lumber River.

Logarithmically transformed monthly mean base flows (in cubic feet per second per square mile) for the Waccamaw River were regressed against those for the Lumber River, and likewise for the monthly mean runoff. Lumber River base flow was more highly correlated with Waccamaw River base flow (r^2 = 0.60) than was Lumber River runoff with Waccamaw River runoff (r^2 = 0.40). This may be explained by (1) the difference in the size of the two drainage basins—

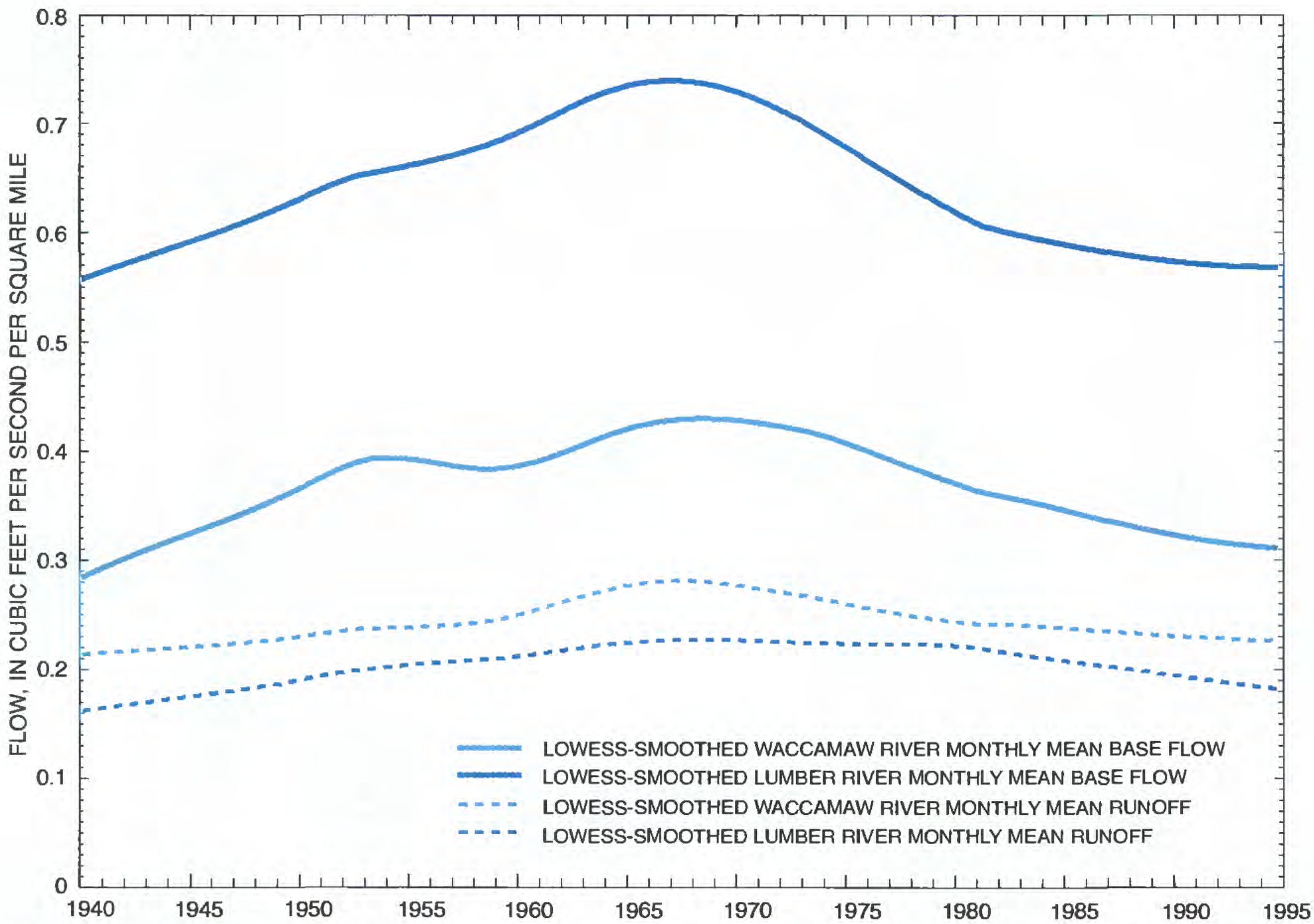

Figure 20. LOWESS-smoothed monthly mean base flow and runoff for the Waccamaw and Lumber Rivers, 1940-94.

Table 9. Results of rank sum tests comparing monthly distributions of runoff and base flow for the Waccamaw and Lumber Rivers during selected 10-year periods

[---, not applicable; bold values are those considered statistically significant, having a *p*-statistic less than 0.1]

10-year period	Waccamaw River *p*-statistic for 10-year period				Lumber River *p*-statistic for 10-year period			
	1945-54	1955-64	1965-74	1975-84	1945-54	1955-64	1965-74	1975-84
				Base flow				
1945-54	---	---	---	---	---	---	---	---
1955-64	0.318	---	---	---	**0.055**	---	---	---
1965-74	.295	0.483	---	---	**.012**	0.276	---	---
1975-84	.479	.258	0.218	---	.455	**.062**	**0.032**	---
1985-94	**.066**	**.016**	**.007**	**0.090**	**.048**	**.0005**	**.0001**	**0.038**
				Runoff				
1945-54	---	---	---	---	---	---	---	---
1955-64	0.447	---	---	---	0.136	---	---	---
1965-74	**.074**	**0.044**	---	---	.230	0.372	---	---
1975-84	.258	.198	0.248	---	**.090**	.444	0.354	---
1985-94	.264	.327	**.017**	0.107	.325	**.068**	.131	**0.041**

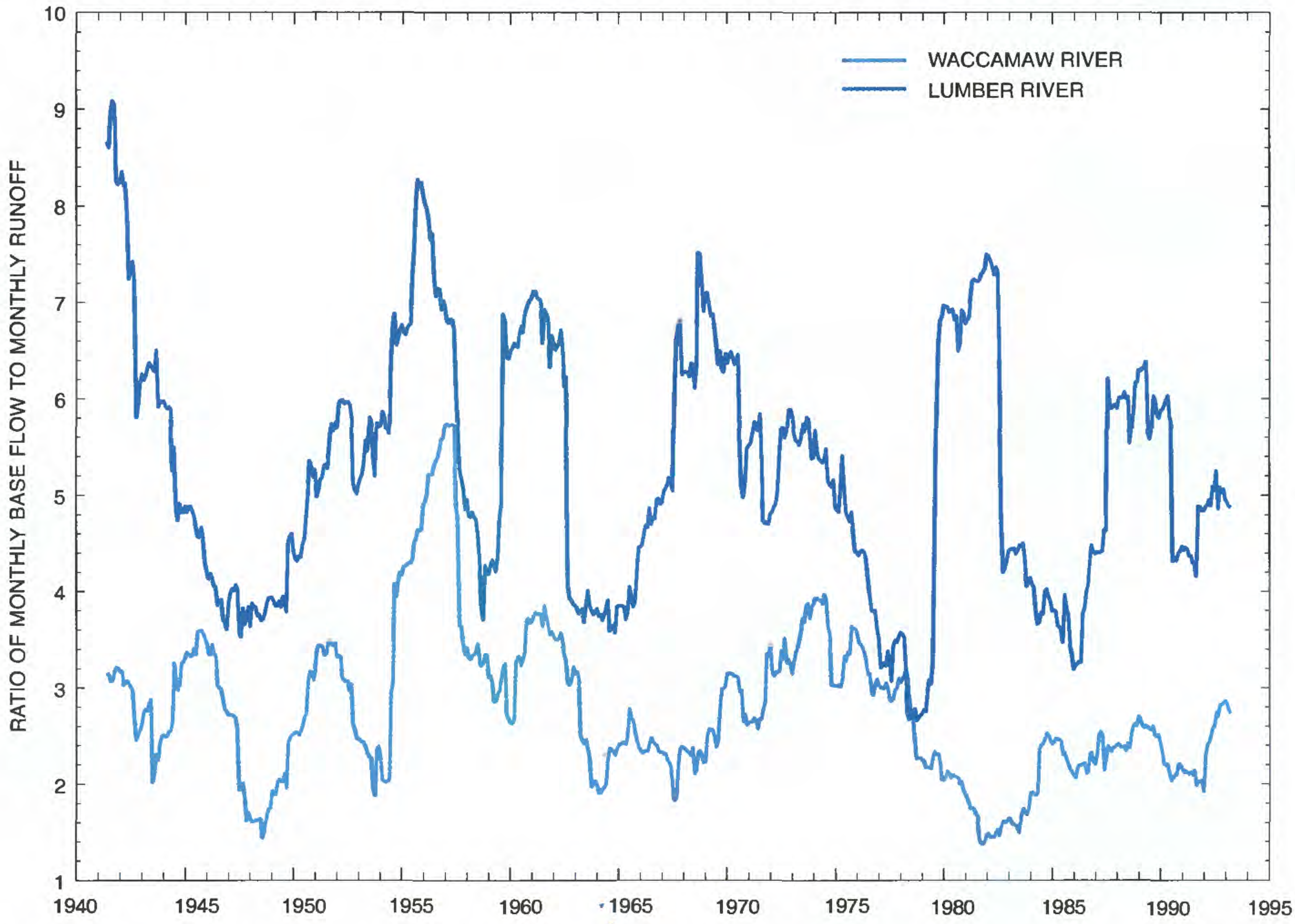

Figure 21. Three-year moving average of the ratio of base flow to runoff for the Waccamaw and Lumber Rivers, 1940-94.

there is a greater likelihood that precipitation events will cover the entire Waccamaw Basin than the larger Lumber River Basin; and (2) the possibility that artificial drainage has increased the efficiency of the drainage network in the Waccamaw Basin relative to that in the Lumber Basin. There was no apparent temporal trend in the residuals from the two regression relations.

Flow Variability

Flow variability was evaluated by using computations of a 12-month moving range of monthly flow and a 10-day moving range of daily flow (Barringer and others, 1994). The moving range was computed for total flow, runoff, and base flow. There was essentially no difference between the flow variability described using the LOWESS-smoothed 12-month moving range and the LOWESS-smoothed 10-day moving range.

There was greater variability in Waccamaw River total flow (in cubic feet per second per square mile) than in Lumber River total flow (fig. 22A). Trends in total flow variability were generally the same for the Waccamaw and Lumber Rivers; however, the difference in the smoothed 12-month moving range for the two rivers was slightly greater at the end of the period of record than at the beginning (fig. 22A). This also was true for the difference between the LOWESS-smoothed 10-day moving ranges for the two rivers.

The variability in runoff generally exceeded the variability in base flow in the Waccamaw River

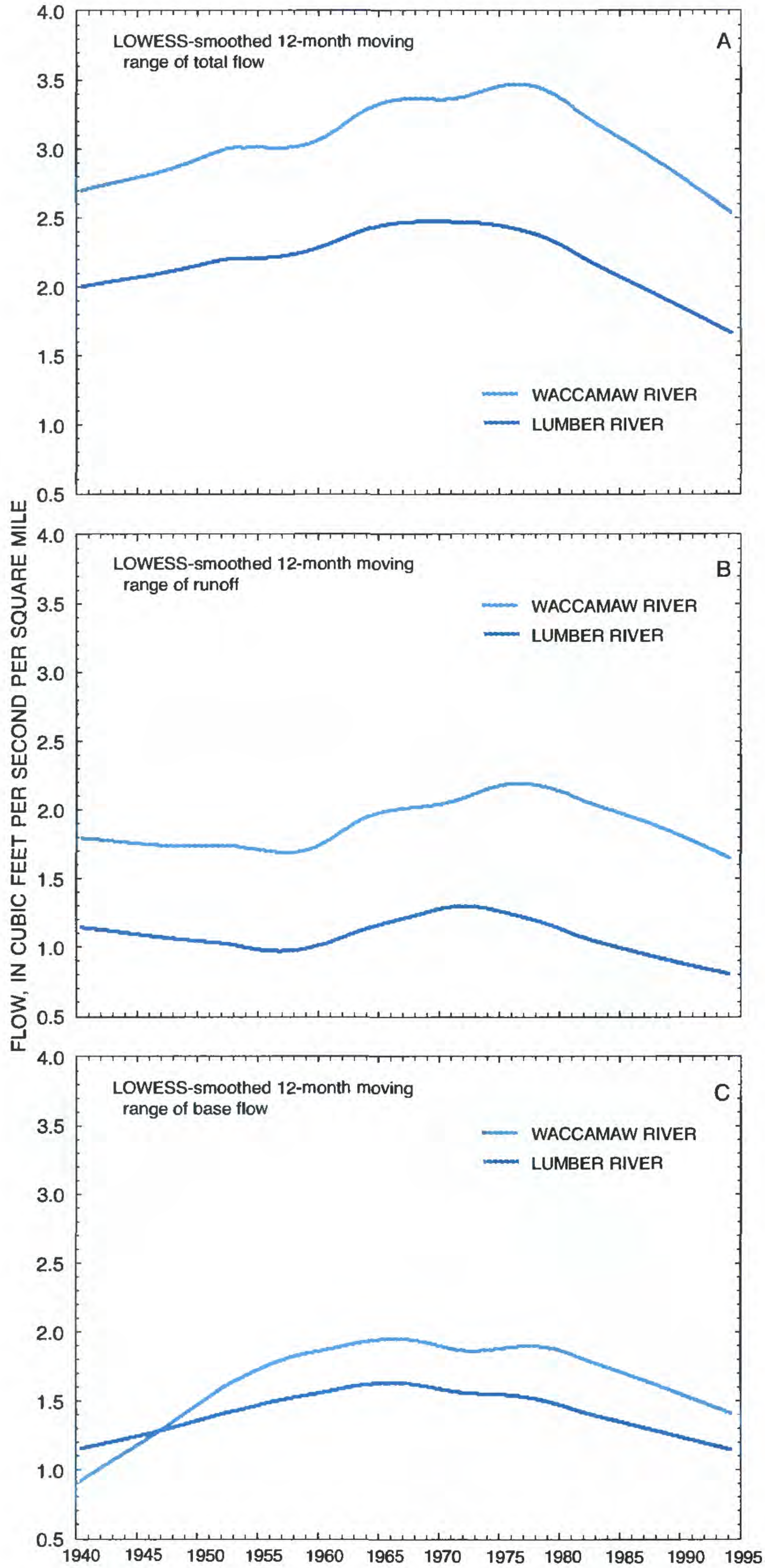

Figure 22. LOWESS-smoothed curves of 12-month moving range of (A) total flow, (B) runoff, and (C) base flow for the Waccamaw and Lumber Rivers, 1940-94.

(fig. 22B and C). The opposite was true for the Lumber River, however, with greater variability in the base flow than the runoff. As previously shown, streamflow in the Lumber River consists of about 70 percent base flow and 30 percent runoff, whereas base flow constitutes about 53 percent of the total flow in the Waccamaw River. Despite the differences in the magnitude of base flow and runoff variability, trends in base flow and runoff 12-month moving ranges were generally the same for the Waccamaw and Lumber Rivers except for the base-flow range prior to about 1960. The increasing variability in Waccamaw River base flow prior to 1960 likely reflects recovery from the severe effects on base flows of the 1940-43 and 1950-57 droughts.

The distributions of the 12-month moving range values were compared for four 10-year periods: 1949-58, the driest 10 years on record; 1970-79, the wettest 10 years on record; 1975-84; and 1985-94, the most recent period and the second driest 10 years on record. The 1975-84 period was selected to compare the previous 10-year period with the most recent 10-year period.

The range in total flow variability, as measured by the interquartile range of the 12-month moving range values (difference between the 75th and 25th percentiles), was smallest during 1985-94 (fig. 23A). In fact, the interquartile range for 1985-94 (0.79) was significantly less than any of the values for the other 10-year periods (1.53, 1.63, and 1.36, respectively). Median 12-month moving ranges of total flow were lower during the drier 10-year periods (1949-58 and 1985-94) than the wetter 10-year periods.

Runoff variability, as measured by the interquartile range of the 12-month moving ranges, was smallest during the driest (1949-58) and wettest (1970-79) 10-year periods (fig. 23B). The difference between the maximum and minimum 12-month moving range values was greatest during 1985-94, possibly suggesting an increase in variability in the runoff component of streamflow. Base-flow variability, however, was much smaller during 1985-94 than the other three 10-year periods, for which the interquartile ranges were approximately equal (fig. 23C). This smaller base-flow variability is reflected in the variability of total flows for the 1985-94 period.

The median value of the 10-day moving range of daily flows for the wettest 10 years (1970-79) was about double the median value for the driest 10-year

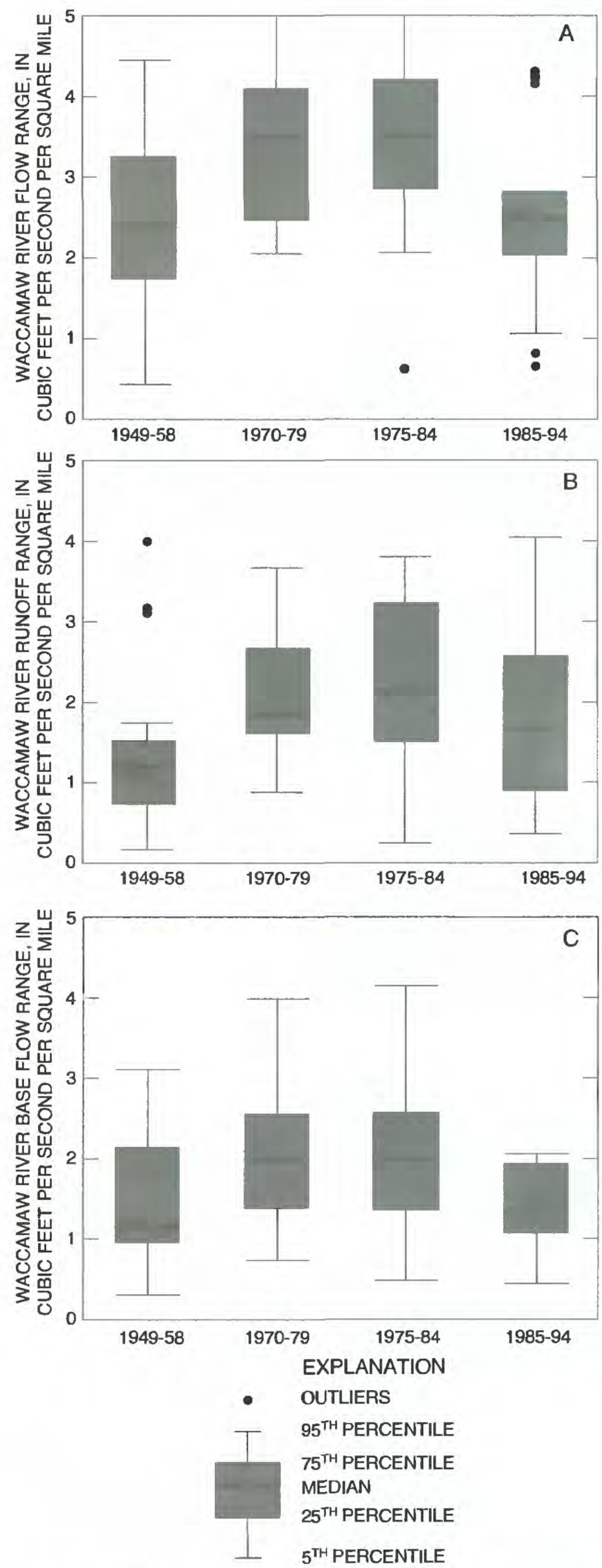

Figure 23. Boxplots of Waccamaw River distributions of monthly 12-month moving ranges of (A) total flow, (B) runoff, and (C) base flow for the periods 1949-58, 1970-79, 1975-84, and 1985-94.

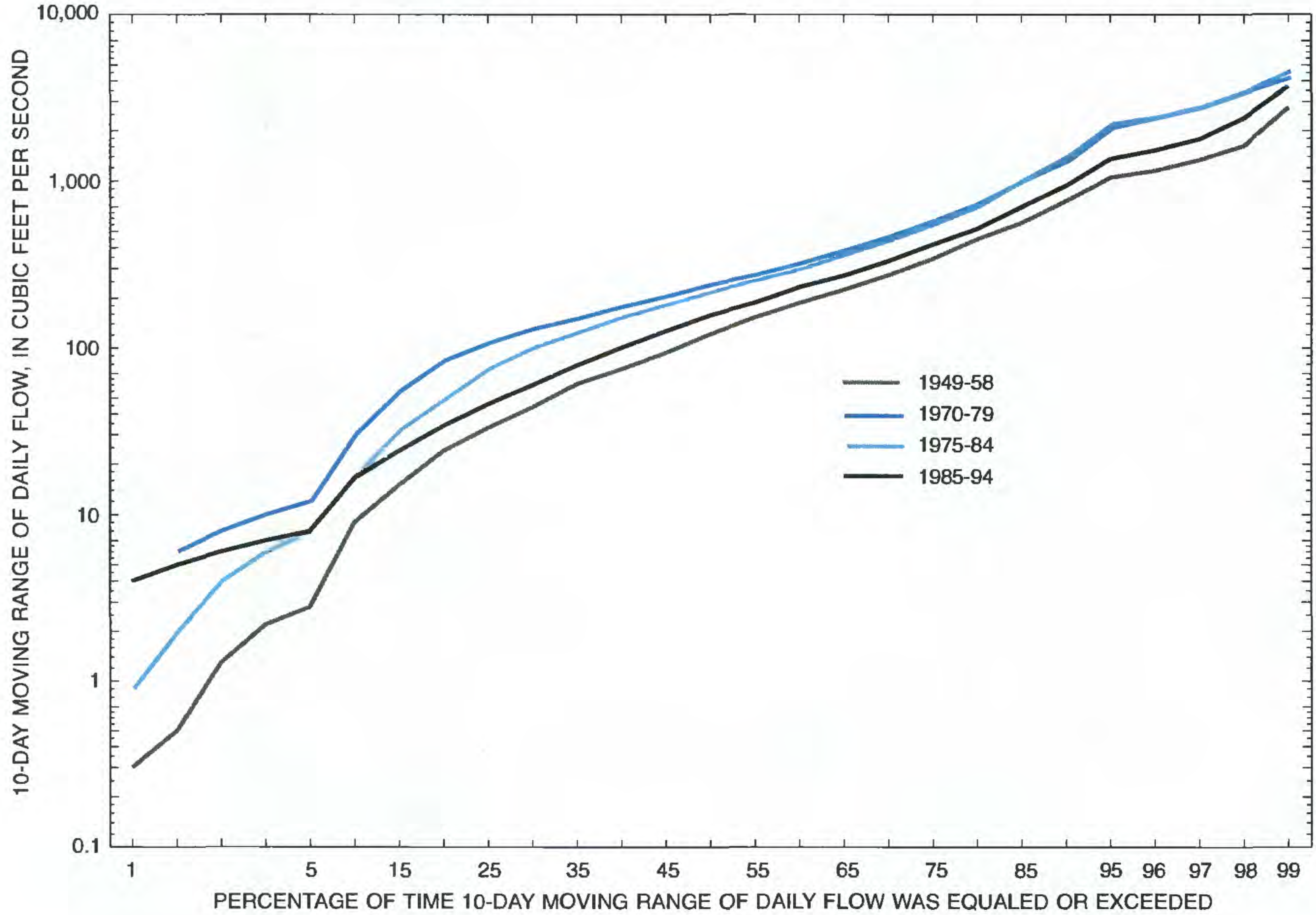

Figure 24. Percentage of time 10-day moving range of daily flow values were equaled or exceeded for the Waccamaw River, 1940-94.

period (1949-58) (fig. 24). The distributions of flow variability (as indicated by 10-day moving ranges of daily flows) for the four different 10-year periods were about the same for the larger variabilities (greater than about the 50-percent exceedance level (fig. 24)), although the magnitudes of the variabilities differed. The distributions of flow variability differed for exceedance levels less than 50 percent (shapes of curves are different). In particular, at an exceedance level of less than 5 percent, the flow variability during 1985-94 increased relative to variability during the other three 10-year periods (fig. 24). However, the change in variability at this exceedance level was small—less than 5 ft^3/s.

CONCLUSIONS

Streamflow characteristics of the Waccamaw River at Freeland, N.C., were described for the period 1940-94. Flows in the Waccamaw River were compared to those in the Lumber River at Boardman and Drowning Creek near Hoffman for the same period. Precipitation at three locations was characterized for the study period and used to interpret flow data. Monthly flow statistics, flow durations, *n*-day low and high flows, and base-flow conditions were evaluated.

Long-term mean and median precipitation amounts at the three rainfall sites were generally the same for the period 1940-94. The distribution of annual rainfall at Elizabethtown was not statistically different from the distributions at Lumberton and Laurinburg. This suggests that any long-term differences in flows between the Waccamaw and Lumber Basins are not the result of differences in precipitation. Periods of four or more consecutive years of less than average precipitation at Elizabethtown occurred in

1940-43, 1951-54, 1965-68, and 1978-81, with the greatest multi-year deficit in 1951-54. Periods of four or more years of greater than average precipitation at Elizabethtown occurred during 1955-60 and 1991-94. Precipitation at Elizabethtown may have been under-reported in the early part of the study period, particularly in 1947.

Thirty percent of rainfall, on average, becomes streamflow in the Waccamaw and Lumber Basins. Fifty-seven percent of the total annual flow in the Waccamaw River typically occurs during January to April, with the greatest flows occurring during March. Conversely, the four months with the greatest precipitation at Elizabethtown are June to September, when 44 percent of the total annual precipitation occurs. Despite the higher rainfall amounts, streamflow is lower during June to September than during January to April because evapotranspiration is greater during the summer months.

The period 1940-43 was one of less than average rainfall and streamflow, and was the second or third most severe drought on record in the Waccamaw and Lumber Basins. The 1950-57 drought was the most persistent on record in North Carolina. The passage of Hurricane Diane in August 1955 briefly interrupted the drought, particularly in the Waccamaw Basin. Streamflows were generally greater than average from 1958 until 1980, except for the period 1966-69. During 1958-83, when annual rainfall was 4 percent greater than average, 33 percent (or 10 percent more than average) of the rainfall became streamflow. The period 1980-94 was characterized by three droughts (1980-81, 1985-88, and 1990-93) with lower than average streamflow. Between 1984 and 1994 when rainfall was 3 percent less than average, 26 percent of annual rainfall in the Waccamaw Basin became streamflow. Although precipitation was greater than average during 1991-94, flows were generally less than average, possibly because of higher-than-average summer temperatures. The distribution of monthly mean flows for the period 1985-94 was statistically different from the distributions for the periods 1955-64, 1965-74, and 1975-84, but was not different from the distribution for 1945-54.

During 1940-63, flows in the Waccamaw and Lumber Basins were essentially identical relative to average conditions. Following 1963, droughts in the Waccamaw Basin seem to have been less severe than in the Lumber Basin. The 5-year moving average of monthly flows and LOWESS-smoothed curves of monthly flows indicate some change in the relation between Waccamaw River flows and Lumber River flows. Prior to the 1980's, flows per unit drainage area in the Waccamaw Basin were generally less than those in the Lumber Basin, but after 1980 the opposite was true. The LOWESS-smoothed curves indicate an increase in Waccamaw flows relative to Lumber flows during the same period.

The lowest 10-year average flow in the Waccamaw River was during 1949-58 (0.749 $(ft^3/s)/mi^2$), and the second lowest, which did not include any of the 1949-58 period, was during 1985-94 (0.866 $(ft^3/s)/mi^2$). The highest 10-year average flow was during 1970-79 (1.235 $(ft^3/s)/mi^2$). At exceedance levels less than about 60 percent, daily mean flows during 1985-94 were not greatly different from those during 1949-58. However, at exceedance levels of 90 percent and greater, daily mean flows during 1985-94 approached those of 1970-79, and were at least three times greater than those during 1949-58.

Annual n-day low flows (in cubic feet per second per square mile) in the Lumber River were typically several times greater than those in the Waccamaw River. However, although the series of annual n-day low flows in the Lumber Basin exhibited a decreasing trend from the 1970's until 1994, n-day low flows in the Waccamaw appeared to be increasing somewhat significantly. This is consistent with the observation that at the higher exceedance levels during 1985-94, daily mean flows were several times greater than those during 1949-58, despite the fact that flows during both periods were much less than average. This apparent increase in low flows could be the result of channelization or artificial drainage.

Computed flood flows for the Waccamaw River having recurrence intervals of 25, 50, and 100 years were only about 10 percent less than those computed for the Lumber River, which drains an area almost twice the size of the Waccamaw. Annual n-day high flows in cubic feet per second per square mile were, with a few exceptions, higher for the Waccamaw than corresponding values for the Lumber during 1940-94. There was an increasing trend in the difference between Waccamaw and Lumber annual n-day high flows, primarily as a result of increases in Waccamaw n-day high flows.

On average, streamflow in the Waccamaw River consisted of 53.3 percent base flow, but base flow accounted for about 70.6 percent of the total flow in the Lumber River, which is more typical of other Coastal Plain streams. Hence, it is not unexpected that *n*-day low flows in cubic feet per second per square mile in the Lumber River are greater than those in the Waccamaw River. More annual variability also occurred in the Waccamaw base-flow index (0.28 to 0.72) than in the Lumber River base-flow index (0.55 to 0.84). Runoff per unit drainage area is greater in the Waccamaw Basin than in the Lumber Basin. There is some indication that the ratio of base flow to runoff in the Waccamaw River changed relative to that in the Lumber River beginning in the late 1970's.

Greater variability occurred in Waccamaw River total flow than in Lumber River total flow for the entire period. Trends in streamflow variability were generally the same for the Waccamaw and Lumber Rivers, but the difference in the smoothed 12-month moving range for the two rivers was greater at the end of the period of record than at the beginning. The variability in runoff generally exceeded the variability in base flow in the Waccamaw River, but the opposite was true for the Lumber River. The range in total flow variability was least during 1985-94, and was significantly less than any of the values for the other 10-year periods. Runoff variability was less during the driest (1949-58) and wettest (1970-79) 10-year periods. Base flow variability, however, was much smaller during 1985-94 than during the other three 10-year periods, for which the interquartile ranges were approximately equal. This smaller base-flow variability is reflected in the variability of total flows for the 1985-94 period.

REFERENCES

Barringer, T.H., Reiser, R.G., and Price, C.V., 1994, Potential effects of development on flow characteristics of two New Jersey streams: Water Resources Bulletin, v. 30, no. 2, p. 283-295.

Cleveland, W.S., 1979, Robust locally weighted regression and smoothing scatterplots: Journal of the American Statistical Association, v. 74, p. 829-836.

Garbrecht, J., and Fernandez, G.P., 1994, Visualization of trends and fluctuations in climatic records: Water Resources Bulletin, v. 30, no. 2, p. 297-306.

Giese, G.L., and Mason, R.R., Jr., 1993, Low-flow characteristics of streams in North Carolina: U.S. Geological Survey Water-Supply Paper 2403, 29 p.

Heath, R.C., 1975, Hydrology of the Albemarle-Pamlico region, North Carolina: A preliminary report on the impact of agricultural developments: U.S. Geological Survey Water-Resources Investigations Report 9-75, 98 p.

Helsel, D.R., and Hirsch, R.M., 1992, Statistical methods in water resources: Amsterdam, Elsevier Science Publishers, B.V., 522 p.

Institute of Hydrology, 1980a, Low flow studies: Wallingford, Oxon, United Kingdom, Report No. 1, 41 p.

_____1980b, Low flow studies: Wallingford, Oxon, United Kingdom, Report No. 3, p. 12-19.

Interagency Advisory Committee on Water Data, 1982, Guidelines for determining flood flow frequency: Reston, Va., U.S. Department of the Interior, Bulletin #17B of the Hydrology Subcommittee.

Mason, R.R., Jr., Simmons, C.E., and Watkins, S.A., 1990, Effects of channel modifications on the hydrology of Chicod Creek Basin, North Carolina, 1975-87: U.S. Geological Survey Water-Resources Investigations Report 90-4031, 83 p.

North Carolina Department of Environment, Health, and Natural Resources, 1992, North Carolina lake assessment report: Raleigh, Division of Environmental Management, Water Quality Section, 353 p.

_____1993, Lumber River basinwide water quality management plan: Raleigh, Division of Environmental Management, Water Quality Section.

Riggs, H.C., 1973, Regional analyses of streamflow characteristics: U.S. Geological Survey Techniques of Water-Resources Investigations, book 4, chap. B3, 15 p.

Stahle, D.W., Cleaveland, M.K., and Hehr, J.G., 1988, North Carolina climate changes reconstructed from tree rings: A.D. 372 to 1985: Science, v. 240, p. 1517-1519.

Wilder, H.B., Robison, T.M., and Lindskov, K.L., 1978, Water resources of northeast North Carolina: U.S. Geological Survey Water-Resources Investigations Report 77-81, 113 p.

Zembrzuski, T.J., Hill, C.L., Weaver, J.C., Coble, R.W., Gunter, H.C., and Davis, J.M., 1991, North Carolina floods and droughts, *in* National water summary 1988-89—Hydrologic events and floods and droughts: U.S. Geological Survey Water-Supply Paper 2375, p. 425-434.