HYDROLOGY OF CREEPING SWAMP WATERSHED, NORTH CAROLINA,

WITH REFERENCE TO POTENTIAL EFFECTS OF STREAM CHANNELIZATION

U. S. GEOLOGICAL SURVEY
WATER RESOURCES INVESTIGATIONS 77-26

PREPARED IN COOPERATION WITH THE
NORTH CAROLINA DEPARTMENT OF NATURAL
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16. Abstract Hydrologic data were collected for four years at six sites in the Creeping Swamp watershed in eastern North Carolina in a preliminary effort to study the effects of stream channelization on the hydrology of a small watershed. A water-budget evaluation for pre-channelized conditions showed that runoff accounts for about 17 percent of the total rainfall, base runoff about 20 percent, ground-water outflow about 2 percent, and evapotranspiration about 61 percent.

Channelization would have caused the greatest decline in ground-water levels nearest the stream, with the decline diminishing with increased distance from the stream. Channelization would also have resulted in a decrease in overland runoff and an increase in the amount of water reaching Creeping Swamp through the ground-water system, although the total volume of runoff would not change significantly.

The water-quality characteristics of Creeping Swamp indicate that the stream is relatively free of pollution, although it is likely that channelization would increase (1) suspended-sediment loads, (2) stream temperatures, and (3) concentrations of dissolved solids, especially during low flows.

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April 1977

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COVER PHOTOGRAPH: Creeping Swamp at site 1 looking upstream about 200 ft southwest of State Highway 43.

USE OF INTERNATIONAL SYSTEM UNITS

The following table gives the factors used to convert English units to metric or International System (SI). The SI equivalent follows the English unit in the text of this report.

Multiply English units	by	to obtain SI units
inches (in)	25.4	millimeters (mm)
	2.54	centimeters (cm)
feet (ft)	.3048	meters (m)
miles (mi)	1.609	kilometers (km)
square feet (ft^2)	.0929	square meters (m^2)
square miles (mi^2)	2.59	square kilometers (km^2)
feet per mile (ft/mi)	.1894	meters per kilometer (m/km)
feet per day (ft/d)	.3048	meters per day (m/d)
cubic feet per second (ft^3/s)	.02832	cubic meter per second (m^3/s)
cubic feet per second per square mile [($ft^3/s)/mi^2$]	.01093	cubic meter per second per square kilometer [($m^3/s)/km^2$]
cubic feet per day (ft^3/d)	.02832	cubic meter per day (m^3/d)
ton (short, 2,000 lbs)	.9072	tonne (t)
tons per day (ton/d)	.9072	tonnes per day (t/d)
tons per cubic feet ($tons/ft^3$)	32.03	tonnes per cubic meter (t/m^3)
tons per square mile ($tons/mi^2$)	.3503	tonnes per square kilometer (t/km^2)

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By M. D. Winner, Jr., and C. E. Simmons

ABSTRACT

Creeping Swamp is a typical North Carolina middle Coastal Plain stream having a flat, swampy, and heavily wooded flood plain. The 28 square-mile watershed is underlain by unconsolidated layers of sand, silt, and clay and semi-consolidated beds of limestone to depths of about 1,500 feet. Of major importance to the stream-aquifer hydrologic system are (1) the surficial aquifer consisting of sands and clays of the Quaternary deposits and the Yorktown Formation, and (2) the Castle Hayne Limestone. These sediments furnish all of the base flow to Creeping Swamp.

Hydrologic data were collected for four years at six sites in the project area before the plans for channelization of Creeping Swamp were cancelled. The potential effects of channelization were estimated using these data and data from Ahoskie Creek which was channelized in 1964 and which is located in a similar hydrologic setting about 60 miles north of Creeping Swamp.

Channelization would have caused the greatest decline in ground-water levels nearest the stream, with the decline diminishing with increased distance from the stream. It is believed that dry periods in this area are not sufficiently long to allow the effects of channelization on the ground-water levels to reach the ground-water divide before the aquifer is recharged. Channelization would also have resulted in a decrease in overland runoff and an increase in the amount of water reaching Creeping Swamp through the ground-water system, although total runoff would not have changed significantly, if at all.

The water-quality characteristics of Creeping Swamp indicate that the stream is relatively free of pollution. Dissolved-solids concentrations increase in a downstream direction at all stages of flow and especially during low flow. The largest increases in major constituent concentrations between stream sites were in calcium and bicarbonate. Concentrations of most chemical constituents appear to be inversely related to stream discharge. During a 12-month period the dissolved load of 8 major dissolved constituents totaled 1,020 tons and ranged from 245 tons of bicarbonate to 8 tons of nitrate. Concentrations of minor elements in surface waters did not exceed 40 micrograms per liter, except for iron.

Concentrations of chemical constituents are much greater in the Yorktown Formation than in the more shallow Quaternary deposits. Chemical analyses indicate that most of the ground-water discharge is from the upper several feet of the Quaternary deposits. During periods of extended low flow, however, a larger proportion of ground-water discharge is from the deeper aquifers and concentrations of most chemical constituents in the stream increase accordingly.

During 1972-74, the average annual sediment yield was a little over 30 tons per square mile. The highest measured suspended-sediment concentration in Creeping Swamp was 100 milligrams per liter, which occurred during a period of intense overland runoff.

INTRODUCTION

The Coastal Plain area of North Carolina is a low-lying region of gentle land-surface and stream slopes. During heavy rains, large areas adjacent to sluggish streams become flooded, and lands in a wider area become saturated. These conditions, if alleviated by improvements in the natural drainage systems, result in substantial gains in agricultural production. For more than a century State and Federal agencies have been engaged in programs to improve drainage in the Coastal Plain by channelization of streams.

The characteristics of the flow of water through improved channels differs substantially from the characteristics of flow in natural channels, but, relatively little is known about the effects of the improved channels on ground-water conditions. Discussions of this problem, involving the U.S. Geological Survey, the Groundwater Section of the North Carolina Department of Natural and Economic Resources, the U.S. Soil Conservation Service, and the U.S. Agricultural Research Service, culminated in 1970 in a joint agreement to study the effects of channelization of the Creeping Swamp watershed (fig. 1).

Because the Creeping Swamp watershed is part of the recharge area of the Castle Hayne Limestone, a major aquifer in eastern North Carolina, the project was designed to answer such questions as: (1) What

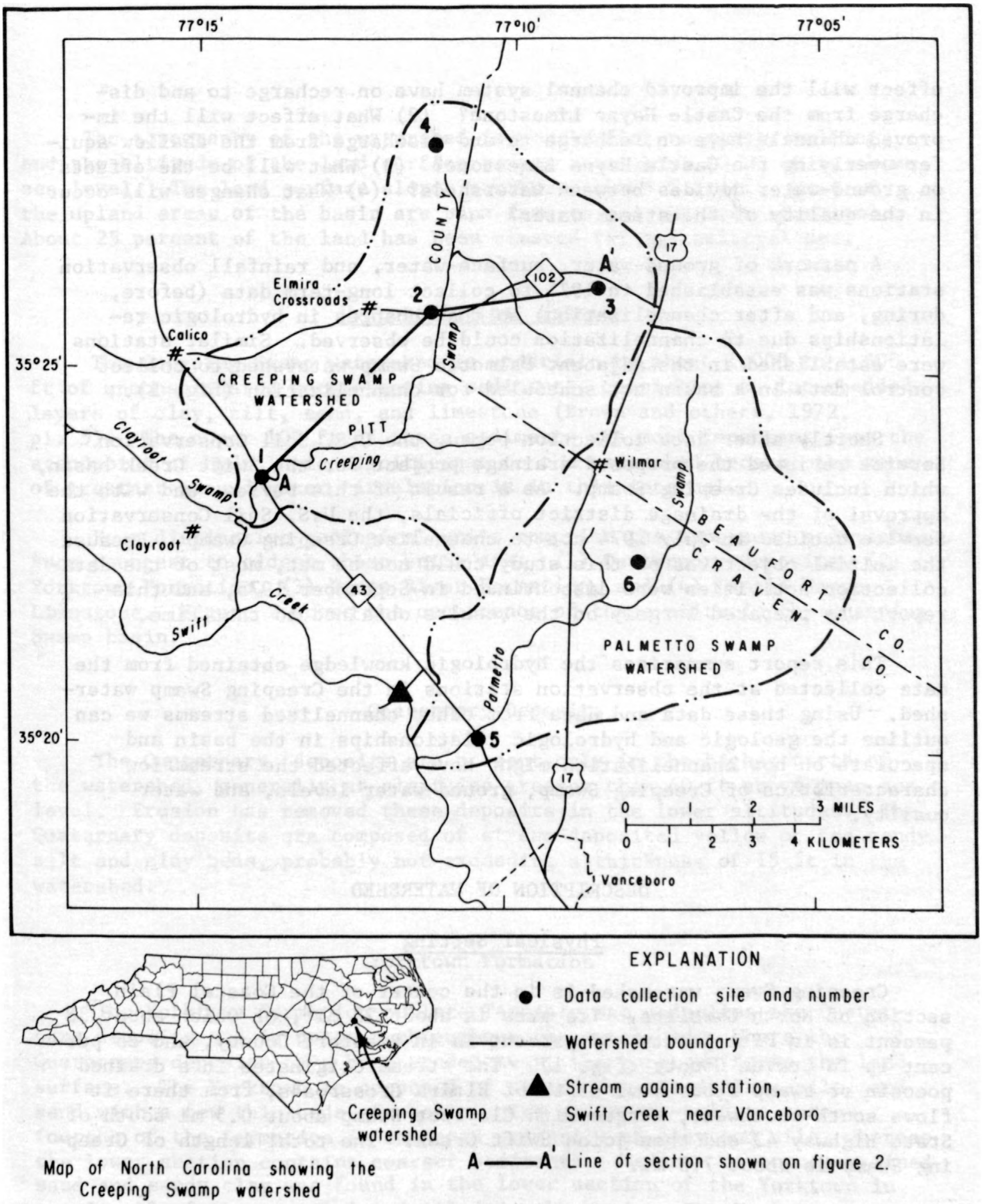

Figure 1.--Location of the Creeping Swamp and Palmetto Swamp watersheds and data-collection sites.

effect will the improved channel system have on recharge to and discharge from the Castle Hayne Limestone? (2) What effect will the improved channels have on recharge to and discharge from the shallow aquifer overlying the Castle Hayne Limestone? (3) What will be the effects on ground-water divides between watersheds? (4) What changes will occur in the quality of the stream water?

A network of ground-water, surface-water, and rainfall observation stations was established in 1971 to collect long-term data (before, during, and after channelization) so that changes in hydrologic relationships due to channelization could be observed. Similar stations were established in the adjacent Palmetto Swamp watershed to collect control data in a basin not scheduled for channelization (fig. 1).

Shortly after data collection began, the U.S. Soil Conservation Service reviewed the proposed drainage project for the Swift Creek basin, which includes Creeping Swamp. As a result of this review, and with the approval of the drainage district officials, the U.S. Soil Conservation Service decided in July 1974 not to channelize Creeping Swamp. Because the initial objectives of this study could not be met, most of the data-collection activities were discontinued in September 1975, and this report was prepared largely on the results obtained to that time.

This report summarizes the hydrologic knowledge obtained from the data collected at the observation stations in the Creeping Swamp watershed. Using these data and data from other channelized streams we can outline the geologic and hydrologic relationships in the basin and speculate on how channelization might have affected the streamflow characteristics of Creeping Swamp, ground-water levels, and water quality.

DESCRIPTION OF WATERSHED

Physical Setting

Creeping Swamp watershed is in the center of the Coastal Plain section of North Carolina. Its area is about 28 mi^2, of which about 38 percent is in Pitt County, 37 percent is in Beaufort County, and 25 percent is in Craven County (fig. 1). The stream originates in a drained pocosin or swamp about 3 mi north of Elmira Crossroads; from there it flows south-southwest, merges with Clayroot Swamp about 0.5 mi south of State Highway 43 and then joins Swift Creek. The total length of Creeping Swamp is about 7.5 mi.

A fairly well-defined flood plain, which is as much as 0.5 mi wide, has developed along the main stream and larger tributaries of Creeping Swamp. The flood plain is swampy and heavily wooded with cypress, gum, pine, and tupelo. Stream channels are not deeply entrenched; the main channel is braided throughout the swamp and has numerous pools.

The topography of the watershed is nearly flat to gently rolling, and the altitude of the land surface ranges from about 20 to 60 ft above sea level. The land surface slopes southwest about 5 ft/mi. Most of the upland areas of the basin are pine forests and cut-over scrubland. About 25 percent of the land has been cleared for agricultural use.

Hydrogeological Setting

The Creeping Swamp watershed is underlain by about 1,000 to 1,500 ft of unconsolidated water-bearing sediments, consisting of interbedded layers of clay, silt, sand, and limestone (Brown and others, 1972, pl. 5). The upper 100 ft of these sediments are most important from the standpoint of hydrologic significance to the watershed because the zone of greatest ground-water circulation is in this interval.

Four distinctive geological units comprise the uppermost sediments. From youngest to oldest these units are: (1) Quaternary deposits, (2) Yorktown Formation, (3) Pungo River Formation, and (4) Castle Hayne Limestone. Figure 2 shows the occurrence of these units in the Creeping Swamp basin.

Quaternary Deposits

The Quaternary deposits are present only in the higher parts of the watershed, generally at altitudes greater than 40 ft above mean sea level. Erosion has removed these deposits in the lower altitudes. The Quaternary deposits are composed of stream-deposited yellow or tan sandy silt and clay beds, probably not exceeding a thickness of 15 ft in the watershed.

Yorktown Formation

The Yorktown Formation of late Tertiary age underlies the Quaternary deposits and is present throughout the watershed. Where the Quaternary deposits have been eroded away, the Yorktown forms the land surface. The Yorktown is composed of marine-deposited clay, silt, and sand with a few thin beds of shells. The upper one-half to three-fourths of the formation is composed primarily of clay and silt, whereas the lower section contains coarser sediments. Medium- to coarse-grained sand and sandy clay was found in the lower section of the Yorktown in nearly all of the test holes drilled in the basin. The Yorktown averages about 40 ft in thickness where it has not been eroded.

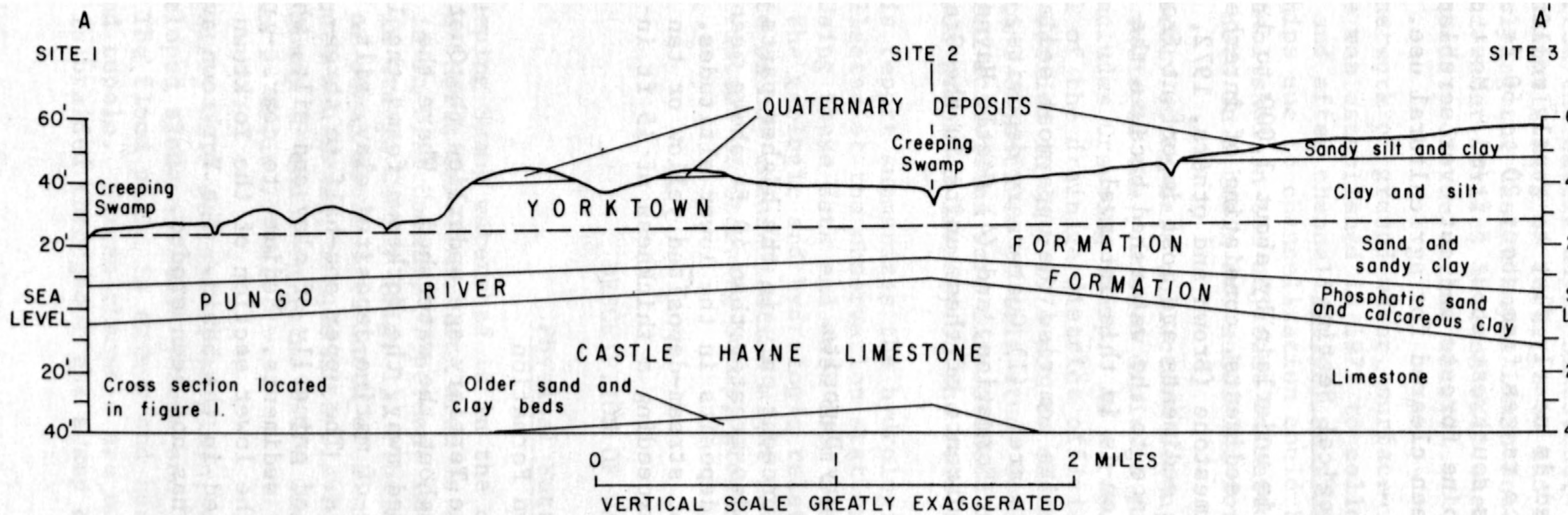

Figure 2.--Geologic units underlying the Creeping Swamp watershed.

The upper part of the Yorktown Formation and the Quaternary deposits form the surficial aquifer in the watershed. Rainfall which infiltrates the surficial aquifer, either moves laterally to provide base flow to streams, or, in the higher parts of the watershed, moves downward to furnish recharge to deeper water-bearing beds. Rainfall that does not infiltrate the surficial aquifer either flows over the surface to streams (overland flow), is transpired, or is evaporated. All of the stream channels in the watershed have cut into the Yorktown Formation; consequently, the Yorktown provides a medium for the exchange of water between the ground-water system and the streams.

Pungo River Formation

The Pungo River Formation of middle and early Miocene age underlies the Yorktown Formation and is composed of phosphatic sand interbedded with silt and calcareous clay. The top of the Pungo River Formation ranges in altitude from about 5 to 15 ft above sea level in the watershed, and does not exceed 20 ft in thickness. Although it is a geologically distinctive unit because of its phosphate content, the Pungo River Formation is hydraulically connected with both the overlying sandy beds of the lower part of the Yorktown Formation, and the underlying Castle Hayne Limestone.

Castle Hayne Limestone

The Castle Hayne Limestone of Eocene age is a major aquifer of eastern North Carolina. Under the Creeping Swamp watershed it is composed of from 10 to 100 ft of porous, coquina limestone interspersed with a few calcareous sand beds. The top of the Castle Hayne dips toward the east and ranges in altitude from about 10 ft above sea level to nearly 30 ft below sea level (fig. 3) in the study area. The western limit of occurrence of the Castle Hayne is near the western boundary of the Creeping Swamp watershed (Sumsion, 1970, p. 19).

Ground-water recharge to the Castle Hayne occurs in areas of high altitudes in the watershed where water in the surficial aquifer percolates through the Yorktown and Pungo River Formations to the Castle Hayne. This downward movement of water is shown in the hydrographs at data-collection site 3 (fig. 4), where the head difference between the surficial aquifer and the Castle Hayne is about 20 ft. At lower altitudes in the watershed, head differences are less and become reversed near streams, as shown by the hydrographs at sites 1 and 2 (fig. 4). The head reversal indicates that water from the Castle Hayne moves upward toward Creeping Swamp at these two sites.

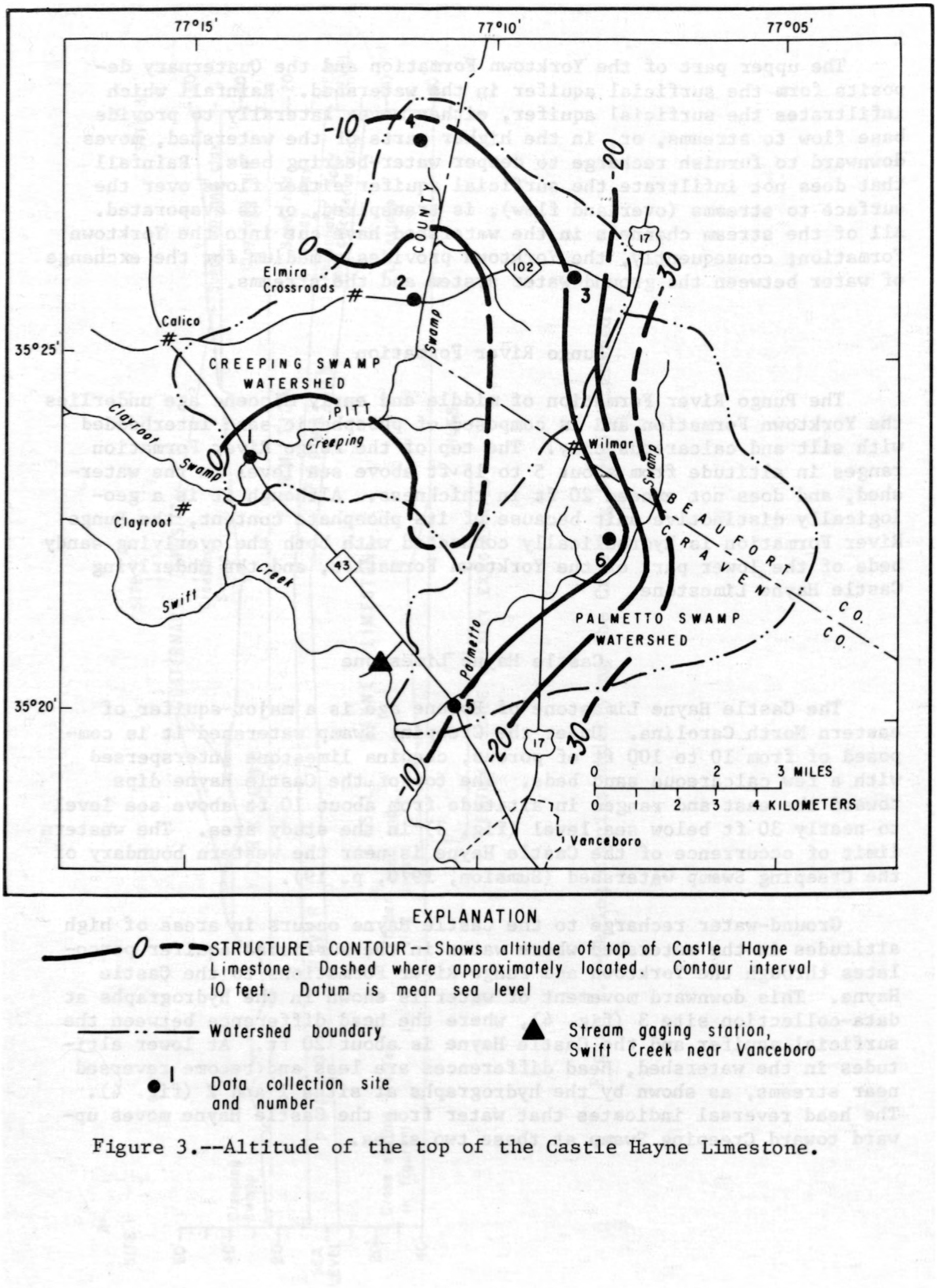

Figure 3.--Altitude of the top of the Castle Hayne Limestone.

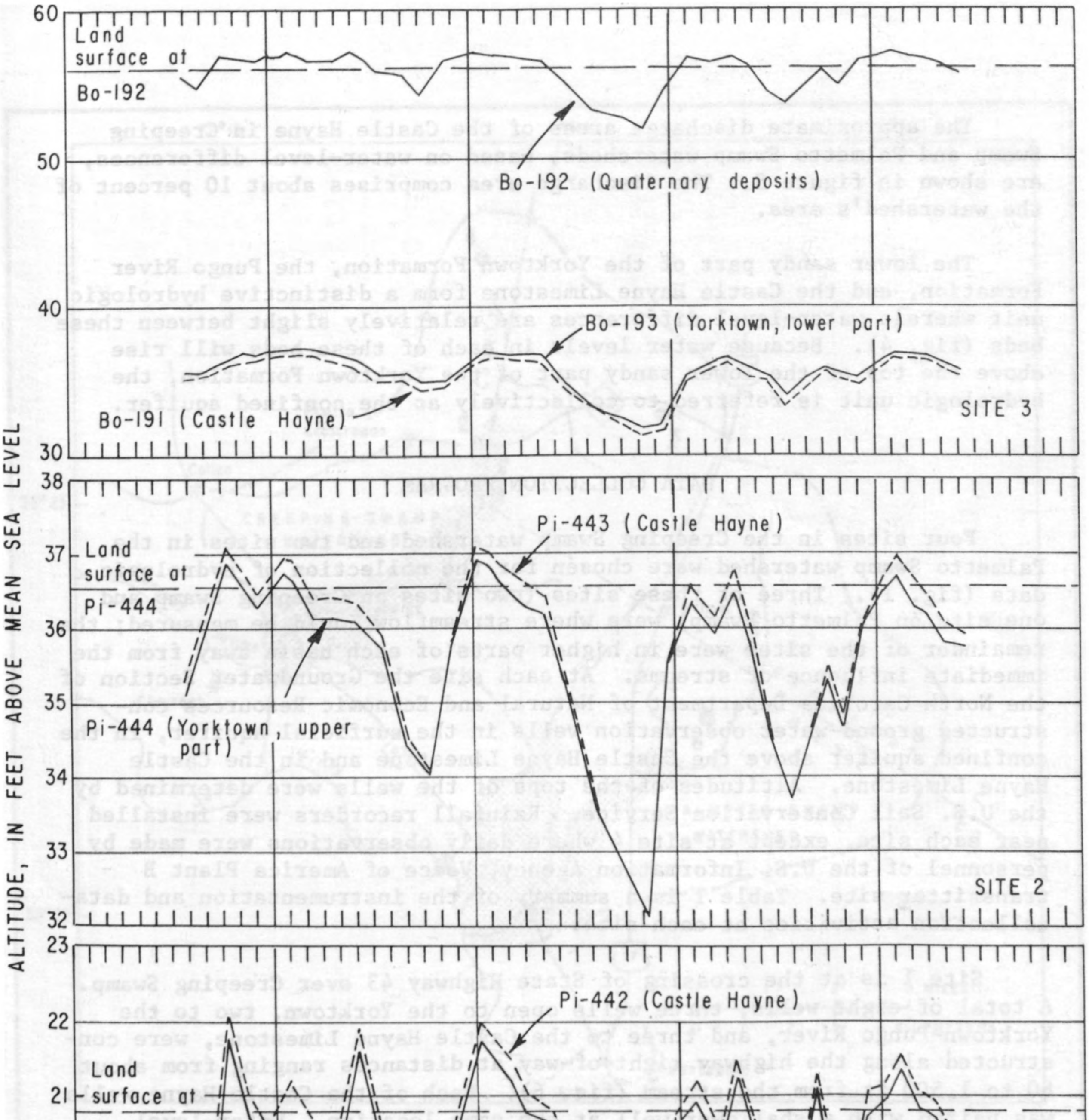

Figure 4.--Comparison of water levels in the surficial aquifer and the potentiometric head in the Castle Hayne Limestone in the Creeping Swamp watershed.

The approximate discharge areas of the Castle Hayne in Creeping Swamp and Palmetto Swamp watersheds, based on water-level differences, are shown in figure 5. The discharge area comprises about 10 percent of the watershed's area.

The lower sandy part of the Yorktown Formation, the Pungo River Formation, and the Castle Hayne Limestone form a distinctive hydrologic unit wherein water-level differences are relatively slight between these beds (fig. 4). Because water levels in each of these beds will rise above the top of the lower sandy part of the Yorktown Formation, the hydrologic unit is referred to collectively as the confined aquifer.

DATA COLLECTION PROGRAM

Four sites in the Creeping Swamp watershed and two sites in the Palmetto Swamp watershed were chosen for the collection of hydrologic data (fig. 1). Three of these sites (two sites on Creeping Swamp and one site on Palmetto Swamp) were where streamflow could be measured; the remainder of the sites were in higher parts of each basin away from the immediate influence of streams. At each site the Groundwater Section of the North Carolina Department of Natural and Economic Resources constructed ground-water observation wells in the surficial aquifer, in the confined aquifer above the Castle Hayne Limestone and in the Castle Hayne Limestone. Altitudes of the tops of the wells were determined by the U.S. Soil Conservation Service. Rainfall recorders were installed near each site, except at site 4 where daily observations were made by personnel of the U.S. Information Agency, Voice of America Plant B transmitter site. Table 1 is a summary of the instrumentation and data-collection activities at each site.

Site 1 is at the crossing of State Highway 43 over Creeping Swamp. A total of eight wells, three wells open to the Yorktown, two to the Yorktown-Pungo River, and three to the Castle Hayne Limestone, were constructed along the highway right-of-way at distances ranging from about 80 to 1,500 ft from the stream (fig. 6). Each of the Castle Hayne wells was paired with a shallower well at the same location. Water-level recorders were installed on each of the paired wells farthest from and nearest to the stream to provide continuous records of water-level fluctuations. The water levels in the remaining wells were periodically measured with a steel tape. Stream stage and stream temperatures were continuously recorded at site 1. A concrete control with a v-notch weir was constructed on the downstream side of the highway bridge to assure accuracy in measuring low stream discharges.

An automatic stream sediment sampler was also installed at site 1. This device activated when the stream stage rose above a pre-selected level and collected samples at regular stage and time intervals until the stream stage fell below the pre-selected level. Sediment samples

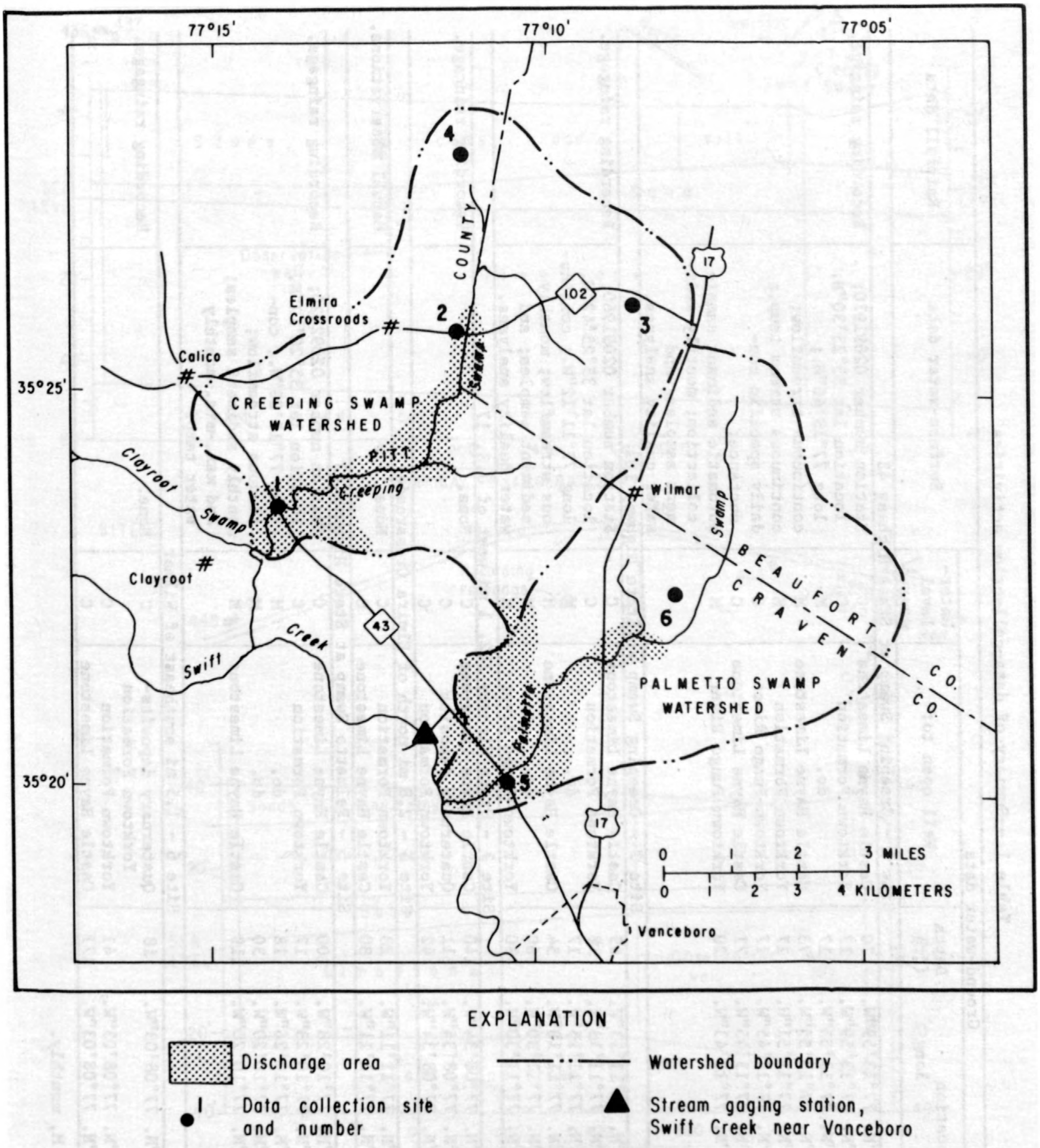

Figure 5.--Discharge areas of the Castle Hayne Limestone in the Creeping Swamp and Palmetto Swamp watersheds.

Table 1.--Summary of data-collection activities

Ground-water data: Well number	Location: lat	Location: long	Depth (ft)	Well open to:	Water-level meas.[1]	Surface-water data	Rainfall data
Site 1 - Creeping Swamp at State Highway 43							
Pi-436	35°23'46"N.	77°13'59"W.	70	Castle Hayne Limestone	C	Station number 02091970; location lat 35°23'30"N. long 77°13'46"W.; continuous streamflow; continuous stream temp.; daily specific conductance; automatic sediment sample collection; monthly sediment samples; and water quality analyses.	Recording raingage.
Pi-437	35°23'46"N.	77°13'59"W.	17	Yorktown Formation	C		
Pi-438	35°23'45"N.	77°13'55"W.	17	do.	M		
Pi-439	35°23'45"N.	77°13'55"W.	73	Castle Hayne Limestone	M		
Pi-440	35°23'39"N.	77°13'51"W.	17	Yorktown Formation	M		
Pi-441	35°23'31"N.	77°13'45"W.	17	Yorktown-Pungo River	C		
Pi-442	35°23'31"N.	77°13'45"W.	71	Castle Hayne Limestone	C		
Cr-465	35°23'28"N.	77°13'43"W.	20	Yorktown Pungo River	M		
Site 2 - Creeping Swamp at State Highway 102							
Pi-443	35°25'42"N.	77°11'13"W.	69	Castle Hayne Limestone	C	Station number 02091960; location lat 35°25'42"N. long 77°11'12"W.; continuous streamflow; monthly sediment samples; and water quality analyses.	Recording raingage.
Pi-444	35°25'42"N.	77°11'13"W.	18	Yorktown Formation	C		
Pi-445	35°25'42"N.	77°11'15"W.	17	do.	M		
Pi-446	35°25'44"N.	77°11'18"W.	54	Castle Hayne Limestone	M		
Pi-447	35°25'46"N.	77°11'30"W.	60	do.	M		
Pi-448	35°25'46"N.	77°11'30"W.	30	Yorktown-Pungo River	M		
Site 3 - State Highway 102, 1 mi west of U.S. 17							
Bo-191	35°26'15"N.	77°08'34"W.	140	Castle Hayne Limestone	C	None.	Recording raingage.
Bo-192	35°26'15"N.	77°08'34"W.	11	Quaternary deposits	C		
Bo-193	35°26'15"N.	77°08'34"W.	42	Yorktown Formation	C		
Site 4 - 2.8 mi north of Elmira Crossroads							
Pi-449	35°27'35"N.	77°11'11"W.	28	Yorktown Formation	C	None.	Manual observations.
Pi-450	35°27'35"N.	77°11'11"W.	80	Castle Hayne Limestone	C		
Site 5 - Palmetto Swamp at State Highway 43							
Cr-457	35°20'12"N.	77°10'28"W.	100	Castle Hayne Limestone	C	Station number 02092020; location lat 35°20'12"N. long 77°10'28"W.; continuous streamflow; monthly sediment samples; and max.-min. monthly water temp.	Recording raingage.
Cr-458	35°20'12"N.	77°10'28"W.	17	Yorktown Formation	C		
Cr-459	35°20'09"N.	77°10'26"W.	18	do.	M		
Cr-460	35°20'00"N.	77°10'20"W.	30	do.	M		
Cr-461	35°20'00"N.	77°10'20"W.	119	Castle Hayne Limestone	M		
Site 6 - 1.5 mi southeast of Wilmar							
Cr-462	35°22'29"N.	77°08'03"W.	18	Quaternary deposits-Yorktown Formation	C	None.	Recording raingage.
Cr-463	35°22'29"N.	77°08'03"W.	41	Yorktown Formation	C		
Cr-464	35°22'29"N.	77°08'03"W.	171	Castle Hayne Limestone	C		

[1] C, Continuous; M, monthly.

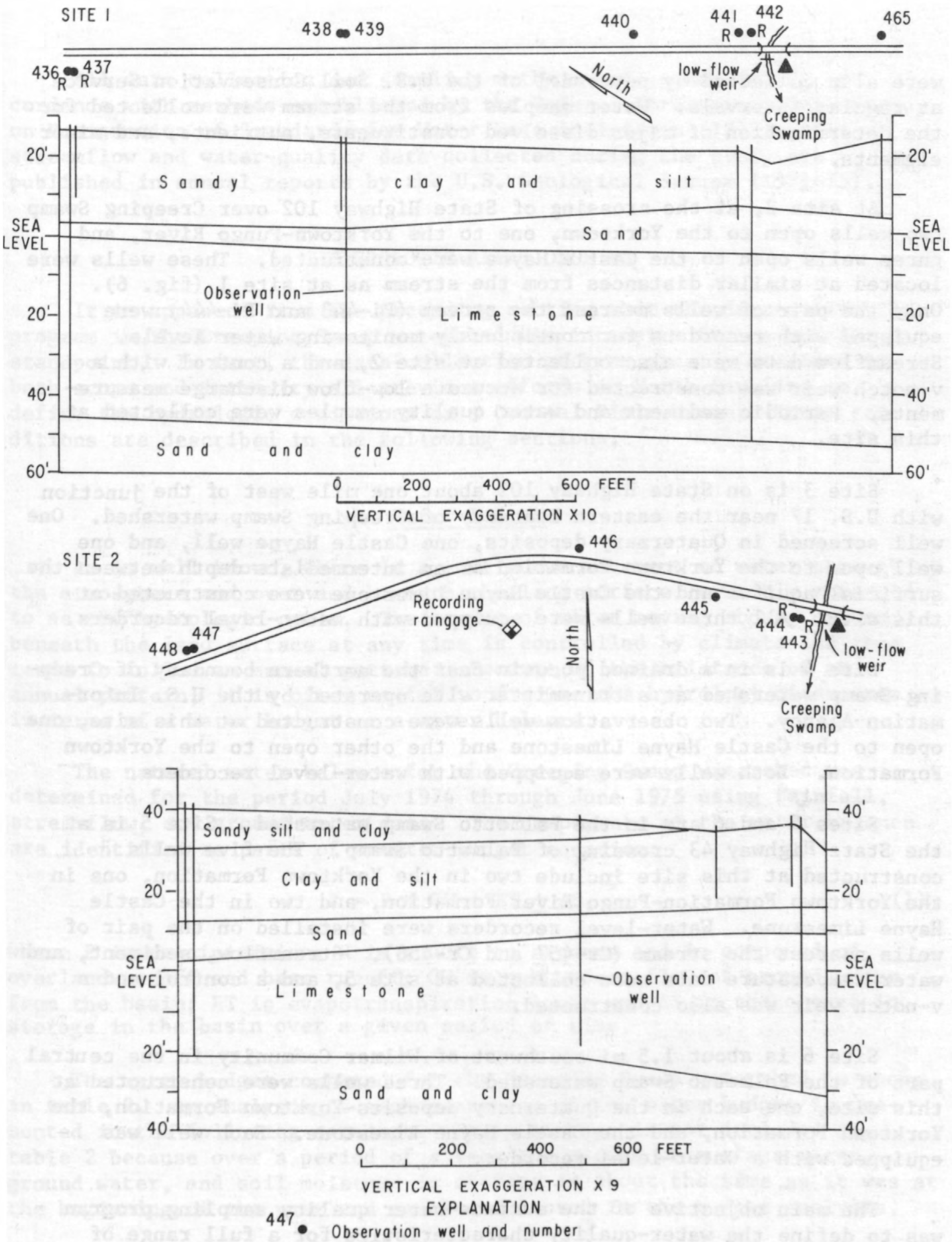

Figure 6.--Well locations at site 1 and site 2 in the Creeping Swamp watershed.

were also collected by personnel of the U.S. Soil Conservation Service at regular intervals. Water samples from the stream were collected for the determination of major dissolved constituents, nutrients, and minor elements.

At site 2, at the crossing of State Highway 102 over Creeping Swamp two wells open to the Yorktown, one to the Yorktown-Pungo River, and three wells open to the Castle Hayne were constructed. These wells were located at similar distances from the stream as at site 1 (fig. 6). Only the pair of wells nearest the stream (Pi-443 and Pi-444) were equipped with recorders for continuously monitoring water levels. Streamflow data were also collected at site 2, and a control with a v-notch weir was constructed for accurate low-flow discharge measurements. Periodic sediment and water quality samples were collected at this site.

Site 3 is on State Highway 102 about one mile west of the junction with U.S. 17 near the eastern boundary of Creeping Swamp watershed. One well screened in Quaternary deposits, one Castle Hayne well, and one well open to the Yorktown Formation at an intermediate depth between the surficial aquifer and the Castle Hayne Limestone were constructed at this site. All three wells were equipped with water-level recorders.

Site 4 is in a drained pocosin near the northern boundary of Creeping Swamp watershed at a transmitter site operated by the U.S. Information Agency. Two observation wells were constructed at this site, one open to the Castle Hayne Limestone and the other open to the Yorktown Formation. Both wells were equipped with water-level recorders.

Sites 5 and 6 are in the Palmetto Swamp watershed. Site 5 is at the State Highway 43 crossing of Palmetto Swamp. The five wells constructed at this site include two in the Yorktown Formation, one in the Yorktown Formation-Pungo River Formation, and two in the Castle Hayne Limestone. Water-level recorders were installed on the pair of wells nearest the stream (Cr-457 and Cr-458). Streamflow, sediment, and water temperature data were collected at site 5, and a control and a v-notch weir was also constructed.

Site 6 is about 1.5 mi southwest of Wilmar Community in the central part of the Palmetto Swamp watershed. Three wells were constructed at this site, one each in the Quaternary deposits-Yorktown Formation, the Yorktown Formation, and the Castle Hayne Limestone. Each well was equipped with a water-level recorder.

The main objective of the surface-water quality sampling program was to define the water-quality characteristics for a full range of flows. All water samples were analyzed for concentrations of major constituents, and selected samples were analyzed for nutrients (the nitrogen-phosphorus series) and minor elements. Several analyses of stream-bottom materials were also made for each site.

All data collection and sampling methods were conducted in accordance with methods established by the Federal Interagency Work Group on Designation of Standards for Water Data Aquisition (1972). The streamflow and water-quality data collected during the study are published in annual reports by the U.S. Geological Survey (1971-75).

HYDROLOGIC RELATIONSHIPS

It is apparent from the preceding section that the data-collection program in the Creeping Swamp watershed was intensive from a hydrologic standpoint. In fact, the data-collection program greatly exceeded in both scope and intensity all previous efforts in North Carolina to define the hydrologic conditions in a Coastal Plain basin. These conditions are described in the following sections.

Water Budget

As is well known, there is a continuous movement of water through the atmosphere and over and beneath the land surface, commonly referred to as the hydrologic cycle. The amount of water moving above, on, and beneath the land surface at any time is controlled by climate and thus tends to follow an annual pattern. Because of the existence of an annual pattern, it is often useful to discuss the hydrology of an area in terms of a water budget or a water balance.

The natural water balance for the Creeping Swamp watershed was determined for the period July 1974 through June 1975 using rainfall, streamflow, and ground-water data. The components of the water balance are identified as parts of a water-budget equation:

$$P = R + GW + ET \pm \Delta S, \quad (1)$$

where P is precipitation; R is runoff to streams and is composed of overland runoff and base runoff; GW is subsurface flow of ground water from the basin; ET is evapotranspiration loss; and ΔS is the change in storage in the basin over a given period of time.

The water budget computed for the Creeping Swamp watershed is shown in table 2. An analysis of each component of the water budget is presented in the following sections. Basin storage is not included in table 2 because over a period of a year the amount of surface water, ground water, and soil moisture in storage is about the same as it was at the beginning of the year and can be neglected in the budget analysis.

Table 2.--The water budget for Creeping Swamp watershed, July 1974 through June 1975

Inflow		Outflow							
Precipitation (P)		Runoff (R)				Ground-water outflow (GW)		Evapotranspiration (ET)	
		Overland runoff		Base runoff					
inches	percent	inches	percent	inches	percent	inches	percent	inches	percent
42.24	100	6.99	17	8.54	20	0.80	2	25.91	61

Inflow

Virtually all water entering the Creeping Swamp watershed is in the form of precipitation. Rainfall was averaged by the Theissen polygon method using data collected at sites 1, 2, 3, and 6. At site 5 the rainfall data did not contribute significantly to the rainfall analysis for Creeping Swamp watershed, and was not used. The total average rainfall for the year July 1974 to June 1975 was 42.24 in.

Surface and subsurface inflow to the watershed, which was not included in equation (1), is believed to be negligible. A small amount of surface inflow from rain falling in an adjacent basin might reach Creeping Swamp through a complex network of ditches used to drain the pocosin at the Voice of America transmitter site (site 4), but this added amount of inflow would be relatively insignificant on an annual basis.

Subsurface inflow to the watershed is assumed to be zero because the watershed boundary coincides with the ground-water divide for the surficial aquifer. The Castle Hayne Limestone receives recharge from the surficial aquifer along the northern boundary of the watershed, and the water in this aquifer subsequently flows southward out of the watershed. Upward leakage from the Castle Hayne to Creeping Swamp is assumed to be derived largely from recharge within the watershed.

Outflow

Runoff.--Runoff from the Creeping Swamp watershed was measured as streamflow at the site 1 gaging station (Creeping Swamp near Vanceboro), and was separated into (1) overland runoff and (2) ground-water runoff, or base runoff. Because one of the principal objectives of the project was to determine how channelization affected the ground-water regime, it was necessary to identify the base flow component of streamflow.

Base flows were determined by a hydrograph separation technique described by Rasmussen and Andreasen (1959, p. 63). This technique establishes a relationship between base runoff in a stream and the average ground-water level during times when all the streamflow is ground-water discharge. The relation between base flow and ground-water levels in the Creeping Swamp watershed is shown in figure 7. Daily average water levels in well Bo-192 (open to the surficial aquifer) at site 3 were plotted against the daily average discharge of Creeping Swamp at site 1 at times during 1971-75 preceding a rise in the stream when base flow conditions prevailed.

The relation in figure 7 shows how base flow contributions to Creeping Swamp may be estimated for all conditions, including periods when overland flow is also occurring. The base flow component of

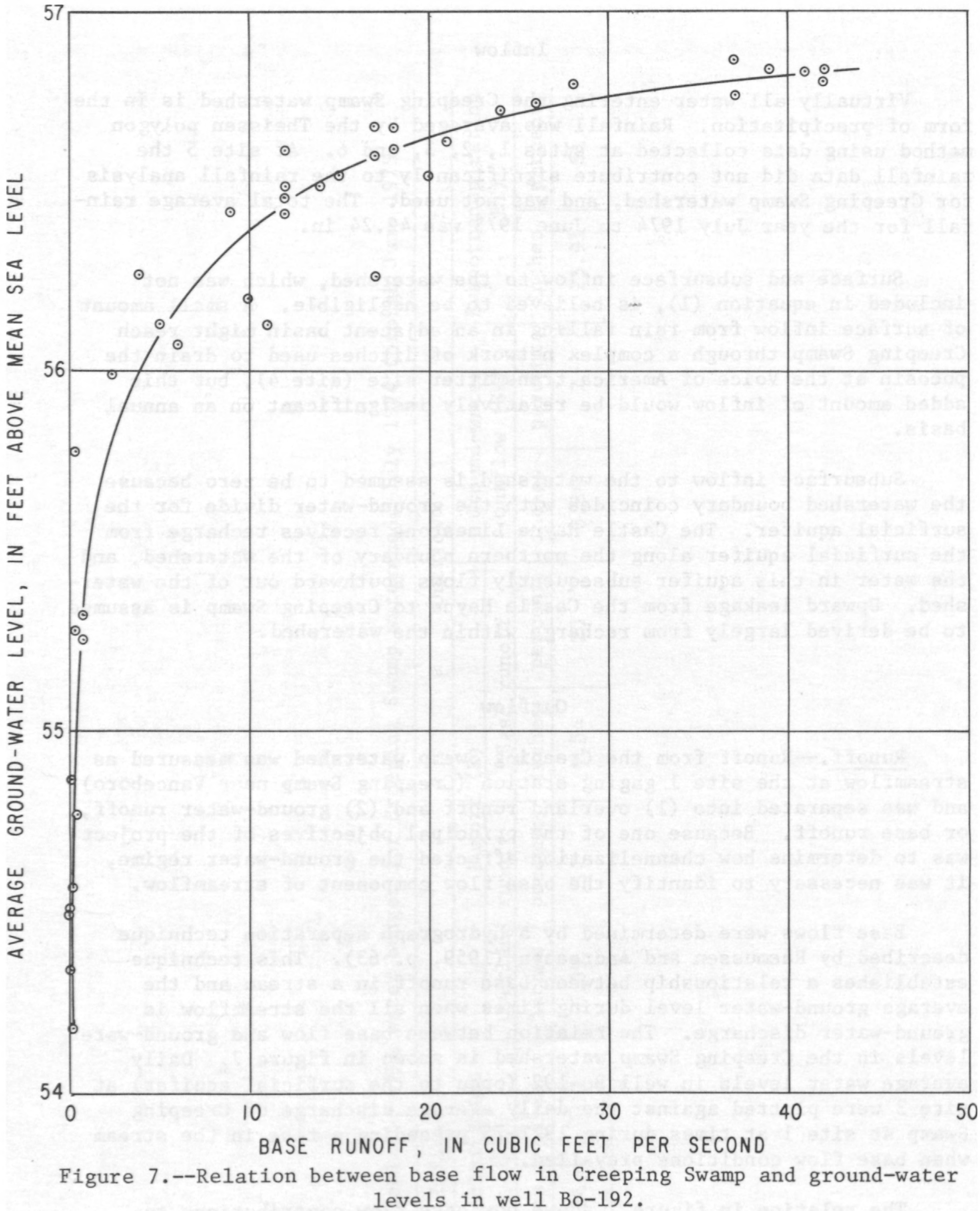

Figure 7.--Relation between base flow in Creeping Swamp and ground-water levels in well Bo-192.

streamflow in Creeping Swamp is compared with total streamflow in figure 8. During July 1974-June 1975, base runoff accounted for the equivalent of 8.54 in of rainfall, or about 20 percent of the rainfall. Subtracting this amount from the total measured runoff of 15.53 in leaves 6.99 in as the overland runoff component of total runoff. Thus, of the total measured runoff of 15.53 in. about 55 percent reached the stream through the ground-water system.

Ground-water outflow.--Subsurface outflow from the basin is through the Castle Hayne Limestone beyond the southern boundary of the basin, and may be estimated using Darcy's law and data from the potentiometric surface of the Castle Hayne shown in figure 9. Darcy's law is expressed as:

$$Q = KIA, \tag{2}$$

where Q is the quantity of ground-water outflow, K is the hydraulic conductivity of the Castle Hayne, I is the hydraulic gradient of the potentiometric surface, and A is the cross-sectional area through which water flows. The estimate of ground-water outflow from the Creeping Swamp watershed is based on the quantity of flow across the 20-ft contour between the flow lines that approximate the eastern and western watershed boundaries (fig. 9).

The value used for the hydraulic conductivity of the Castle Hayne is 135 ft/d as reported by Sumsion (1970) for Pitt County, and by Floyd (1969) for Craven County. The hydraulic gradient is 3.8 ft/mi, which is the difference in altitude between the 35- and 20-ft contours divided by the average distance between these contours, or about 4.0 mi.

The cross-sectional area is 1.2×10^6 ft^2, which is the average thickness of the Castle Hayne (50 ft) multiplied by the average length of the contours between the flow lines shown in figure 9, or about 4.7 mi.

On the basis of these data, the ground-water outflow from the watershed was about 120,000 ft^3/d. This is equivalent to about 0.84 in of yearly rainfall over the 22.6 mi^2 basin area contributing to the flow across the contour.

The potentiometric map for January 1975 (fig. 9) was used as the basis for this calculation, and is typical for winter conditions when outflow is the greatest during the year. A similar computation using summertime data when outflow is the least (a July potentiometric map) shows the outflow is equivalent to 0.76 in per year. The January and July outflows are rounded to 0.80 in, and this value is taken as the average annual ground-water outflow through the Castle Hayne Limestone.

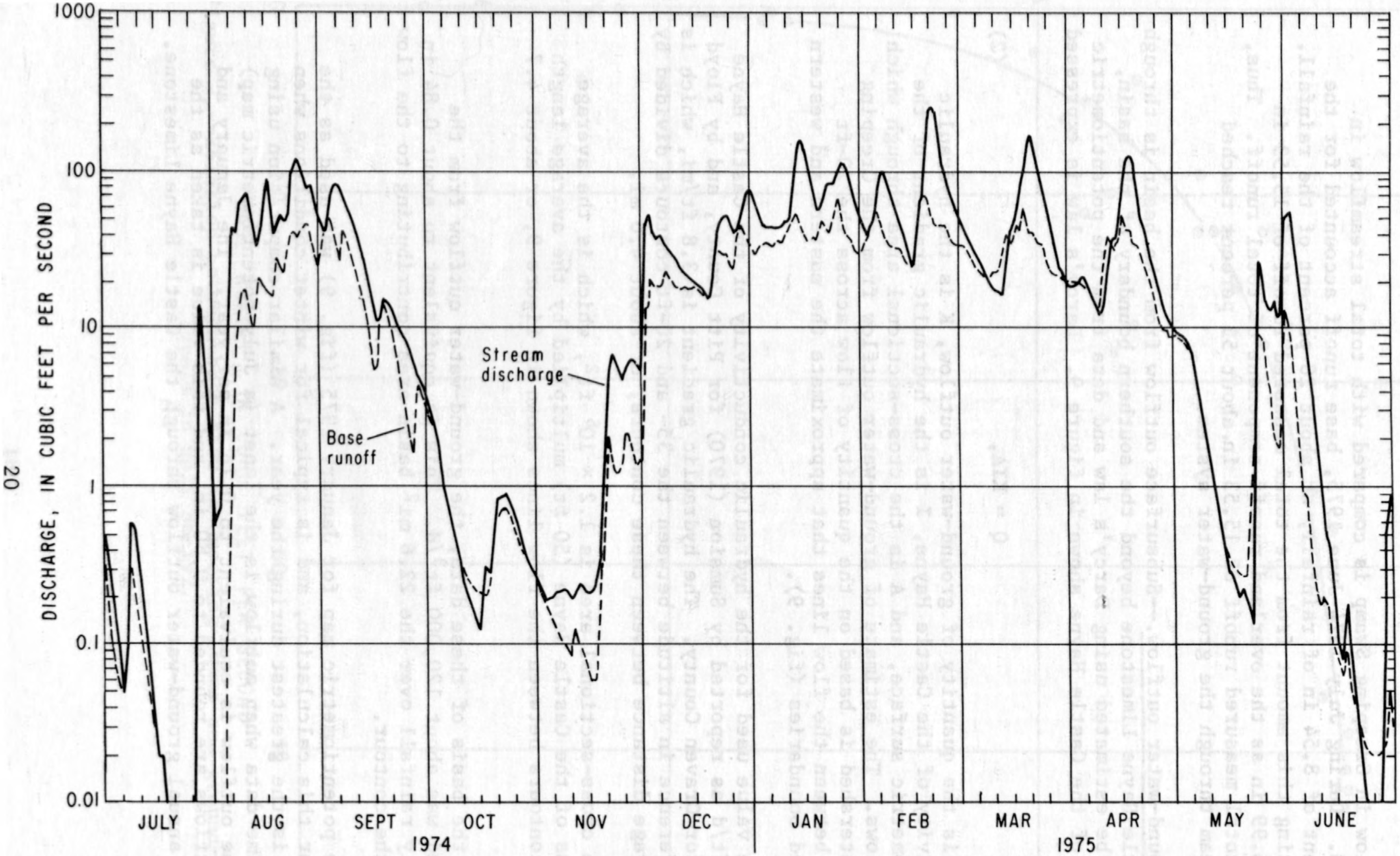

Figure 8.--Mean daily discharge and base runoff of Creeping Swamp at site 1.

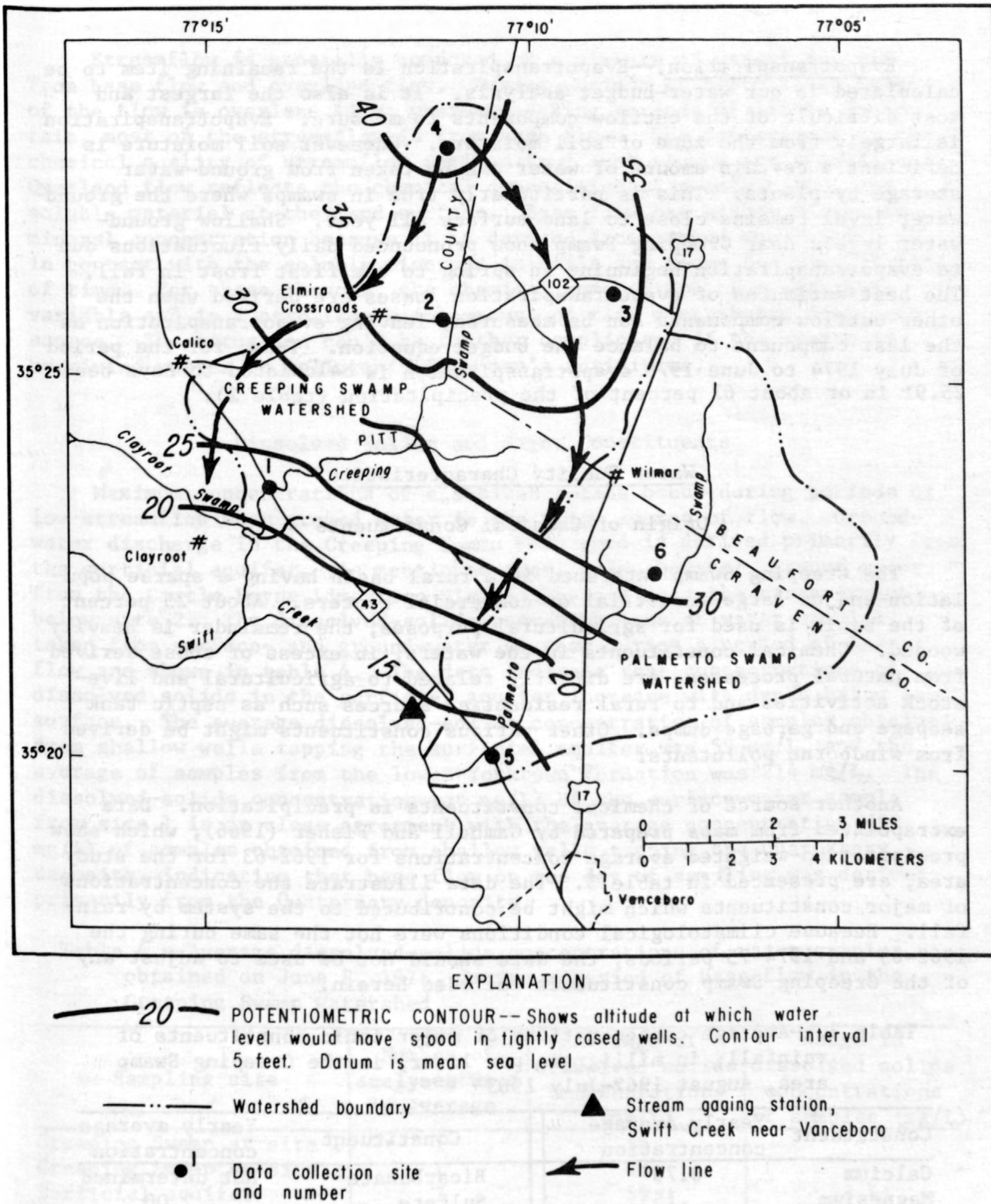

Figure 9.--Potentiometric surface in the Castle Hayne Limestone, January 1975.

Evapotranspiration.--Evapotranspiration is the remaining item to be calculated in our water-budget analysis. It is also the largest and most difficult of the outflow components to measure. Evapotranspiration is largely from the zone of soil moisture. Whenever soil moisture is deficient a certain amount of water can be taken from ground-water storage by plants. This is particularly true in swamps where the ground-water level remains close to land surface all year. Shallow ground-water levels near Creeping Swamp show pronounced daily fluctuations due to evapotranspiration beginning in spring to the first frost in fall. The best estimates of evapotranspiration losses are derived when the other outflow components can be measured, leaving evapotranspiration as the last component to balance the budget equation. Thus, for the period of July 1974 to June 1975 evapotranspiration is calculated to have been 25.91 in or about 61 percent of the precipitation (table 2).

Water Quality Characteristics

Origin of Chemical Constituents

The Creeping Swamp watershed is a rural basin having a sparse population and no large industrial or commercial centers. About 25 percent of the basin is used for agricultural purposes; the remainder is heavily wooded. Chemical constituents in the waters, in excess of those derived from natural processes, are directly related to agricultural and livestock activities and to rural residential sources such as septic tank seepage and garbage dumps. Other various constituents might be derived from windborne pollutants.

Another source of chemical constituents is precipitation. Data extrapolated from maps prepared by Gambell and Fisher (1966), which show precipitation-weighted average concentrations for 1962-63 for the study area, are presented in table 3. The data illustrate the concentrations of major constituents which might be contributed to the system by rainfall. Because climatological conditions were not the same during the 1962-63 and 1974-75 periods, the data should not be used to adjust any of the Creeping Swamp constituents included herein.

Table 3.--Average concentrations of major ionic constituents of rainfall, in milligrams per liter, in the Creeping Swamp area, August 1962-July 1963

Constituent	Yearly average concentration	Constituent	Yearly average concentration
Calcium	0.70	Bicarbonate	Not determined
Magnesium	.15	Sulfate	2.00
Sodium	.70	Chloride	0.90
Potassium	.10	Nitrate (as NO_3^-)	.40

Streamflow is generally composed of a mixture of waters derived from base flow and overland flow. During periods of heavy rains, most of the flow is overland flow; whereas, during periods of little or no rain, most of the streamflow is from base flow. The differences in the chemical quality of streamflow derived from each source are significant. Overland flow reflects the chemical composition of precipitation and soluble material at the land surface. Base flow has higher dissolved-mineral concentration because it is derived from ground water which is in contact with the soluble minerals in soils and rocks for long periods of time. For these reasons, the chemical composition of a stream is variable and is controlled by the amount of flow contributed from each source. The situation could be further complicated if the system is receiving wastes or pollutants from man's activities.

Dissolved Solids and Major Constituents

Maximum concentrations of dissolved solids occur during periods of low streamflow when ground water is the major source of flow. Ground-water discharge in the Creeping Swamp watershed is derived primarily from the surficial aquifer. As mentioned previously, however, ground water from the Castle Hayne Limestone also discharges into the stream reach below site 2. The dissolved-solids concentrations of water samples taken from surface- and ground-water sources during a period of base flow are shown in table 4. The data indicate that concentrations of dissolved solids in the surficial aquifer increase with depth below land surface. The average dissolved-solids concentration of samples obtained from shallow wells tapping the surficial aquifer was 59 mg/L, and the average of samples from the lower Yorktown Formation was 214 mg/L. The dissolved-solids concentration (56 mg/L) of the surface-water sample from site 1 is in close agreement with the average concentration (59 mg/L) of samples obtained from shallow wells tapping the Quaternary deposits, indicating that base flow on the day of sampling was derived primarily from the Quaternary deposits.

Table 4.--Average dissolved-solids concentrations of water samples obtained on June 8, 1976, during a period of base flow in the Creeping Swamp watershed

Sampling site	Number of analyses used in average	Average of dissolved solids concentrations (mg/L)	Range in dissolved solids concentrations of samples (mg/L)
Creeping Swamp at site 1	1	56	-
Creeping Swamp at site 2	1	48	-
Surficial aquifer	7	59	48-64
Lower Yorktown Formation	5	214	104-326
Castle Hayne Limestone	4	292	217-386

The effects of ground-water inflow on dissolved-solids concentrations during a prolonged period of base flow is illustrated in figure 10. The increase in dissolved-solids concentration during decreasing streamflow from October 25 to November 6, 1974, might be attributed to the derivation of a larger proportion of streamflow to ground-water inflow from the confined aquifer. As discussed previously, dissolved-solids concentrations increase with depth and, during a period of prolonged drought, the proportion of base flow derived from deeper sources becomes more significant as the water table declines. Because of the complexities of the hydrologic system, however, the quantities of discharge from the various aquifer systems cannot be determined.

In many streams, a direct relation exists between specific conductance of the water and concentrations of dissolved solids and several major ionic constituents. If the relations are known, they can be used to estimate the concentration of the desired constituent from the corresponding value of specific conductance. Generally, the relations are not constant, however, and often vary from stream to stream or at different points along the same stream. In the case of Creeping Swamp, dissolved solids concentrations increase in a downstream direction; therefore, the dissolved solids/specific conductance relations are somewhat different at sites 1 and 2 (figure 11).

Dissolved-solids concentrations vary during changing flow conditions with minimum values occurring during periods of intense rains and subsequent heavy overland flow. Also, the values of dissolved solids during rising stages are generally greater than those at the same stream discharge during receding stages of the same rise (figure 12). This is caused by the flushing effects of overland runoff which, during the early phases of the rise, picks up soluble materials that have accumulated on the land surface and along the stream channels. Examples of this characteristic are shown in figure 12, which was prepared from data obtained during two rises, one large and one small. A maximum dissolved-solids concentration of 70 mg/L, occurred on October 20, 1974, during the rising stage at a discharge of 0.8 ft^3/s; however, on October 23, during the recession at about the same discharge, the dissolved-solids concentration was only 43 mg/L.

Daily dissolved-solids concentrations during July 1974 to June 1975 ranged from 25 to 79 mg/L for Creeping Swamp at site 1. The average during the same period was 37 mg/L. These data vary somewhat from the data presented in table 4 for site 1 because the data in table 4 are averages of water samples collected at infrequent intervals.

Relations established between specific-conductance values and concentrations of major ions allow the use of daily specific-conductance values and daily discharge to compute loads of major ions. The first step in computing loads is to determine the daily concentrations of the desired constituent by using the appropriate linear regression equation

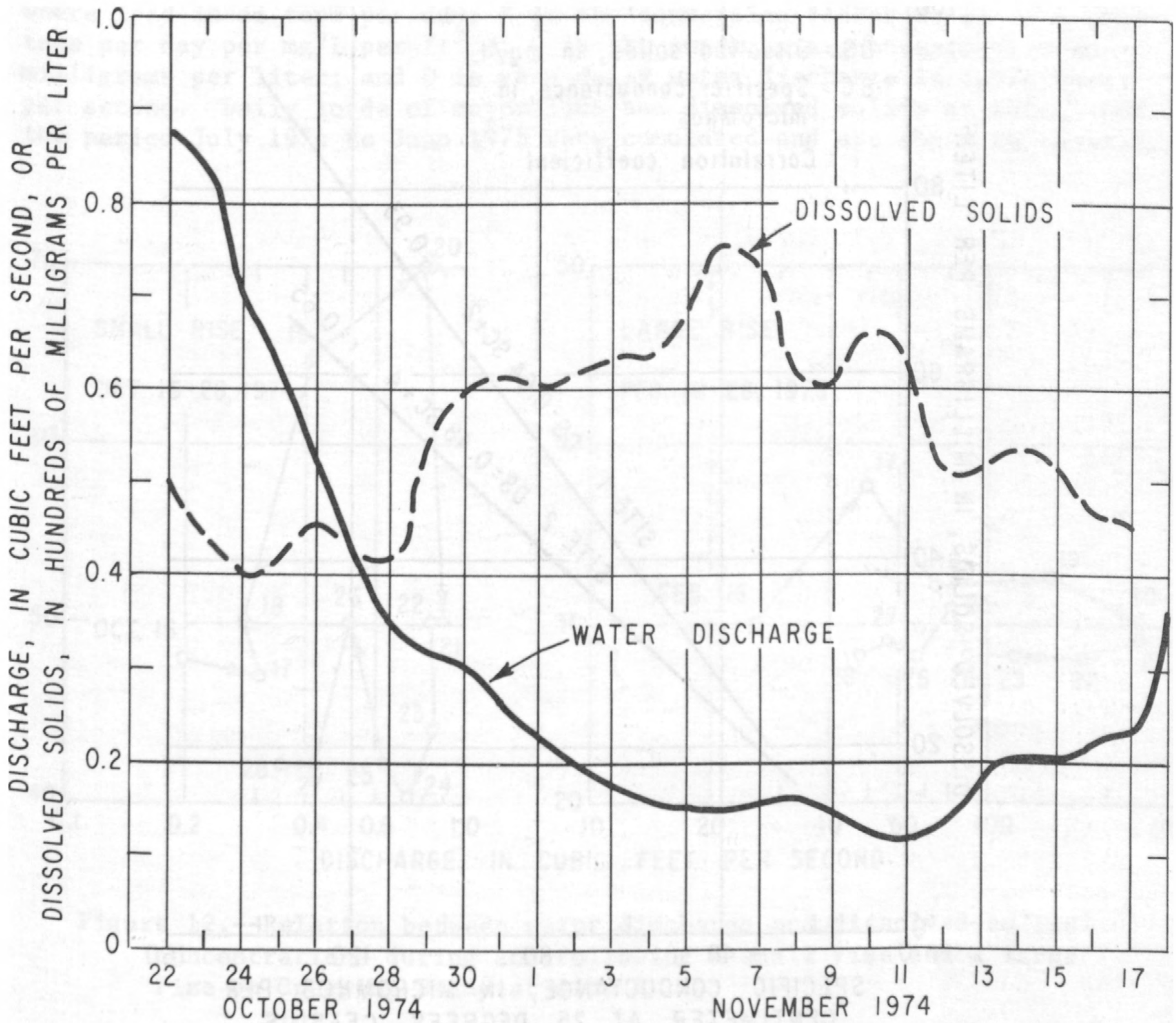

Figure 10.--Comparison of stream discharge with concentrations of dissolved solids during a receding base-runoff period at site 1.

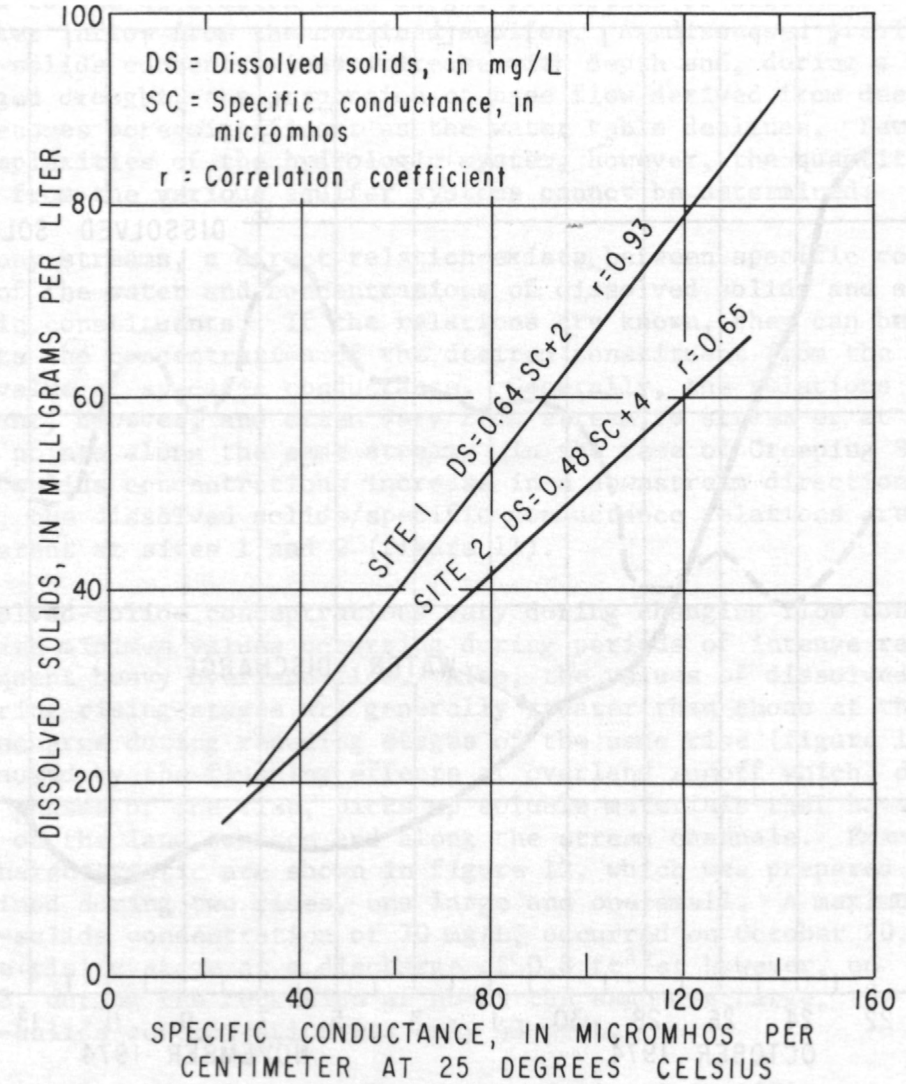

Figure 11.--Relation between specific conductance and dissolved solids in Creeping Swamp at sites 1 and 2.

shown in table 5, where SC is the daily value of specific conductance. Daily loads are then computed from the equation:

$$\text{Load} = KCQ, \tag{3}$$

where load is in tons per day; K is the conversion factor equal to 0.0027 tons per day per mg/L per ft^3/s; C is the constituent concentration in milligrams per liter; and Q is mean daily water discharge in cubic feet per second. Daily loads of major ions and dissolved solids at site 1 for the period July 1974 to June 1975 were cumulated and are shown in table 5.

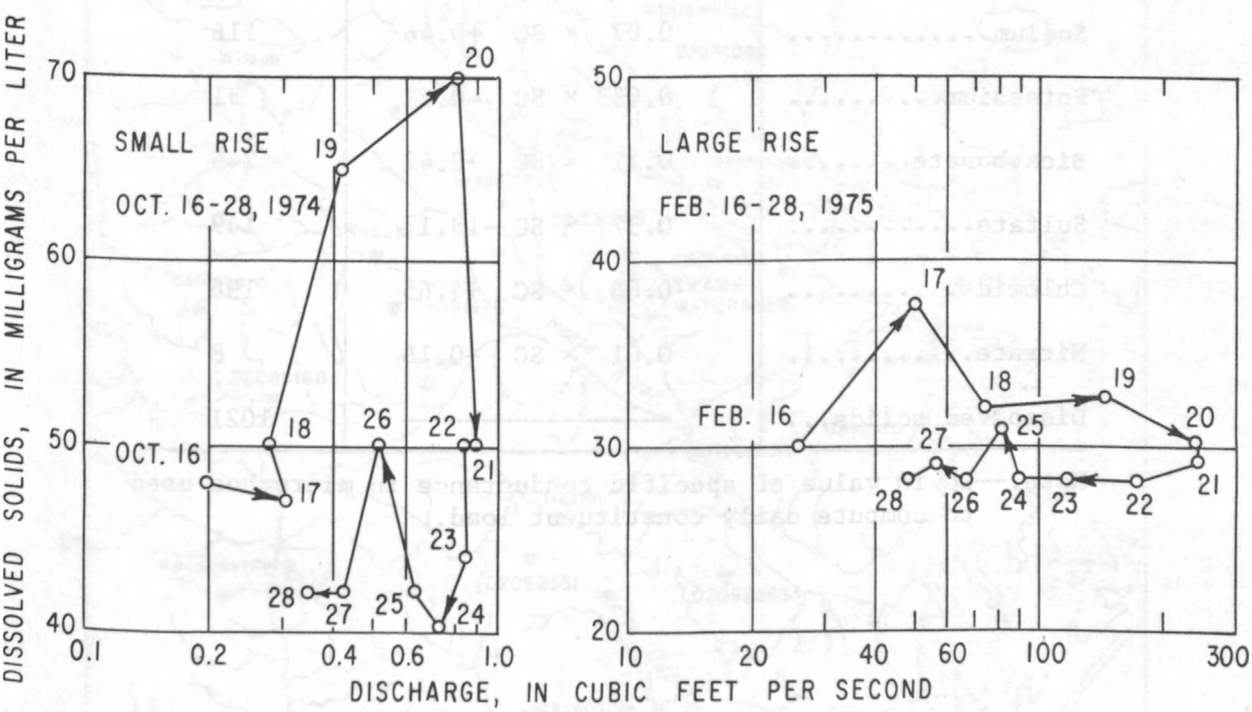

Figure 12.--Relation between water discharge and dissolved-solids concentrations during and following a small rise and a large rise on Creeping Swamp at site 1.

Since 1974 water-quality samples have been collected periodically from a number of small streams across the State which represent unpolluted, natural conditions. Six of these natural water-quality stations are located within a 50-mile radius of Creeping Swamp (fig. 13) and have drainage areas ranging from 2 to 6 mi^2. Analyses of samples collected at these sites during periods of base flow and overland flow are listed in table 6 with similar data collected at Creeping Swamp sites. These data (table 6) are presented in two main groups, base flow and overland flow, representing the hydrologic conditions during which the samples were collected. The constituent values in table 6 are the mean of four or more analytical values per constituent. The close

Table 5.--Estimated total loads of dissolved solids and major constituents in Creeping Swamp at site 1, for the period July 1974 to June 1975

Constituent	Regression equation for computing concentration of constituent (mg/L)	Constituent load (tons)
Calcium..........	0.105 × SC −0.81	129
Magnesium..........	0.014 × SC +0.29	27
Sodium............	0.07 × SC +0.46	116
Potassium..........	0.033 × SC −0.51	31
Bicarbonate........	0.11 × SC +2.42	245
Sulfate...........	0.37 × SC −13.1	149
Chloride..........	0.04 × SC +4.65	196
Nitrate...........	0.01 × SC −0.16	8
Dissolved solids...	-----------------	1021

Note.--SC is value of specific conductance in micromhos used to compute daily constituent load.

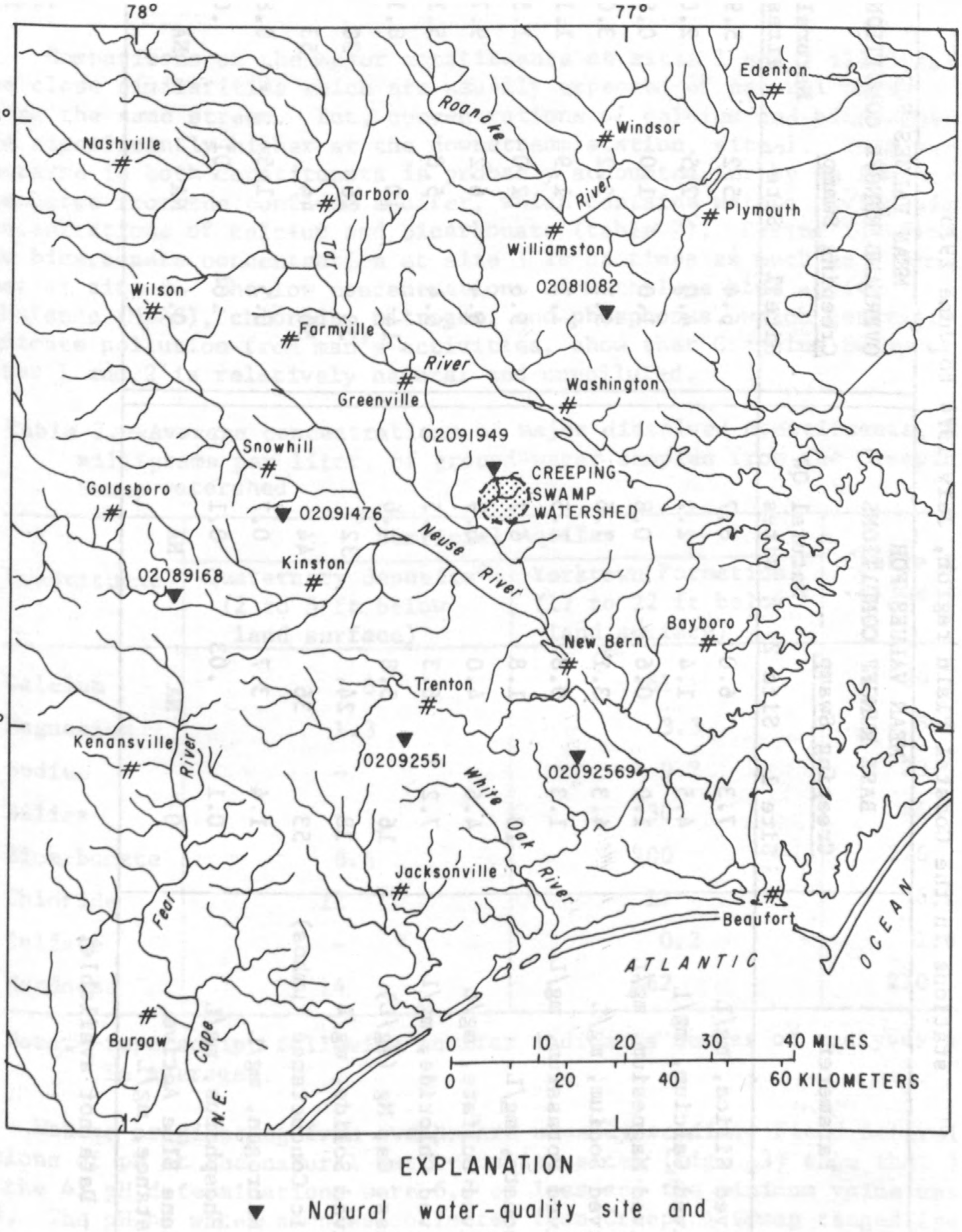

Figure 13.--Natural water-quality sites within a 50-mile radius of Creeping Swamp.

Table 6.--Water-quality constituents and properties at sites 1, 2, and natural water quality stations in the Coastal Plain region, July 1974 to June 1975

Parameter	MEAN VALUES FOR BASE RUNOFF CONDITIONS			MEAN VALUES FOR OVERLAND RUNOFF CONDITIONS		
	Creeping Swamp			Creeping Swamp		
	Site 1	Site 2	Natural QW sites	Site 1	Site 2	Natural QW sites
Dissolved Silica, mg/L	7.3	6.0	8.7	6.4	5.2	5.9
Dissolved Calcium, mg/L	4.5	1.4	2.2	4.0	2.5	2.0
Dissolved Magnesium, mg/L	1.0	0.6	0.8	1.0	1.0	0.8
Dissolved Sodium, mg/L	4.3	3.1	3.6	3.7	3.2	3.0
Dissolved Potassium, mg/L	1.3	0.8	1.5	1.1	1.9	1.1
Bicarbonate, mg/L	13	1.8	6.7	5.6	2.0	1.5
Dissolved Sulfate, mg/L	4.6	4.0	6.9	6.4	6.2	9.7
Dissolved Chloride, mg/L	7.2	6.3	5.5	6.4	5.8	5.1
Hardness, Ca, Mg (mg/L)	16	5.8	8.6	14	10	8.1
Dissolved Solids, mg/L	38	24	32	33	26	30
Specific Conductance (µmhos)	53	36	44	50	44	53
Total Nitrogen, mg/L	1.4	3.7	0.7	0.5	1.5	0.8
Total Phosphorus, mg/L	0.1	.03	0.1	.04	.01	.06
Methylene Blue Active Substance, mg/L	0	NA	NA	0.1	NA	NA

NA - Data not available.

similarity of the data from Creeping Swamp and the natural water-quality basins suggests that there is relatively little pollution in Creeping Swamp.

Comparisons of the major constituents at sites 1 and 2 illustrate the close similarities which are usually expected of natural waters along the same stream. But, concentrations of calcium and bicarbonate are significantly higher at the downstream station, site 1. This marked increase in both constituents is probably accounted for by an increased discharge from the confined aquifer, which contains waters having high concentrations of calcium and bicarbonate (table 7). During low flow, the bicarbonate concentration at site 1 is at times as much as 8 times that at site 2. The low concentrations of methylene blue active substance (MBAS), chloride, nitrogen, and phosphorus, which generally indicate pollution from man's activities, show that Creeping Swamp at sites 1 and 2 is relatively natural and unpolluted.

Table 7.--Average concentrations of major dissolved constituents, in milligrams per liter, of ground-water samples from the Creeping Swamp watershed

Constituent	Surficial Aquifer		Castle Hayne Limestone[4]
	Quaternary deposits[7] (2 to 5 ft below land surface)	Yorktown Formation[5] (17 to 22 ft below land surface)	
Calcium	3.8	61	69
Magnesium	1.3	3.3	5.4
Sodium	-	9.2	23
Silica	-	30	46
Bicarbonate	8.4	200	276
Chloride	12	11	6.2
Sulfate	-	0.2	1.8
Hardness	14	162	210

Note.--Superscript following aquifer indicates number of analyses used in averages.

Waters originating from swamps are usually acidic. Field determinations of pH at the natural water-quality sites (fig. 13) show that 36 of the 41 pH determinations were 6.7 or less and the minimum value was 3.8. The pH of water samples collected from Creeping Swamp ranged from 4.6 to 5.1 at site 2 and 4.9 to 6.5 at site 1. The marked increase in pH between the sites indicates the presence of neutralizing factors along the reach. The main factor appears to be the availability of abundant bicarbonate between the two sites as discussed above.

Nutrients

Although other elements are important in controlling the rate of biologic activity, nitrogen and phosphorus are the primary nutrients which affect plant growth and biologic productivity. Sufficient quantities of phosphorus (as phosphate) and nitrogen compounds in waters can cause undesirable growths of algae and promote eutrophication. Samples collected from July 1974 to June 1975 show a range of total nitrogen from a minimum of 0.32 mg/L at site 2 to a maximum of 2.1 mg/L at site 1. Organic nitrogen ranged from 43 to 98 percent of the total nitrogen. Ammonia nitrogen was the primary source of inorganic nitrogen. Concentrations of total phosphorus ranged from 0.01 mg/L at both sites to a maximum of 0.14 mg/L at site 1.

A direct relationship exists between total phosphorus and total nitrogen at both sites, but concentrations are greater at site 1. Nutrient concentrations in Creeping Swamp also appear to be inversely related to stream discharge, with maximum concentrations occurring during low flow. Maximum concentrations also occur during the spring and summer, which is concurrent with peak agricultural activities in the basin. Analyses of water samples taken from wells penetrating the Yorktown Formation in the watershed show maximum concentrations of total nitrogen and total phosphorus to be 0.33 mg/L and 0.38 mg/L, respectively.

Concentrations of nutrients in water samples from the Castle Hayne Limestone at sites 1 and 2 are as much as 0.35 mg/L for total nitrogen and 0.18 mg/L for total phosphorus. While part of the nutrients might originate from agricultural sources, the data suggest that the nutrients are largely derived from natural sources such as the decomposition of organic materials or the leaching of soluble material in the underlying sedimentary formations. Minor but significant quantities of nutrients might also be derived from precipitation (table 3).

Minor Elements

Selected surface-water samples were analyzed for minor elements and the results are shown in table 8. The concentrations of iron, copper, lead, and zinc generally decrease in Creeping Swamp as stream discharge increases. The analyses also show that iron concentrations increase in a downstream direction at all stages of flow. Concentrations of other minor elements, such as arsenic, cadmium, chromium, cobalt, selenium, and mercury, are too low to develop conclusive correlations, but constituent concentrations are either zero or about the same in samples collected on the same days at the two sites.

Table 8.--Concentrations of minor elements in Creeping Swamp, 1974-75, in micrograms per liter (µg/L)

Date	Instantaneous Discharge (ft^3/s)	Total Iron	Total Arsenic	Total Cadmium	Total Chromium	Total Cobalt	Total Selenium	Total Copper	Total Lead	Total Zinc	Total Mercury
		Creeping Swamp at site 2									
1974											
Oct. 1	0.28	3100	1	1	<10	7	0	5	10	10	0
1975											
Jan. 13	64	330	0	0	<10	0	0	0	0	6	0
Jan. 17	24	180	1	0	<10	0	0	1	1	20	0
Apr. 28	1.8	1500	-	-	<10	-	-	1	8	20	-
May 21	.36	5000	-	-	20	-	-	3	10	10	-
		Creeping Swamp at site 1									
1974											
July 31	.97	2000	2	1	40	11	6	4	23	40	.1
Oct. 1	2.6	4500	2	0	<10	3	0	4	7	10	0
1975											
Jan. 13	120	540	0	0	<10	0	0	1	0	0	0
Jan. 14	156	520	0	0	<10	0	0	1	2	0	-
Jan. 17	86	400	0	0	<10	1	0	5	4	0	0
Apr. 28	12	1400	-	-	<10	-	-	1	10	10	-
May 21	.17	4000	-	-	<10	-	-	4	4	10	-
June 18	.04	4200	-	-	<10	-	-	0	-	-	-

Note: Values of suspended and dissolved constituents are published by the U.S. Geological Survey (1975).

With the exception of iron, concentrations of minor elements did not exceed 40 µg/L (micrograms per liter) and were well within the recommendations of the Environmental Protection Agency (1972) for public water supply sources. During low flow, however, iron exceeded the recommended maximum limit of 300 µg/L on numerous occasions at both sampling sites. According to the water-quality criteria recommended by the Environmental Protection Agency (1972), concentrations of minor elements in Creeping Swamp are also well below toxic levels for most forms of aquatic life.

The sources of minor elements in Creeping Swamp are not known, but they are believed to be of non-point origin. Because a significant part of the total streamflow is from ground-water discharge, ground-water samples were collected for analysis of iron, lead and zinc. The results are listed in table 9. These data indicate that concentrations of these elements in ground water are generally the same or greater than those in surface waters and that ground water is the most probable source for the largest part of these constituents in Creeping Swamp. Ground-water analyses of other minor elements, such as cobalt, selenium, and chromium, are not available.

Table 9.--Minor-element concentrations, in micrograms per liter, in ground-water samples obtained in the Creeping Swamp watershed, February 1976

Location	Source	Total iron	Total lead	Total zinc
Site 1	Yorktown Formation	-	23	35
	Castle Hayne Limestone	4,600	27	40
Site 2	Yorktown Formation	15,000	11	20
	Castle Hayne Limestone	3,500	0	30
Private well near site 2	Castle Hayne Limestone	3,900	0	-

Small amounts of minor elements might be derived from additional sources other than ground water. Lead, zinc, arsenic and copper are sometimes minor constituents in pesticides, fertilizers, and fungicides. These constituents could be transported from the point of application to the stream system by overland flow, wind, or through the ground-water system. Another possible source of lead in the area might be from the combustion of leaded gasolines used in motor vehicles.

Attempts to correlate concentrations of minor elements with specific conductance, stream discharge, and suspended-sediment concentrations were satistically unsuccessful. Minor-element data are also insufficient to develop reliable correlations needed for computing loads.

Dissolved Oxygen

The dissolved oxygen (DO) in water is derived primarily from the atmosphere and aquatic plants. Concentrations of DO are affected by numerous chemical, physical, and biological processes, the most important of which are temperature, photosynthesis, respiration, turbulence, and oxidation (Joyner, 1974, p. 18). Although the number of DO determinations obtained during the study are not sufficient to compute reliable statistical means or show seasonal variations, the data reflect an extreme range of hydrologic conditions. The minimum DO concentration observed, 0.8 mg/L, occurred during low flow (0.17 ft^3/s) at site 1; the maximum concentration, 8.6 mg/L, occurred at site 2 during high flow. Other DO determinations are sufficient to show that DO concentrations in Creeping Swamp are related to stream discharge and approach anaerobic conditions during periods of little or no flow.

The primary causes of the low DO values are decomposition of organic material on the swamp floor and the lack of turbulence during low flow. As turbulence increases with increasing stream discharge, aeration causes an increase in DO concentrations. During low flow, little movement of the sluggish swamp stream exists, aeration is minimal, and DO concentrations are low. In its present unchannelized state, Creeping Swamp has many of the characteristics which decrease the amount of dissolved oxygen in water; these include pooled areas having little or no velocity, reducing conditions, and a large supply of organic bottom material.

Suspended Sediment

In most streams, the rate of sediment discharge increases as the water discharge increases. Although suspended-sediment discharge and water discharge are usually related, the relation is generally not fixed and varies from time to time at the same water discharge. In other words, points of equal water discharge during different floods may not have the same suspended-sediment discharge. The relation between the two, however, can usually be defined accurately enough to estimate sediment loads and other sediment characteristics within limits accepted by most users of sediment data.

Computations of annual sediment loads and yields, which is the quantity of suspended sediment contributed to the stream system per unit of area, were performed using the method outlined by Miller (1951) and Colby (1956). The method involves the development of a sediment/water discharge relation commonly called a sediment-transport curve. The curve is defined by plotting suspended-sediment discharge data, which are the suspended-sediment concentration data converted to equivalent units of tons per day, versus the corresponding water discharge in cubic feet per second. Sediment-transport curves for sites 1, 2, and 5 are given in figure 14. A summary of suspended-sediment data for the 1972-74 water years is presented in table 10.

During the study, sediment concentrations, as determined by actual analyses, ranged from near zero at the three stations during periods of extreme low flow to 159 mg/L at Palmetto Swamp at site 5 during high flow. Particle size of suspended material was predominately in the range of clay (finer than 0.004 mm) at low flows and mostly clay and silt (0.004-0.062 mm) at higher flows.

Although this study deals only with suspended-sediment, an unknown amount of bedload is also transported downstream. Bedload is that part of the sediment discharge that is too large to be carried in suspension and is rolled or bounced along the stream bed by current action. The suspended fraction and bedload comprise the total sediment discharge. Presently (1976) there are no accurate methods for measuring or computing bedload; however, because of soil characteristics and the low velocities associated with Coastal Plain streams, bedload is probably insignificant, and the total load probably is almost entirely suspended materials.

Comparisons with nearby long-term streamflow and climatological stations were made to determine if the suspended-sediment data for the three project stations are representative of average, long-term climatological and hydrological conditions. Streamflow data for the gaging station on Swift Creek near Vanceboro, established in 1950, and National Weather Service precipitation data for Greenville were used for the comparison. Both, Creeping Swamp and Palmetto Swamp are tributaries to Swift Creek, and hydrologic conditions are generally similar at each of the stations, especially over a period of a year or more. Annual precipitation during 1972-74, was either equal to or greater than the long-term average for the area. Moreover, annual precipitation at the project stations ranged from 18 to 60 percent above the long-term average for Swift Creek. Thus, these comparisons indicate that at least two of the major factors affecting sediment yields--streamflow and rainfall--were above normal. Therefore, the larger values of sediment data presented in table 10 are probably greater than the long-term averages.

Stream Water Temperatures

Stream temperatures in both the Creeping Swamp and Palmetto Swamp watersheds are representative of natural conditions because neither is subjected to thermal loading from industrial sources. Temperature data collected at site 1 during July 1974 to June 1975 show a direct relation with air temperature (fig. 15). On the average, daily maximum water temperatures during the winter were about 3° to 5.5°C less than the corresponding daily maximum air temperatures. During summer, the daily maximum water temperatures were usually about 8°C less than the maximum

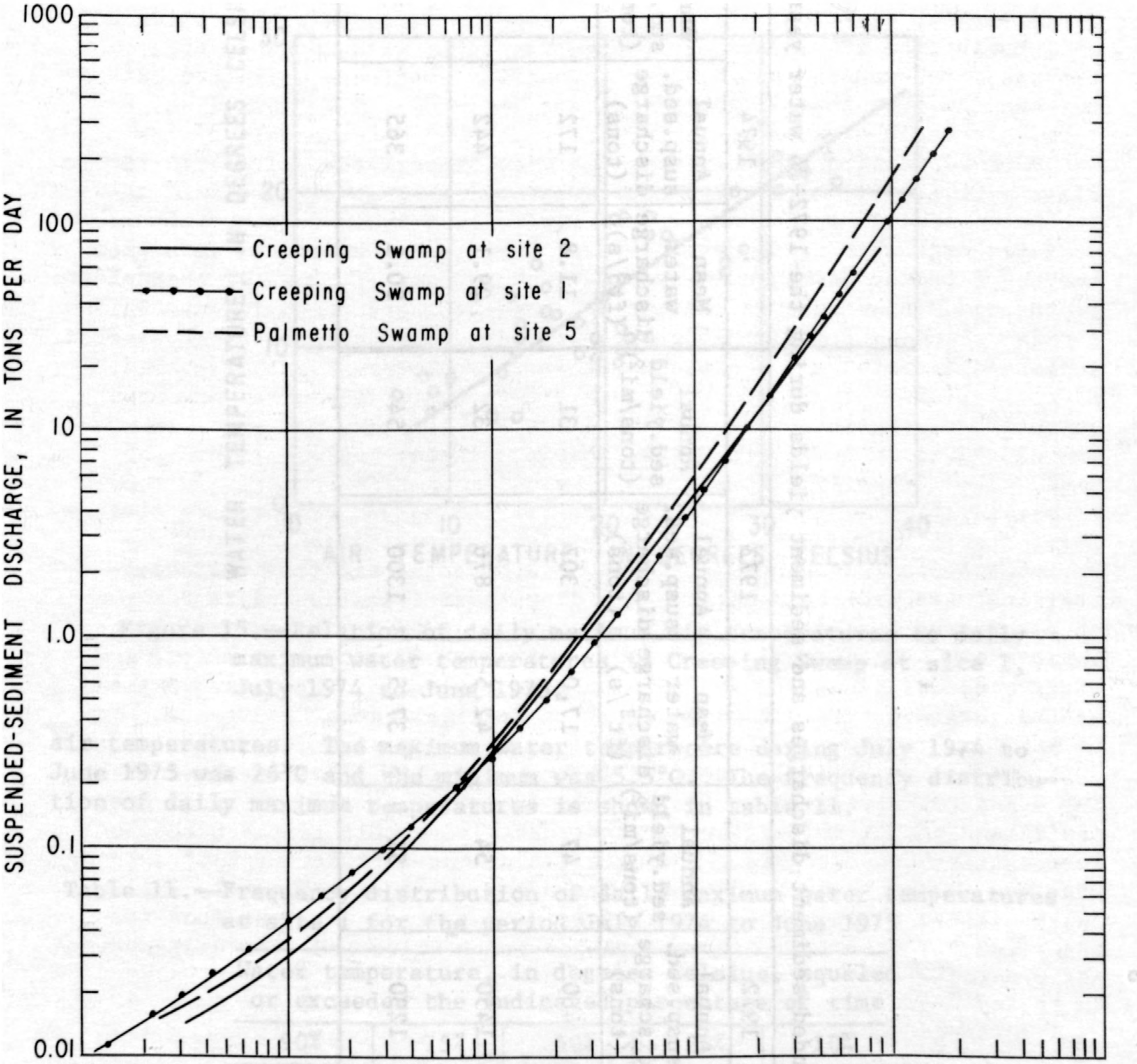

Figure 14.--Sediment-transport curves for three study sites, 1972-74 water years.

Table 10.--Annual suspended-sediment discharges and sediment yields during the 1972-74 water years

Station	1972			1973			1974		
	Mean water discharge (ft^3/s)	Annual susp.sed. discharge (tons)	Annual sed.yield ($tons/mi^2$)	Mean water discharge (ft^3/s)	Annual susp.sed. discharge (tons)	Annual sed.yield ($tons/mi^2$)	Mean water discharge (ft^3/s)	Annual susp.sed. discharge (tons)	Annual sed.yield ($tons/mi^2$)
Creeping Swamp at site 2	23.5	460	47	17.0	307	31	11.8	172	17
Creeping Swamp at site 1	61.5	1450	54	42.5	876	32	29.1	442	16
Palmetto Swamp at site 5	39.8	1230	51	37.5	1300	54	20.1	365	15

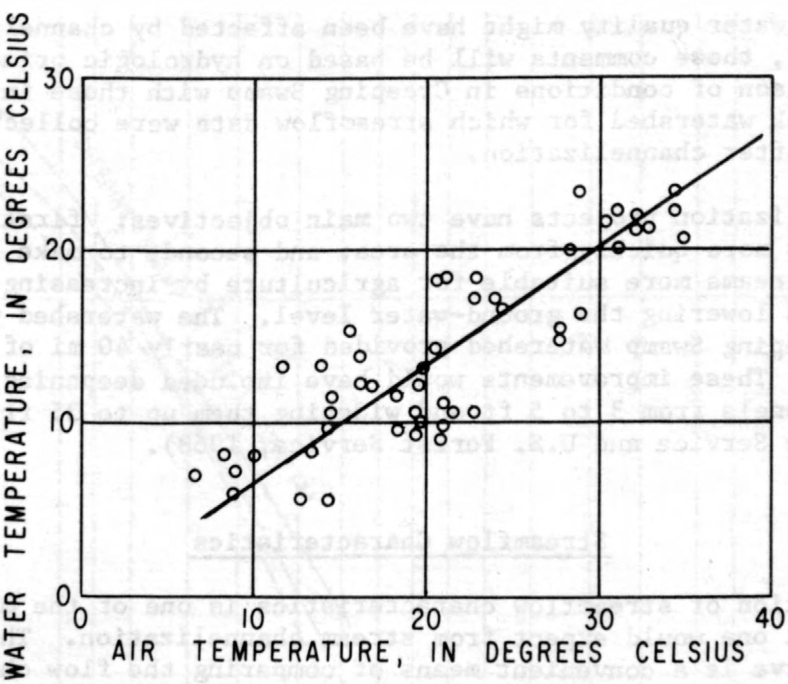

Figure 15.--Relation of daily maximum air temperatures to daily maximum water temperatures in Creeping Swamp at site 1, July 1974 to June 1975.

air temperatures. The maximum water temperature during July 1974 to June 1975 was 26°C and the minimum was 5.5°C. The frequency distribution of daily maximum temperatures is shown in table 11.

Table 11.--Frequency distribution of daily maximum water temperatures at site 1 for the period July 1974 to June 1975

Water temperature, in degrees Celsius, equaled or exceeded the indicated percentage of time				
90%	75%	50%	25%	10%
7.5°C	10°C	16°C	22°C	25°C

POTENTIAL EFFECTS OF CHANNELIZATION

In the preceding sections we have discussed the hydrologic conditions and chemical quality of the ground water and surface water of the Creeping Swamp watershed as they exist at this time--that is, virtually under natural conditions. As noted at the beginning, one of the primary objectives of the investigation was to determine the extent to which the existing conditions would be modified by channelization. Although plans to improve the channels in the basin have been cancelled, we believe it will be useful to comment on the extent to which the hydrologic conditions and water quality might have been affected by channelization. By necessity, these comments will be based on hydrologic principles and on a comparison of conditions in Creeping Swamp with those in the Ahoskie Creek watershed for which streamflow data were collected both before and after channelization.

Channelization projects have two main objectives: first, to remove flood waters more quickly from the area; and second, to make land adjacent to streams more suitable for agriculture by increasing subsurface drainage and lowering the ground-water level. The watershed work plan for the Creeping Swamp watershed provided for nearly 40 mi of channel improvements. These improvements would have included deepening the natural channels from 3 to 5 ft and widening them up to 35 ft (U.S. Soil Conservation Service and U.S. Forest Service, 1968).

Streamflow Characteristics

Alteration of streamflow characteristics is one of the more obvious effects that one would expect from stream channelization. The flow-duration curve is a convenient means of comparing the flow characteristics of different streams, or the flow characteristics of the same stream for different periods of time. The flow-duration curves for Ahoskie Creek at Ahoskie, N. C. (drainage area 57 mi^2) both before and after channelization and the flow-duration curve for Creeping Swamp at site 1 (drainage area 28 mi^2) are shown in figure 16.

Ahoskie Creek is in Hertford County, about 60 miles north of Creeping Swamp. The surface of the basin is underlain by fine-grained sediments similar in composition to those underlying most of the Creeping Swamp watershed. The major geologic difference between the basins is that the Castle Hayne Limestone, which is present at relatively shallow depths in the Creeping Swamp watershed is not present in the Ahoskie watershed. The channels in the Ahoskie Creek watershed were deepened and widened between 1962 and 1964.

As shown in figure 16, the duration curve for Creeping Swamp is similar to that for Ahoskie Creek prior to channelization; note particularly that the flows of both streams reach very low levels at about the 80 percent point. Prior to channelization there was no flow in Ahoskie Creek about 8 percent of the time. During 1971-74 there was no flow in Creeping Swamp about 6 percent of the time. The slightly greater low flows in Creeping Swamp relative to Ahoskie Creek before channelization may be accounted for by upward leakage from the Castle Hayne Limestone.

Comparison of the duration curves for Ahoskie Creek show three significant changes resulting from channelization. First, the higher

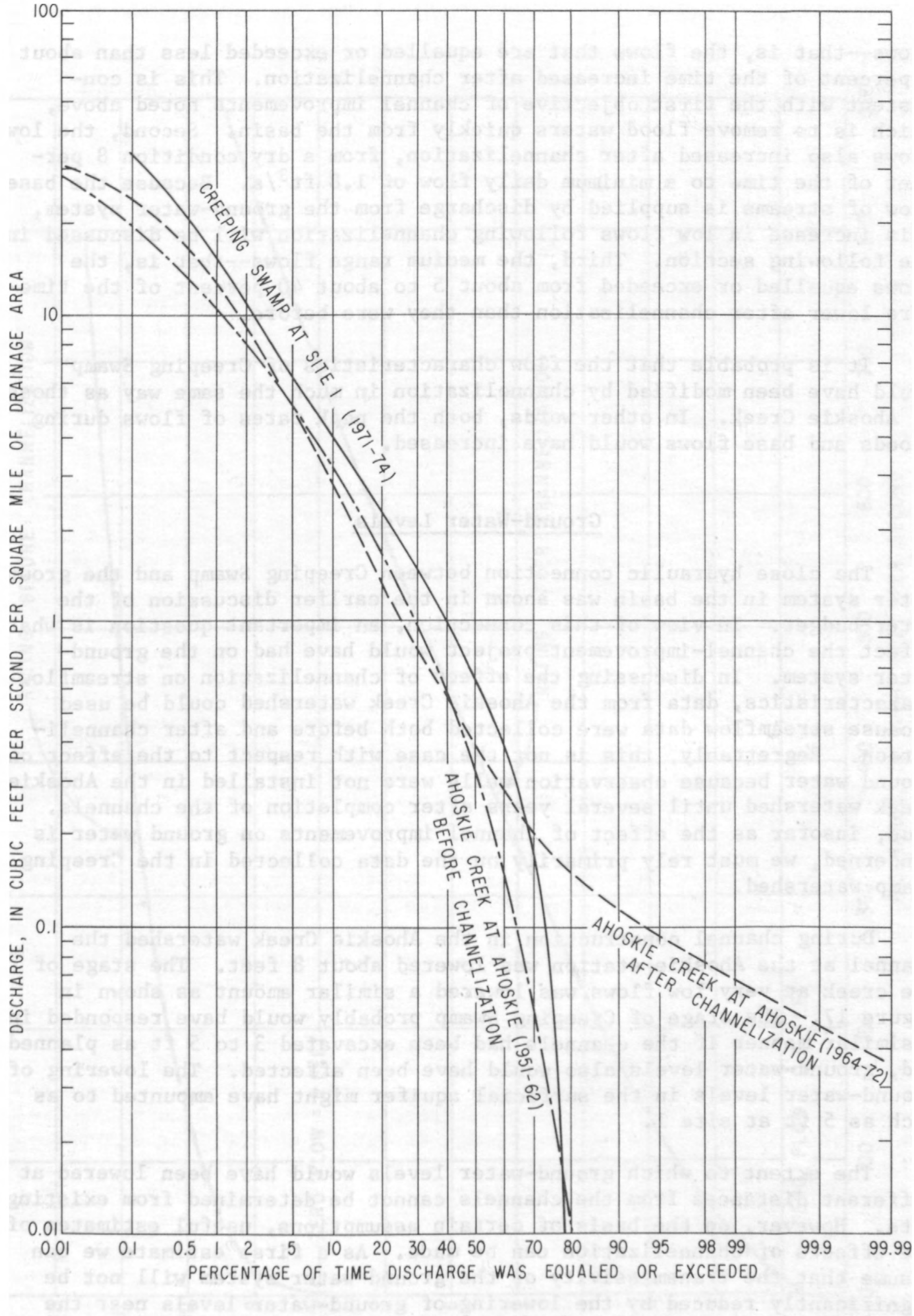

Figure 16.--Flow-duration curves for Ahoskie Creek at Ahoskie before and after channelization and Creeping Swamp.

flows--that is, the flows that are equalled or exceeded less than about 5 percent of the time increased after channelization. This is consistent with the first objective of channel improvements noted above, which is to remove flood waters quickly from the basin. Second, the low flows also increased after channelization, from a dry condition 8 percent of the time to a minimum daily flow of 1.8 ft^3/s. Because the base flow of streams is supplied by discharge from the ground-water system, this increase in low flows following channelization will be discussed in the following section. Third, the medium range flows--that is, the flows equalled or exceeded from about 5 to about 40 percent of the time--were lower after channelization than they were before.

It is probable that the flow characteristics of Creeping Swamp would have been modified by channelization in much the same way as those of Ahoskie Creek. In other words, both the peak rates of flows during floods and base flows would have increased.

Ground-Water Levels

The close hydraulic connection between Creeping Swamp and the ground-water system in the basin was shown in the earlier discussion of the water budget. In view of this connection, an important question is what effect the channel-improvement project would have had on the ground-water system. In discussing the effect of channelization on streamflow characteristics, data from the Ahoskie Creek watershed could be used because streamflow data were collected both before and after channelization. Regrettably, this is not the case with respect to the effect on ground water because observation wells were not installed in the Ahoskie Creek watershed until several years after completion of the channels. Thus, insofar as the effect of channel improvements on ground water is concerned, we must rely primarily on the data collected in the Creeping Swamp watershed.

During channel construction in the Ahoskie Creek watershed the channel at the Ahoskie station was lowered about 8 feet. The stage of the creek at very low flows was lowered a similar amount as shown in figure 17. The stage of Creeping Swamp probably would have responded in a similar manner if the channels had been excavated 3 to 5 ft as planned and, ground-water levels also would have been affected. The lowering of ground-water levels in the surficial aquifer might have amounted to as much as 5 ft at site 1.

The extent to which ground-water levels would have been lowered at different distances from the channels cannot be determined from existing data. However, on the basis of certain assumptions, useful estimates of the effects of channelization can be made. As a first estimate we can assume that the transmissivity of the ground-water system will not be significantly reduced by the lowering of ground-water levels near the creek and that the amount of ground water reaching the stream would remain unchanged after channelization. Under these assumptions, the

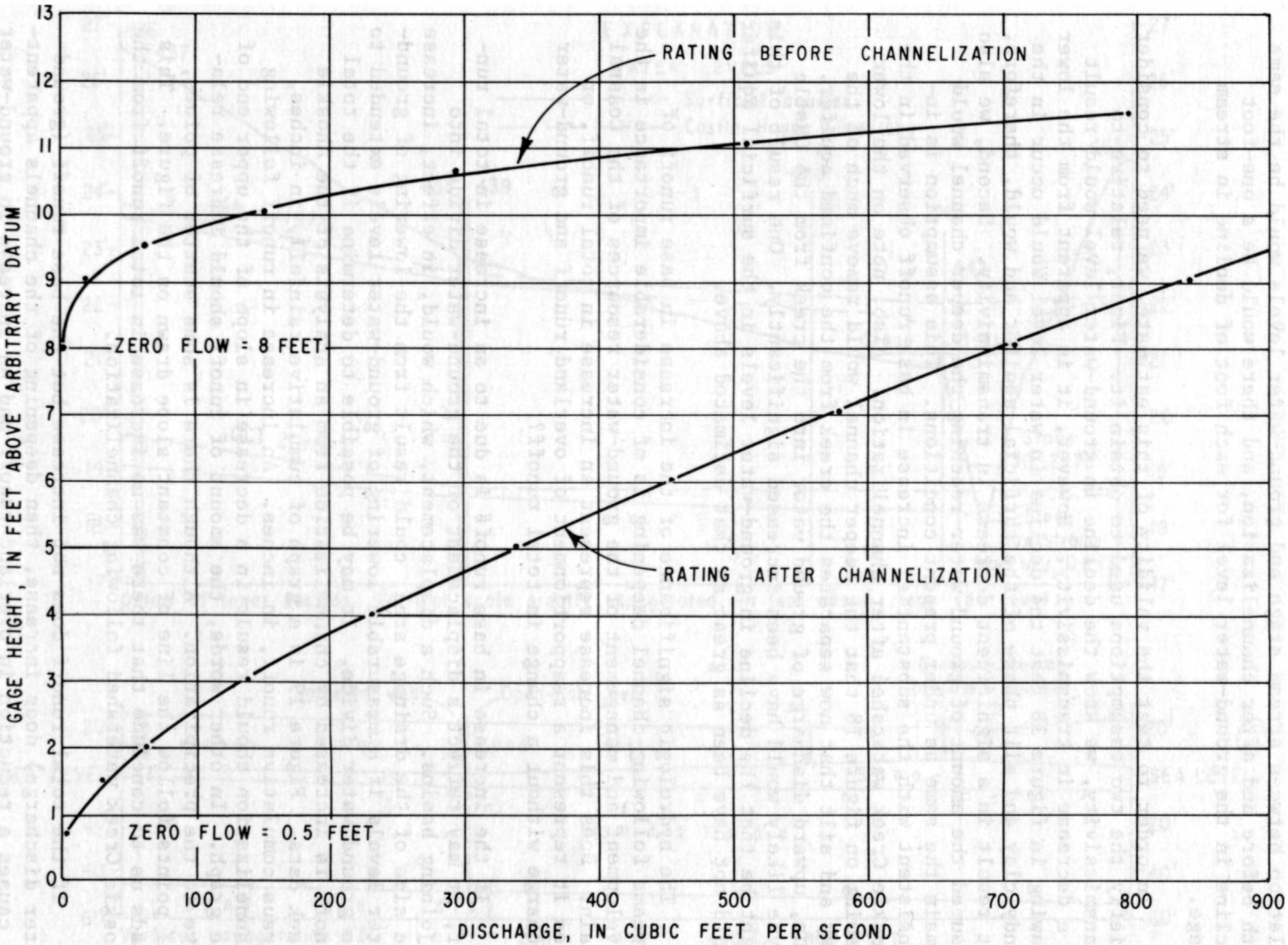

Figure 17.--Stage-discharge rating curves for Ahoskie Creek at Ahoskie before and after channelization.

relation between stream stage and ground-water levels would be the same both before and after channelization, and there would be a one-foot decline in the ground-water level for each foot of decline in stream stage.

In order to test the validity of this estimate, we need to consider briefly the two assumptions used to obtain it. First, relative to transmissivity, we know the decline in ground-water level would result in a decrease in transmissivity. However, it is apparent from the lower drawing in figure 18 that the decline in water level would occur in the sandy clay and silt phase of the surficial aquifer and would, therefore, not result in a significant decrease in transmissivity. Second, we also assumed the amount of ground water reaching the deeper channel would remain the same as under present conditions. This assumption is inconsistent with the substantial increase in base runoff observed in the Ahoskie Creek watershed after channelization. Also, note on the lower drawing on figure 18 that the deeper channel would remove much of the clay and silt that now separates the creek from the confined aquifer. Thus, upward discharge of ground water into the creek from the Castle Hayne likely would have been increased significantly. One result of this might be that the decline in ground-water levels in the surficial aquifer would not have been as great as that estimated above.

The hydrologic significance of the increase in base runoff of streams following channel deepening is of considerable importance in the development and management of the ground-water resources of the Coastal Plain. Does this increase represent an increase in total runoff, or does it represent a reapportionment of overland runoff and ground-water recharge without a change in total runoff?

If the increase in base runoff is due to an increase in total runoff, it may reflect a displacement of the ground-water divide into adjoining basins. Such a displacement, which would, in effect, increase the size of the drainage area, could result from the lowering of ground-water levels if a measurable lowering of ground-water levels extended to the ground water divide. It may be possible to determine if the total runoff is increased by channelization from an analysis of the Ahoskie Creek data. Figure 19 is a graph of cumulative rainfall, in inches, versus cumulative runoff, in inches. An increase in runoff following channelization should result in a decrease in slope of the upper end of the graph. In other words, the amount of runoff should increase relative to the precipitation. Although there is some scatter of points, all points follow the line of constant slope drawn on the figure. This leads us to conclude that there was no increase in total runoff from the Ahoskie Creek watershed following channelization.

If the total runoff does not increase but the base runoff (ground-water discharge) does increase, then deepening of the channels apparently causes a reduction in overland runoff and an increase in ground-water

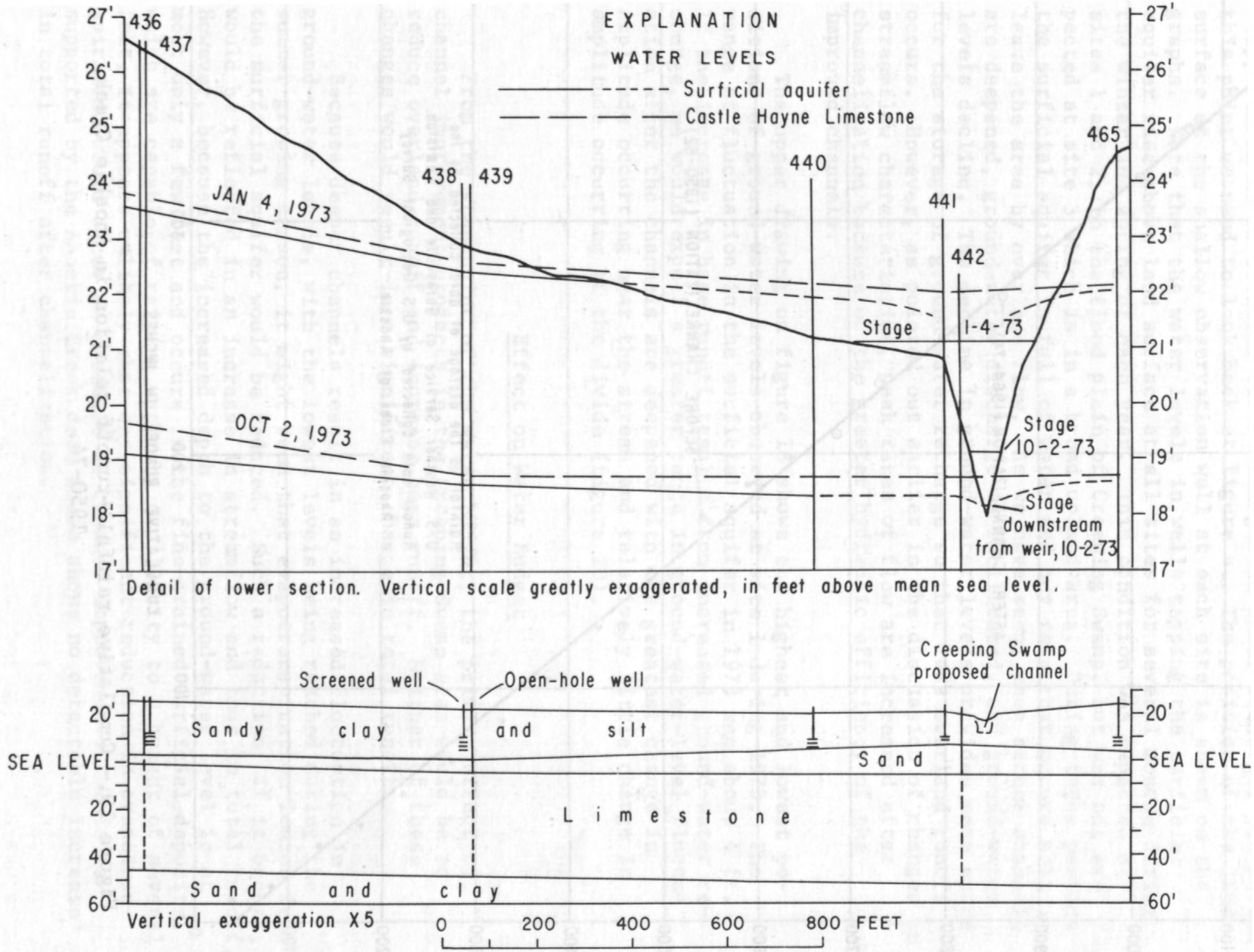

Figure 18.--Geologic section at site 1 showing depths penetrated by observation wells (lower) and maximum and minimum ground-water levels (upper).

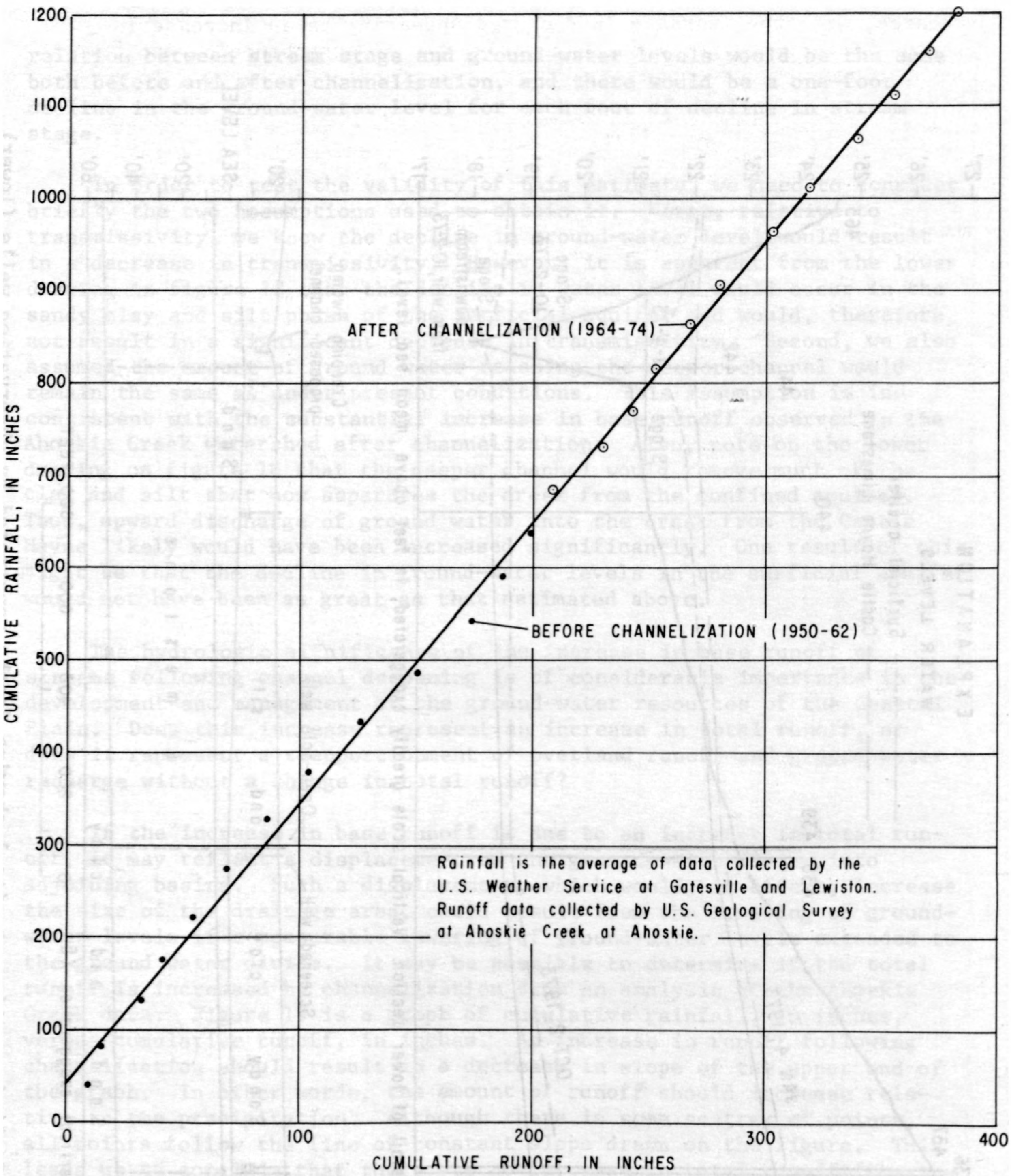

Figure 19.--Cumulative rainfall-runoff relation in Ahoskie Creek, 1950-74.

recharge, with the increase in recharge appearing as an increase in ground-water discharge. In other words, the deeper channels result in a reapportionment of overland runoff and ground-water recharge. To pursue this point we need to look back at figure 4. The position of the land surface at the shallow observation well at each site is shown on the graphs. Note that the water levels in wells tapping the surficial aquifer rise above land surface at all sites for several months during the winter and spring of each year. This condition was expected at sites 1 and 2, in the flood plain of Creeping Swamp, but was not expected at site 3 which is in a broad upland area. During these periods the surficial aquifer is full of water and any rain that occurs must leave the area by overland flow. As we have seen, when stream channels are deepened, ground-water discharge is facilitated, and ground-water levels decline. The decline in ground-water levels provides more space for the storage of ground-water recharge so that less overland runoff occurs. However, as pointed out earlier in the discussion of changes in streamflow characteristics, peak rates of flow are increased after channelization because of the greater hydraulic efficiency of the improved channels.

The upper drawing on figure 18 shows the highest and lowest positions of ground-water levels observed at site 1 during 1973. The range of fluctuation in the surficial aquifer in 1973 was about 4 ft. If the increase in base runoff results from increased ground-water recharge, we would expect a greater range in ground-water-level fluctuation after the channels are deepened with the greatest change in amplitude occurring near the stream and relatively little change in amplitude occurring at the divide (figure 20).

Effect on Water Budget

From the standpoint of the water budget, the primary effect of channel improvement projects in the Creeping Swamp area would be to reduce overland runoff and increase base runoff. Neither of these changes would result in a significant change in total runoff.

Because deeper channels result in an increased fluctuation in ground-water levels, with the lowest levels being reached during the summer growing season, it might seem that evapotranspiration losses from the surficial aquifer would be reduced. Such a reduction, if it occurs, would be reflected in an increase in streamflow and thus in total runoff. However, because the increased depth to the ground-water level is at most only a few feet and occurs in the fine-grained surficial deposits, which are capable of raising water by capillarity to a height of several feet, it appears unlikely that any significant reduction in evapotranspiration would occur as a result of channel improvements. This is supported by the Ahoskie Creek data which shows no detectable increase in total runoff after channelization.

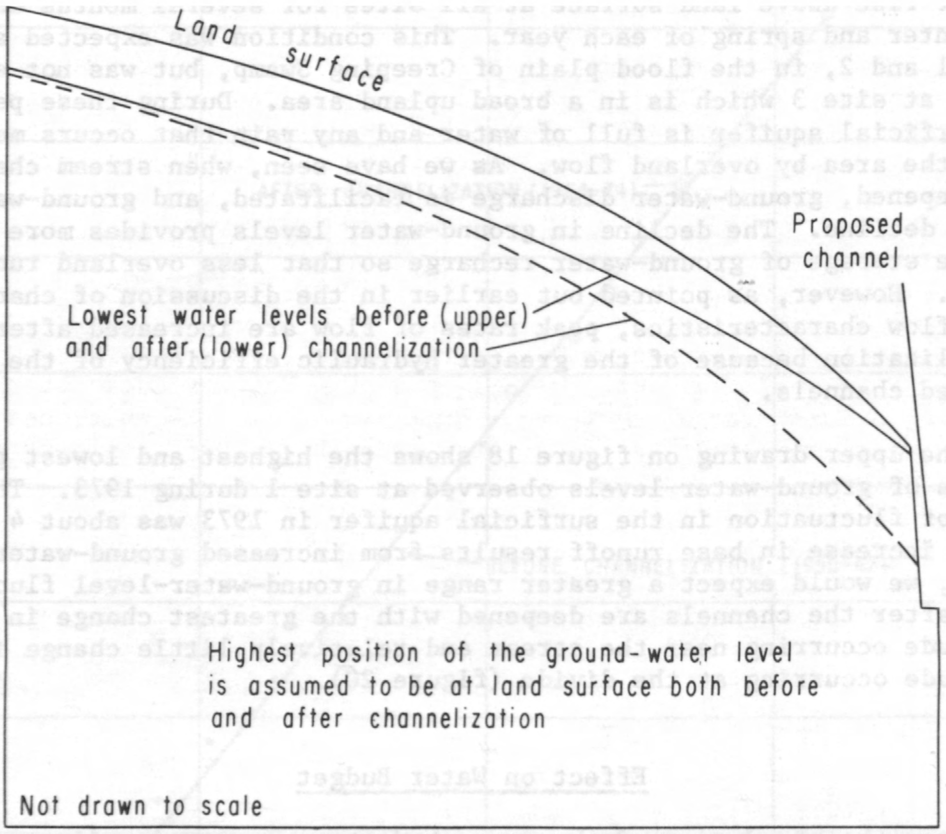

Figure 20.--Drainage of surficial aquifer after channelization.

Castle Hayne Limestone

The Castle Hayne Limestone normally discharges some ground water to Creeping Swamp below site 2 (figs. 4 and 5). It is likely that channelization would affect this upward discharge in two ways. First, the removal of clay and silt in the channel would reduce the thickness of the confining bed and would allow greater upward leakage of ground water to the stream. If we assume no change in the vertical hydraulic conductivity of the confining bed and in the head difference between the stream and the Castle Hayne, then the change in upward leakage can be estimated by a simple proportion using Darcy's Law (equation 2, p. 19), where the hydraulic gradient, I, would be expressed as a vertical hydraulic gradient:

$$I = \frac{\Delta h}{b}, \qquad (4)$$

where Δh is the difference in head between the stream and the confined aquifer (virtually the Castle Hayne), and b is the thickness of the confining bed (surficial aquifer). From figure 18, the thickness of the confining bed under the stream at site 1 is about 10 ft. A 5-ft channel excavation would leave 5 ft of the confining bed, so that,

$$I(\text{before}) = \frac{\Delta h}{10}, \text{ and}$$

$$I(\text{after}) = \frac{\Delta h}{5}, \text{ therefore,}$$

$$Q(\text{after}) = 2\ Q(\text{before}),$$

assuming the other factors of equation (2) remain unchanged. This factor of 2 times the pre-channelization discharge is only an estimate of the magnitude of increased upward leakage within the deepened channel because (1) head relations are likely to change, (2) the value for the vertical hydraulic conductivity of the confining bed could change, and (3) neither the depth of channel excavation nor the thickness of confining bed under the stream are constant factors.

The other effect of channelization could be an increase in the amount of upward leakage away from the excavated channel. Figure 18 shows that the Δh between the surficial aquifer and the Castle Hayne is increased during times of low ground-water levels, which suggests that any further decrease in the water level in the surficial aquifer due to channelization will also increase the Δh and, hence, upward leakage. However, any increase in the amount of upward leakage would occur only when the ground-water level in the surficial aquifer drops below the lowest levels of the pre-channelized conditions. The magnitude of increased upward leakage away from the channel can be estimated using data at site 1 (fig. 18), where the Δh averages about 0.25 ft. Here, a four-fold increase in upward leakage would occur for every foot of change in head differential due to channel deepening.

Water-Quality Characteristics

The preceding discussion indicates that the channelization of Creeping Swamp as originally proposed would have increased the proportion of ground-water discharge into the stream system. Because concentrations of chemical constituents are greater in ground water than in surface water (tables 6 and 7), an increase in the base flow component would cause an increase in the concentrations of these constituents in the surface waters.

Because a greater proportion of water would pass through the ground-water system after channelization, it is reasonable to expect that a greater proportion of the surface contaminants might also be carried through the soil zone and clayey material in the shallow deposits rather than directly to the stream in overland flow. Although ground water normally has a higher concentration of dissolved solids than overland flow, and these higher concentrations would end up in the stream in the increased proportion of baseflow, a beneficial aspect of increases in ground-water contributions might be that the ion-adsorption or exchange capacity of soil and clayey material would result in the retention of fertilizers, insecticides and herbicides and decrease the amount of them reaching the stream. The amount of constituent increases that might occur as a result of channelization are impossible to predict because of the numerous variables in the geochemical/hydrological system.

Few data are available which scientifically document the effects of channelization on the sediment regime of a stream, and no such data exist for streams in this State. Although suspended-sediment concentrations are generally small in natural Coastal Plain streams as compared to streams in other parts of the State (Simmons, 1976), an important part of this study was devoted to determining the fluvial-sediment characteristics of Creeping Swamp. Without doubt, the channelization of a stream would cause a considerable increase in its sediment discharge during and for some time following the construction phase.

The largest increases in sediment concentration would occur during the channel construction phase at times of high overland runoff and high flow. The effects of hydraulic efficiency and higher stream velocities, which are other characteristics of improved channels, would also increase the stream sediment-transport capabilities. Increased sediment concentrations and larger median grain diameters of suspended materials generally result when stream velocities are increased. An increase in sediment discharge of unknown magnitude would obviously be expected in a channelized stream at least until the stream banks and spoil areas are stabilized with vegetation and the channel bottom reached a new state of equilibrium. It is possible, however, that Creeping Swamp would eventually return to its natural, pre-channelized sediment characteristics.

The changes in water temperatures which might be caused by the proposed channelization of Creeping Swamp are speculative. The main stream channels in the Creeping Swamp watershed are shaded by a heavy canopy of trees and dense underbrush. The removal of this canopy during channelization, resulting in direct exposure of the stream to the sun's rays, suggests that water temperatures might be slightly higher after channelization (Pluhowski, 1972). The increased discharge of cooler ground waters resulting from channelization, however, might be expected to partly offset any increase in stream temperatures.

SUMMARY

Creeping Swamp is a typical North Carolina central Coastal Plain stream that has a swampy and heavily wooded flood plain and whose natural channel is braided and not deeply entrenched. The stream drains about 28 mi^2 of flat-to-gently-rolling timberland and cleared farmland at altitudes between 20 and 60 ft above mean sea level.

The watershed is underlain by unconsolidated sand, silt and clay, and by beds of semi-consolidated limestone to depths of about 1,500 ft (460 m). Of main importance to the stream-aquifer hydrologic system is the surficial aquifer, consisting of Quaternary deposits and the upper part of the Yorktown Formation, the lower sandy part of the Yorktown Formation, the Pungo River Formation, and the confined aquifer composed of the Castle Hayne Limestone. These aquifers furnish all the base runoff of Creeping Swamp.

Rainfall recharges the surficial aquifer, which stores and slowly transmits the water either to the underlying Castle Hayne Limestone or to Creeping Swamp. Discharge from the Castle Hayne along the lower reaches of Creeping Swamp contributes a significant but unknown amount of water to the base runoff of the stream. Part of the ground water in the Castle Hayne is discharged outside the watershed.

Hydrologic data collected at six sites in the project area provided a basis for estimating the water budget for the Creeping Swamp watershed. Between July 1974 and June 1975 about 17 percent of the 42.24 in of rainfall reached the stream by overland runoff; 20 percent reached it by ground-water base runoff; 2 percent left the basin by ground-water outflow; and 61 percent returned as vapor to the atmosphere by the process of evapotranspiration.

The water-quality characteristics in Creeping Swamp are largely controlled by natural processes such as the contribution of dissolved mineral matter in ground water discharged to the stream, surface runoff, biological activities, the decay of organic material, and precipitation. Dissolved-solids concentrations of ground waters in the area sometime exceed those in overland flow by tenfold or more. The highest dissolved-solids concentration in Creeping Swamp was 79 mg/L, which occurred during base flow when ground-water discharge was the major source of streamflow. Dissolved-solids concentrations increase in a downstream direction at all stages of flow and especially during low flow. The largest increases in major constituents between sites were observed in concentrations of calcium and bicarbonate, which is indicative of waters derived from a limestone source, such as the Castle Hayne Limestone or Yorktown Formation.

Concentrations of dissolved solids and most chemical constituents in waters of the surficial aquifer vary with depth below land surface and are much greater in the upper part of the Yorktown Formation than in the more shallow Quaternary deposits. Chemical analyses of samples taken from surface and ground-water sources during a period of base flow show that the Quaternary deposits were the major source of ground-water discharge at the time of sampling. As the water table declines during periods of little or no aquifer recharge, a larger proportion of ground-water discharge is derived from the deeper aquifers, thereby causing an increase in concentrations of dissolved constituents in Creeping Swamp.

Suspended-sediment concentrations vary directly with discharge; the highest measured concentration during the period in Creeping Swamp was 100 mg/L, which occurred at site 1 during a period of rain. The average annual sediment yield during 1972-74 was 32 tons/mi^2 at site 2 and 34 tons/mi^2 at site 1.

Because plans to improve the channels in the watershed were canceled, it was not possible to observe the effect of channelization on the hydrologic system. However, analysis of the data collected in Creeping Swamp in conjunction with data collected both before and after the construction of channels in the Ahoskie Creek watershed provided a basis for estimating some of the changes that would have occurred. It is believed these would have included:

1. A redistribution of the flow-duration curve for Creeping Swamp to show:

   a. An increase in peak flow rates during floods.

   b. A reduction in the amount of water reaching streams by overland flow and an increase in the amount of water reaching streams through the ground-water system.

c. Total runoff would not change.

2. An increase in the fluctuation of ground-water levels, with the greatest increases occurring nearest the channels. It is doubtful that there would be any change in the position of the ground-water divide.

3. An increase in suspended-sediment concentrations and loads.

4. An increase in stream temperatures.

5. An increase in concentrations of dissolved solids especially during periods of low flow.

REFERENCES

Brown, P. M., Miller, J. A., and Swain, F. M., 1972, Structural and stratigraphic framework, and spatial distribution of permeability of the Atlantic Coastal Plain, North Carolina to New York: U.S. Geol. Survey Prof. Paper 796, 79 p.

Colby, B. R., 1956, Relationship of sediment discharge to streamflow: U.S. Geol. Survey open-file report, 170 p.

Environmental Protection Agency, 1972, Water quality criteria, 1972: Environmental Protective Agency report R3-73-033, 594 p.

Federal Interagency Work Group, 1972, Recommended methods for water-data acquisition: U.S. Geol. Survey Office of Water Data Coordination, 412 p.

Floyd, E. O., 1969, Ground-water resources of Craven County, North Carolina: U.S. Geol. Survey Hydrol. Inv. Atlas HA-343.

Gambell, A. W., and Fisher, D. W., 1966, Chemical composition of rainfall in eastern North Carolina and southeastern Virginia: U.S. Geol. Survey Water-Supply Paper 1535-D, 41 p.

Joyner, B. F., 1974, Chemical and biological conditions of Lake Okeechobee, Florida, 1969-72: Florida Bur. Geology Rept. Inv. No. 71, 94 p.

Miller, C. R., 1951, Analysis of flow-duration, sediment-rating curve method of computing sediment yield: U.S. Bur. of Reclamation, Hydrology Br., 55 p.

Pluhowski, E. J., 1972, Clear-cutting and its effect on the water temperature of a small stream in northern Virginia: U.S. Geol. Survey Prof. Paper 800-C, 6 p.

Rasmussen, W. C., and Andreasen, G. E., 1959, Hydrologic budget of the Beaverdam Creek basin, Maryland: U.S. Geol. Survey Water-Supply Paper 1472, 106 p.

Simmons, C. E., 1976, Sediment characteristics of streams in the eastern Piedmont and western Coastal Plain regions of North Carolina: U.S. Geol. Survey Water-Supply Paper 1798-O, 32 p.

Sumsion, C. T., 1970, Geology and ground-water resources of Pitt County, North Carolina: North Carolina Dept. Water and Air Resources Ground-Water Bull. 18, 75 p.

U.S. Geological Survey, issued annually for 1971-75 water years, Water resources data for North Carolina; pt. 1, surface water records: U.S. Geol. Survey, Raleigh, N.C.

U.S. Geological Survey, issued annually for 1971-75 water years, Water resources data for North Carolina; pt. 2, water quality records: U.S. Geol. Survey, Raleigh, N.C.

U.S. Soil Conservation Service and U.S. Forest Service, 1968, Swift Creek watershed work plan, Pitt, Beaufort and Craven Counties North Carolina: U.S. Dept. Agriculture, 44 p.

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