UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY - WATER RESOURCES DIVISION

Hydrology of the Dismal Swamp, Virginia-North Carolina

by

William F. Lichtler and Patrick N. Walker

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U.S. GEOLOGICAL SURVEY
200 West Grace Street
Richmond, Virginia 23220

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ENGLISH-METRIC CONVERSION TABLE

Length:

Inches × 0.0254 = meters
Feet × 0.3048 = meters
Yards × 0.9144 = meters
Miles × 1.609 = kilometers

Area:

Square inches × 0.0006452 = square meters
Square feet × 0.09290 = square meters
Square yards × 0.8361 = square meters
Acres × 4047 = square meters
Square miles × 2,590,000 = square meters

Volume:

Cubic inches × 0.01639 = liters
Cubic feet × 28.32 = liters
Cubic yards × 764.6 = liters
Pints × 0.4732 = liters
Quarts × 0.9463 = liters
Gallon × 3.785 = liters
Acre-feet × 1233 = cubic meters

Weight:

Grains × 0.06480 = grams
Ounces (avoirdupois) × 28.35 = grams
Pounds (avoirdupois) × 453.6 = grams
Tons (short) × 907.2 = kilograms
Tons (long) × 1016 = kilograms

Specific combinations:

Feet per second × 1.097 = kilometer per hour
× 0.3048 = meters per second

Miles per hour × 1.609 = kilometers per hour
× 0.4470 = meters per second

Pounds per square inch × 70.3 = grams per square centimeter

Pounds per square foot × 0.4885 = grams per square centimeter

Tons (short) per square foot × 0.9765 = kilograms per square centimeter

Tons (short) per acre × 0.2241 = kilograms per square meter

Tons (short) per square mile × 0.0003502 = kilograms per square meter

Pounds per cubic foot × 0.01602 = grams per cubic centimeter

Cubic feet per second × 1.699 = cubic meters per minute
× 0.02832 = cubic meters per second

Cubic feet per second for 1 day × 1.983 = acre feet
× 2446 = cubic meters

Degrees Fahrenheit − 32 × 0.556 = degrees Celsius.

HYDROLOGY OF THE DISMAL SWAMP
VIRGINIA - NORTH CAROLINA

By W. F. Lichtler and P. N. Walker

ABSTRACT

The Dismal Swamp, on the border between eastern Virginia and North Carolina is one of the few remaining large (approximately 210,000 acres) areas of wet wilderness in the eastern United States. There has been much speculation concerning the hydrologic conditions that led to the formation of the swamp.

Oaks and Coch (1973) recently completed a detailed investigation of the geology and morphology of the area. An analysis of their geology and the pollen work of Whitehead (1972) has lead the authors to the following hypothesis concerning the hydrologic conditions that led to the formation of the peat in the swamp.

A permeable sand facies of the Norfolk Formation underlies Dismal Swamp. This facies was originally completely covered by the Sand Bridge Formation, which is a confining layer, and underlain by the impermeable Yorktown Formation. Movement of water eastward within the Norfolk Formation from the outcrop area on the top of the Suffolk Scarp was further restricted by a less permeable facies of the Norfolk east of the swamp; thereby creating an artesian head within the permeable sand facies of the Norfolk Formation.

Erosion during the Pleistocene age breached the Sand Bridge confining layer and allowed upward seepage of water along the shallow stream valleys. This seepage, combined with the abundant rainfall and naturally sluggish surface drainage, may have been sufficient to trigger the formation of

peat along stream valleys about 9,000 years ago. The peat further inhibited surface drainage, which in turn, accelerated the accumulation of peat until the interfluve areas were covered. The present role of the Norfolk Formation in the hydrology of the swamp is not clear, but it is considered to be one of the most important aspects of the hydrology to be studied in future investigations.

Surface inflow is from small streams draining from the west. The flow of these streams varies widely, being generally less in the summer than in winter. Outflow is primarily through the Feeder Ditch-Dismal Swamp Canal system, which discharges at South Mills and Deep Creek locks.

Rates and direction of surface flow within the swamp are partly controlled by gates on many of the ditches. Inadequately controlled ditches penetrating the Norfolk Formation plus withdrawal of water from wells along Suffolk Scarp have altered the flow of ground water under the swamp. These modifications and the loss of water through the Dismal Swamp Canal have probably resulted in a generally drier swamp as indicated by changes in the vegetation. It is feasible to preserve Dismal Swamp, but more detailed studies of the hydrology are needed to aid in future management.

INTRODUCTION

The Dismal Swamp, on the border between eastern Virginia and North Carolina, is one of the few remaining large areas of wet wilderness in the eastern United States. (See fig. 1.) The flora and fauna of the swamp are predominantly southern, yet a large number of northern plants and animals are present. Recognizing the unusual character of the swamp,

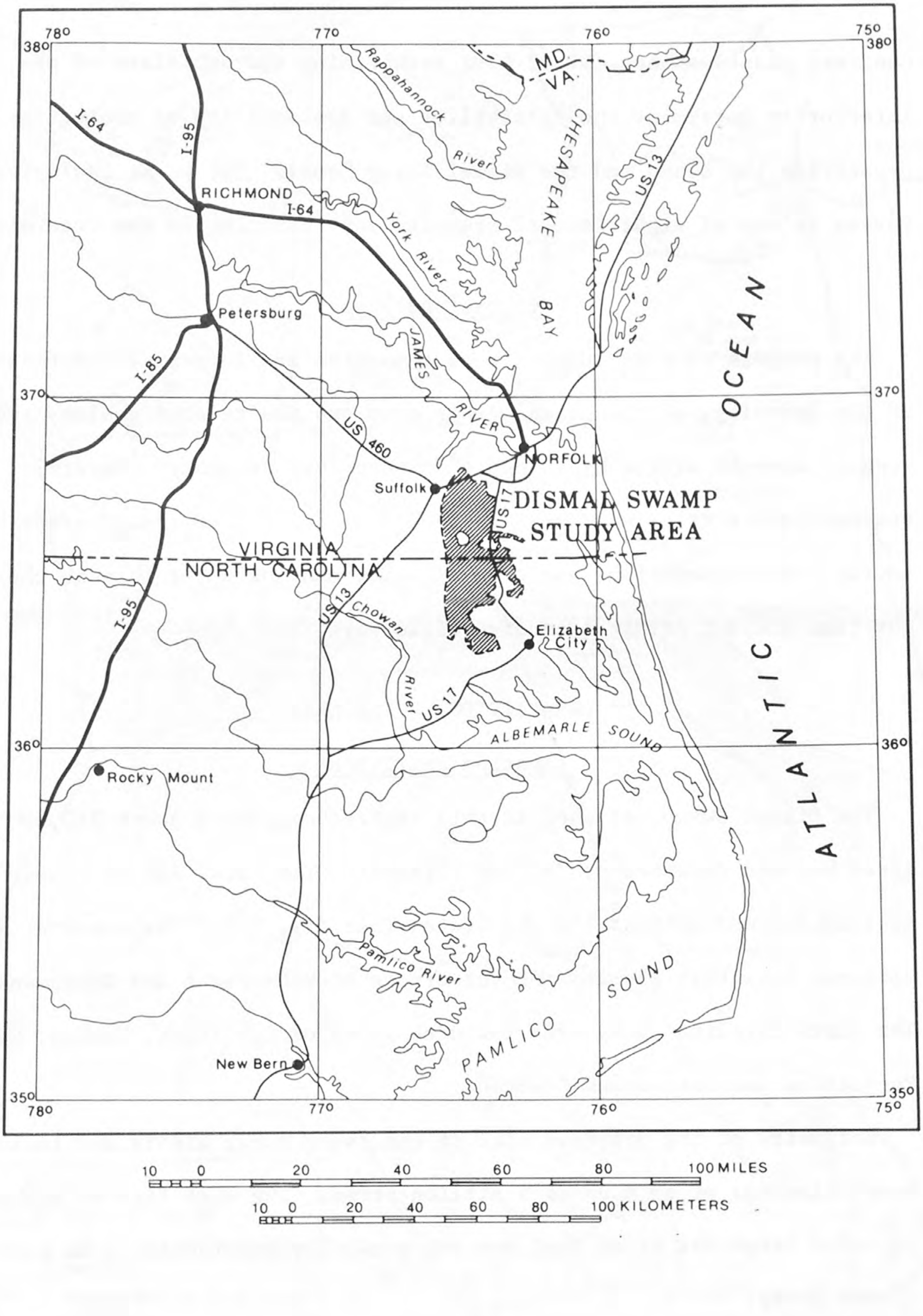


Figure 1.--Location of Dismal Swamp study area.

Congress passed an Act (PL 92-478) authorizing the Secretary of the Interior to determine the feasibility and desirability of protecting and preserving the swamp and the Dismal Swamp Canal. The U. S. Geological Survey is one of eight Federal agencies participating in the determination.

Purpose and Scope

The purpose of this report is to summarize and interpret information on the hydrology of the Dismal Swamp area and the related geology and to suggest aspects of the hydrology that need further study. Several reconnaissance trips were made to the swamp to observe ground-water and surface-water conditions and to hand-auger shallow holes through the peat but time did not permit extensive field work.

DESCRIPTION OF THE AREA

Location and Extent

The Dismal Swamp, as used in this report, comprises about 210,000 acres between Chesapeake, Va. and Elizabeth City, N.C. and is almost equally divided between the two States (see fig. 2). The study area in Virginia is within the independent cities of Chesapeake and Nansemond. The North Carolina study area includes parts of Currituck, Camden, Gates, Perquimans and Pasquotank Counties.

Estimates of the original size of the swamp range widely and include some estimates of as much as 1 million acres. The high figures probably included large wet areas that are not generally considered to be part of Dismal Swamp.

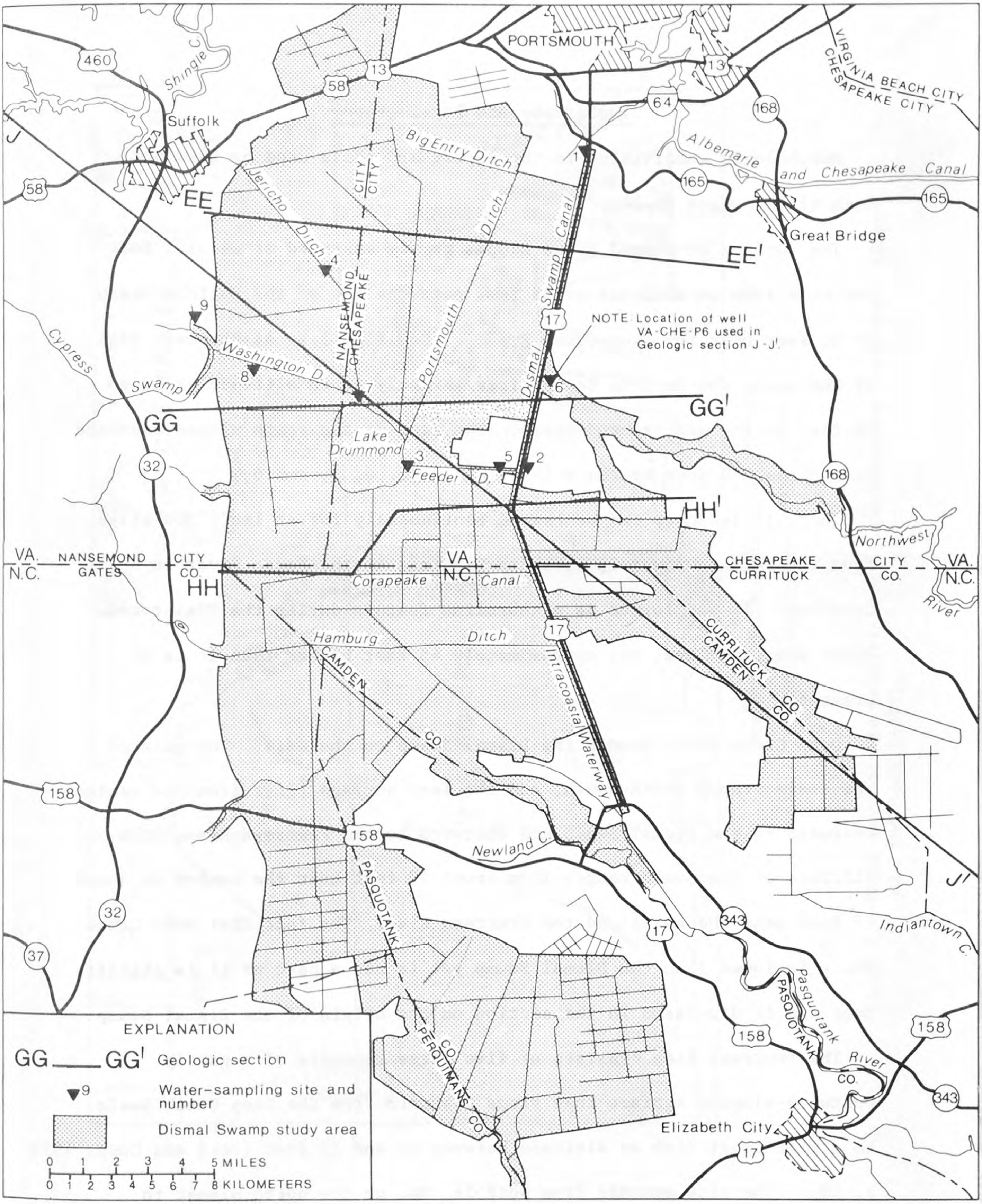


Figure 2.--Dismal Swamp study area showing location of geologic sections and water sampling sites.

Topography and Physiography

Morphologic subdivision in the report are those used by Oaks and Coch (1973, pages 14-24).

The surface of Dismal Swamp slopes gently eastward at about 1 foot per mile from an altitude of 25 feet near the toe of the Suffolk Scarp to 15 feet near the Deep Creek Swale. (See fig. 3.) At the west edge of the swamp the Suffolk Scarp rises abruptly to an altitude of 60 to 70 feet on its undissected crest. The face of the scarp slopes eastward as much as 130 feet to the mile. (See figs. 4, 5, and 6.)

The Suffolk Scarp can be traced continuously for at least 210 miles from the Potomac River in northern Virginia to the Neuse River in North Carolina. It was formed as a shoreline feature during the Pleistocene Epoch when sea level was approximately 45 feet higher than it is at present.

Deep Creek Swale bounds the Dismal Swamp on the east. The axis of the swale trends north-south, and the land surface rises from the center westward to the Dismal Swamp and eastward to the Fentress Rise. The altitude of the swale ranges from about 10 feet near the center to about 15 feet near the swamp and the Fentress Rise. The fact that Deep Creek Swale is lower than the Dismal Swamp yet is not a part of it is significant and is discussed in the section on the origin of the Dismal Swamp.

The Fentress Rise consists of five large remnants of a gently westward-sloping surface that rises eastward from the Deep Creek Swale to a flat crest with an altitude between 20 and 25 feet (Oaks and Coch, 1973 p. 19). The rise extends from Norfolk, Va. on the north almost to Albemarle Sound in North Carolina. It is broken by four east-west-trending

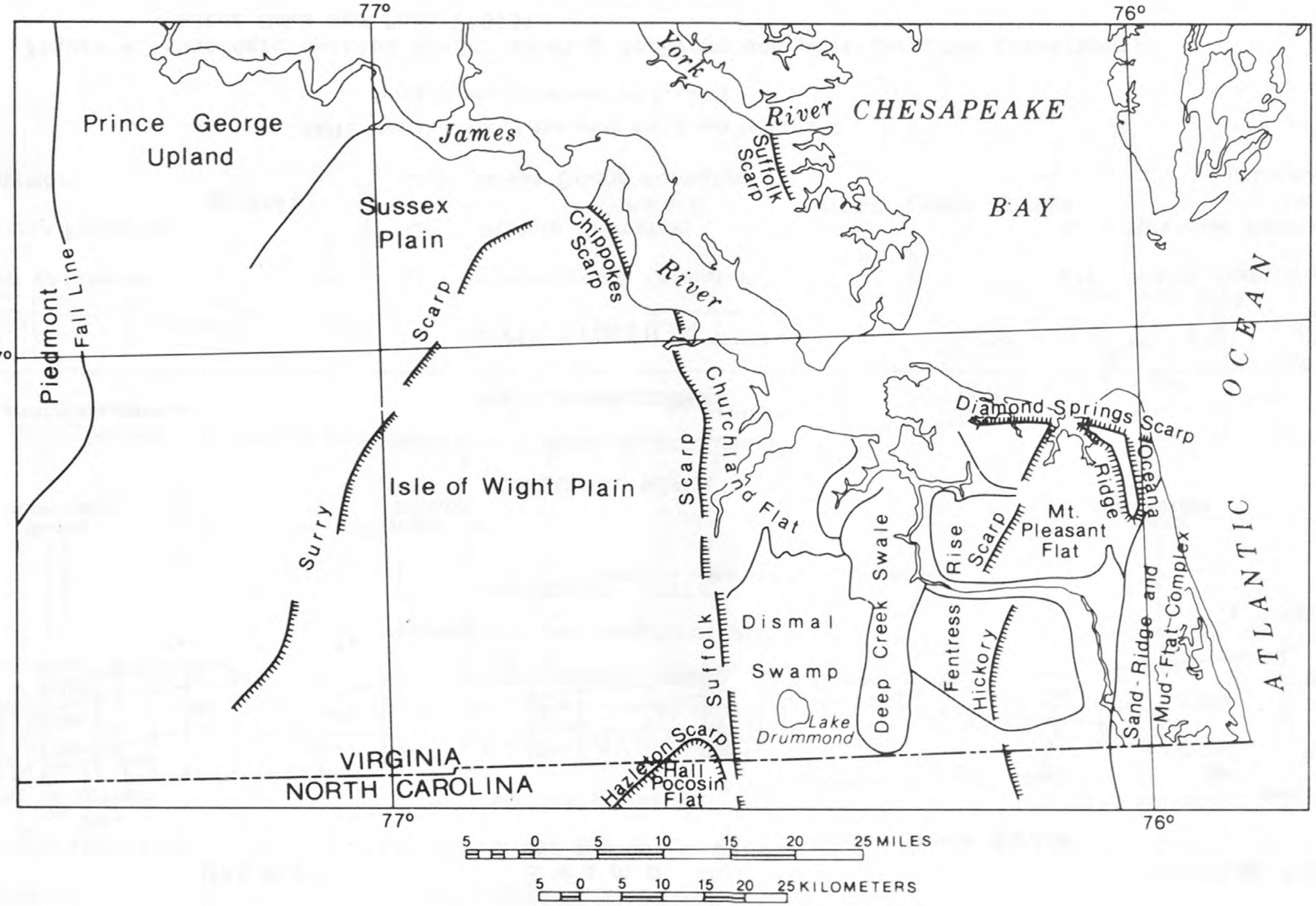
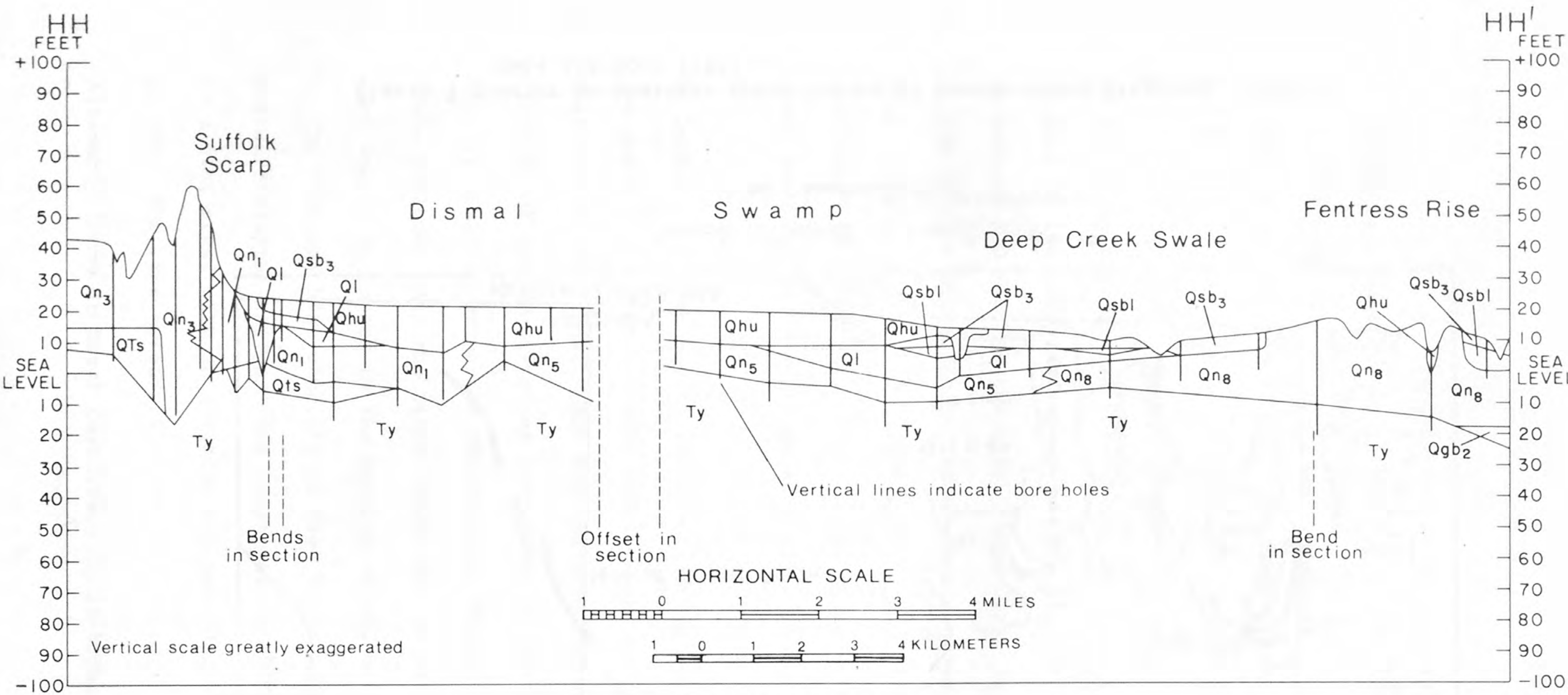


Figure 3.--Major morphologic subdivisions of southeastern Virginia. After Oaks and Coch (1973).



EXPLANATION

Qhu – Undivided sediments

Qsb – Sand Bridge Formation

Qsbl – Lower member

Ql – Londonbridge Formation

Qn – Norfolk Formation

Qgb – Great Bridge Formation

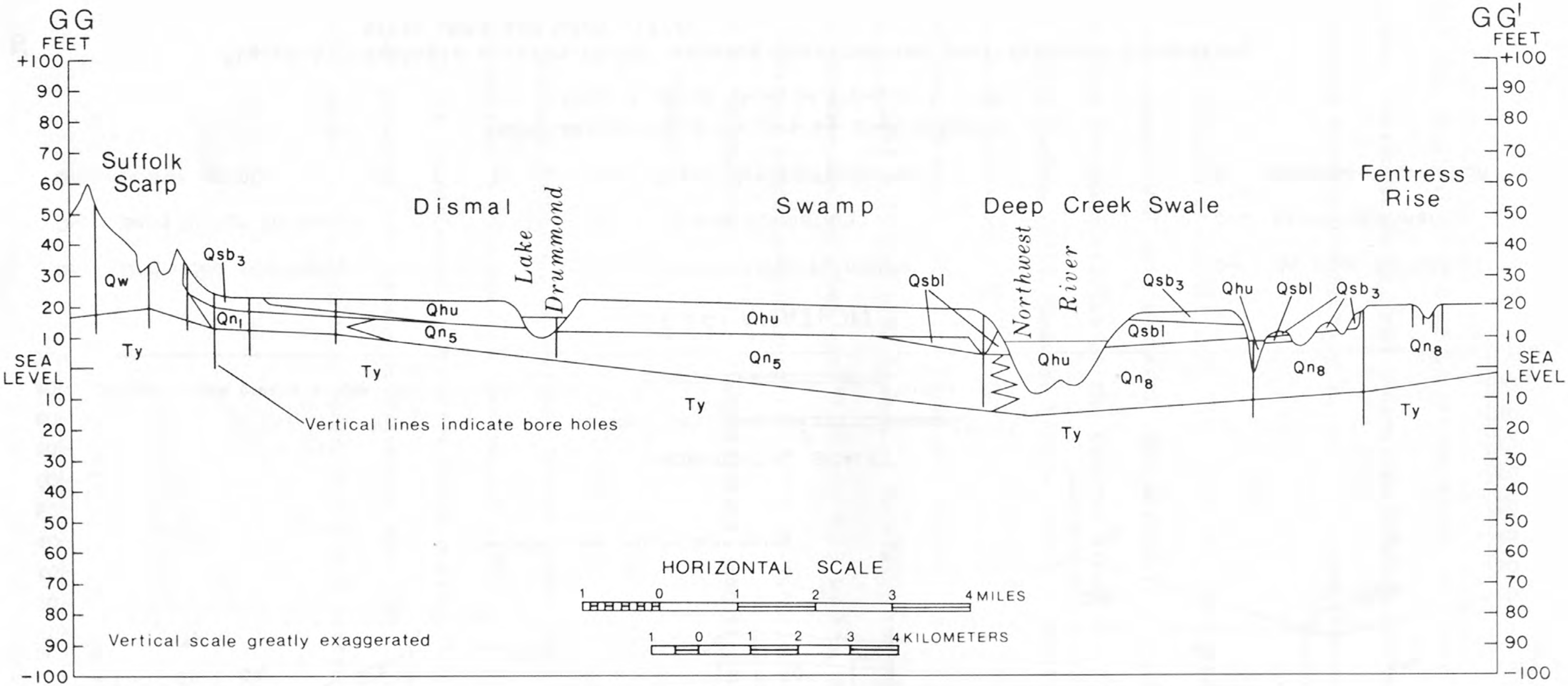
QTs – Sedley Formation

Ty – Yorktown Formation

NOTE: Descriptions of the units are given in Table 2.

Trace of section shown on Figure 2.

Figure 4.--Geologic section HH-HH' showing Yorktown and post-Yorktown formations. After Oaks and Coch (1973).



EXPLANATION

Qhu – Undivided sediments

Qsb – Sand Bridge Formation

Qsbl – Lower member

Qn – Norfolk Formation

Qgb – Great Bridge Formation

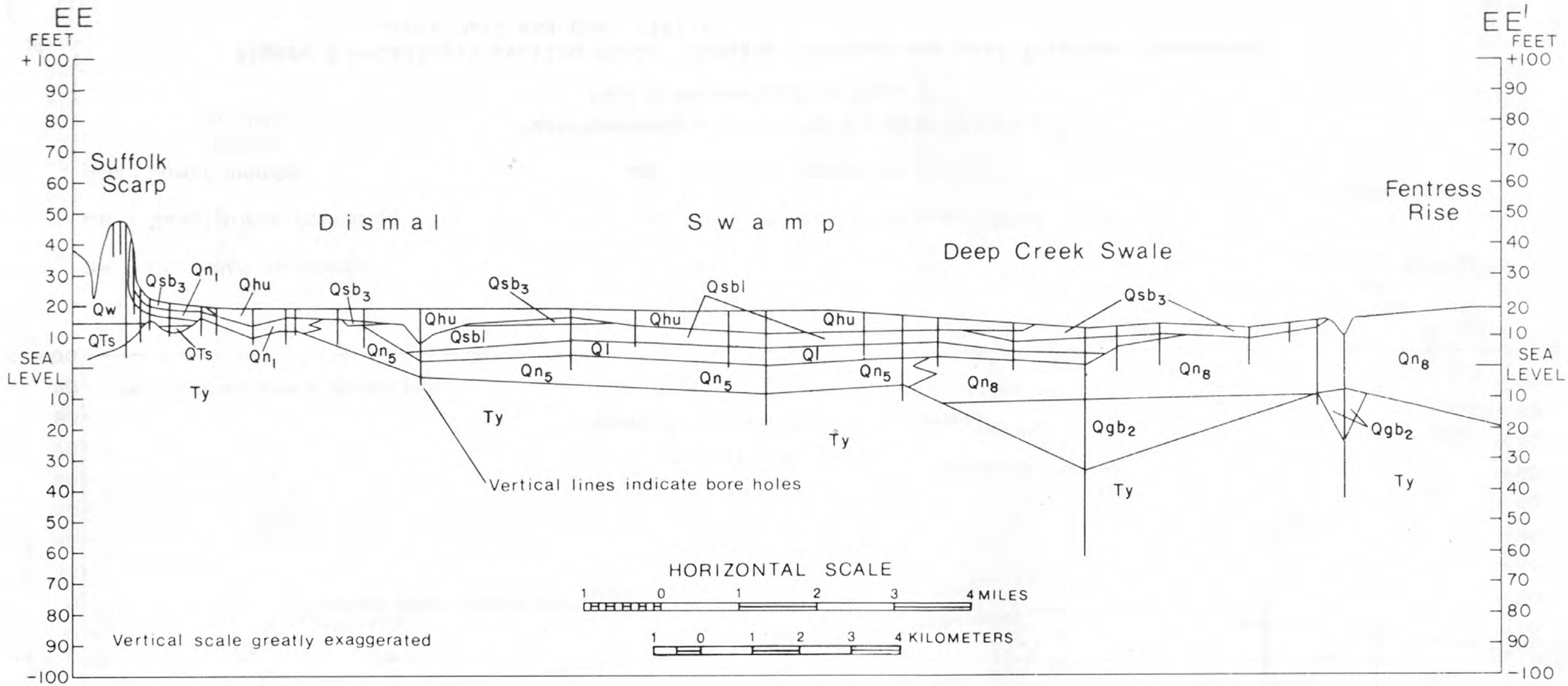
Qw – Windsor Formation

Ty – Yorktown Formation

NOTE: Descriptions of the units are given in Table 2.

Trace of section shown on Figure 2.

Figure 5.--Geologic section GG-GG' showing Yorktown and post-Yorktown formations. After Oaks and Coch (1973).



EXPLANATION

Qhu – Undivided sediments	Ql – Londonbridge Formation	Qw – Windsor Formation
Qsb – Sand Bridge Formation	Qn – Norfolk Formation	QTs – Sedley Formation
Qsbl – Lower member	Qgb – Great Bridge Formation	Ty – Yorktown Formation

NOTE: Descriptions of the units are given in Table 2.

Trace of section shown on Figure 2.

Figure 6.--Geologic section EE-EE' showing Yorktown and post-Yorktown formations. After Oaks and Coch (1973).

valleys--Eastern Branch of Elizabeth River, Southern Branch of Elizabeth River, Northwest River, and Indiantown Creek. The east boundary of the Fentress Rise is the Hickory Scarp.

Climate

The climate of Dismal Swamp is temperate--characterized by long, humid summers and mild winters. The average annual rainfall at Wallaceton-Lake Drummond station at the control structure on the Feeder Ditch is 50.42 inches (U. S. Weather Bureau, 1965). The average annual rainfall is 47.19 inches at Suffolk - Lake Kilby and 44.94 inches at Norfolk airport. The wettest months at Wallaceton-Lake Drummond station are July and August, with 6.73 and 5.92 inches of rainfall, respectively. The driest are October and December with 3.20 and 3.28 inches, respectively (table 1).

Average annual temperature is 59.0°F at Suffolk - Lake Kilby and 59.7°F at Norfolk airport. Temperature is not recorded at Wallaceton-Lake Drummond station.

GEOLOGY

Geologic formations underlying Dismal Swamp range in age from Precambrian to Holocene. Approximately 2,800 feet of unconsolidated or poorly consolidated sedimentary rocks overlie the crystalline "basement" rocks of Precambrian or Paleozoic age (fig. 7). The unconsolidated rocks range in age from Late Jurassic (?) and Cretaceous to Holocene.

Table 1.--Normal Precipitation (in inches)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Norfolk W. B. Airport	3.33	3.21	3.45	3.16	3.36	3.61	5.92	5.97	4.22	2.92	3.05	2.74	44.94
Suffolk Lake Kilby*	3.36	3.53	3.50	3.12	3.89	4.15	5.86	5.67	3.98	3.39	3.58	3.16	47.19
Wallaceton Lake Drummond	3.64	3.65	3.95	3.76	3.98	4.49	6.73	5.92	4.37	3.20	3.45	3.28	50.42

* Record years 15 to 18 years
Data from climatic Summary of the United States Supplement for 1951 through 1960

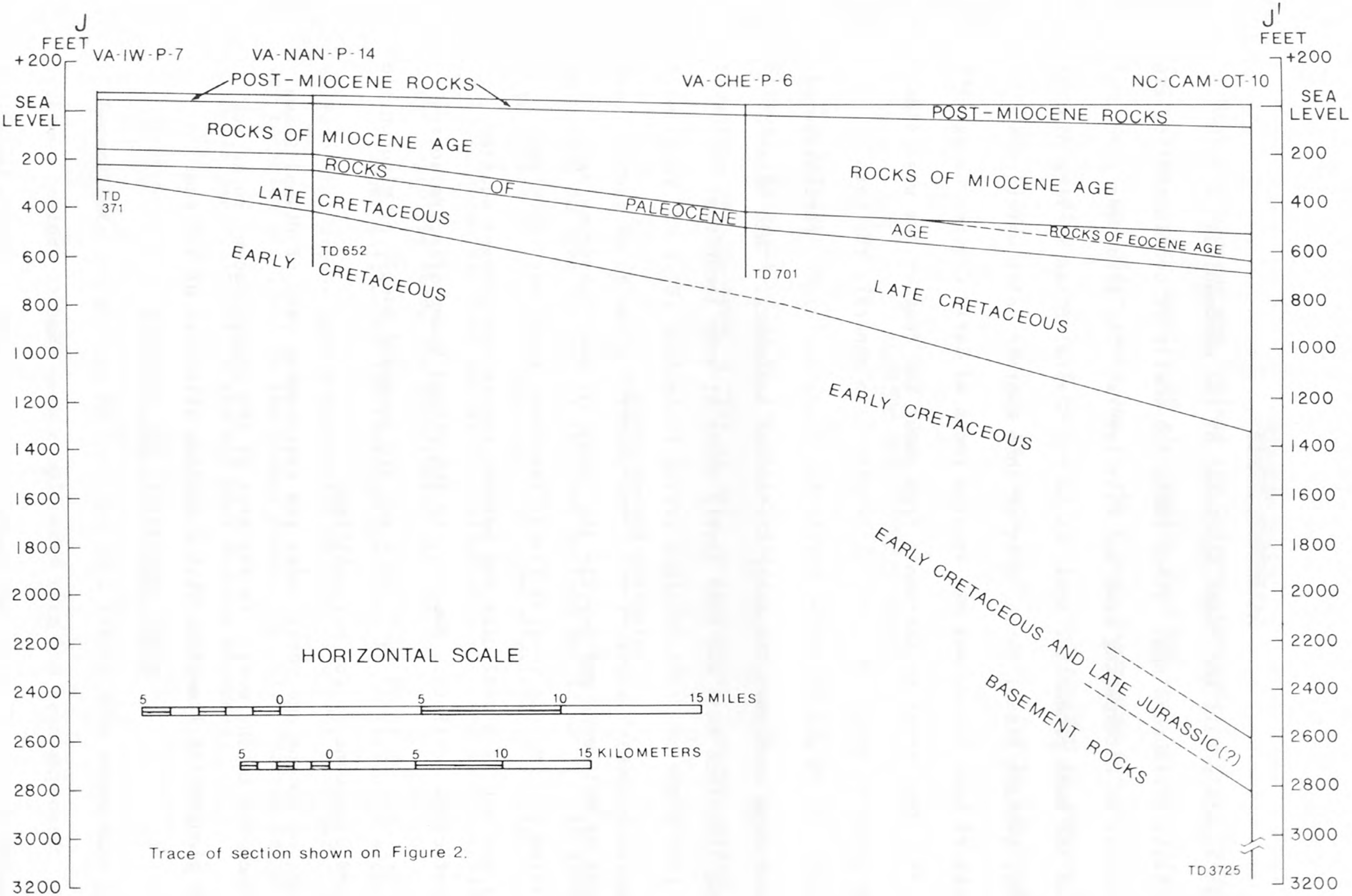


Figure 7.--Geologic section J-J' showing rock units under Dismal Swamp (Post-Miocene rocks include those of Pliocene, Pleistocene and Holocene age) after Brown, Miller and Swain (1972).

Cretaceous rocks

Approximately half the total thickness of the unconsolidated rock is of Early Cretaceous age. These rocks are mostly of continental origin and consist of alternating sand and clay layers. The sand beds form some of the most productive aquifers in the Coastal Plain of Virginia; however, beneath Dismal Swamp, most of them contain salty water.

Rocks of Late Cretaceous age overlie rocks of Early Cretaceous age (fig. 7). They range in thickness from about 200 feet on the west side of the swamp to about 600 feet on the east. In general, the Late Cretaceous rocks are of marine origin and contain a higher percentage of clay and fine sand than the Early Cretaceous sediments. Thin water bearing limestone beds and sand layers occur at some locations.

Paleocene-Eocene rocks

Rocks of Paleocene age overlie the rocks of Late Cretaceous age. In a large part of the Coastal Plain, Paleocene rocks are thick and clayey, and act as a confining bed between Eocene and younger aquifers, and Cretaceous aquifers. However, in the Dismal Swamp area, Paleocene rocks are only 25 to 30 feet thick and are composed mostly of glauconitic sand and limestone of low permeability.

Rocks of Eocene age occur under the easternmost part of Dismal Swamp but pinch out to the west. In the area of the swamp, Eocene rocks are mostly glauconitic limestone with a maximum thickness of 100 feet.

Miocene rocks

Rocks of Miocene age include the Calvert, Choptank, and St. Marys Formations. They consist of alternating sand and clay layers overlying the Eocene and older rocks and in the Dismal Swamp area are 400 to 500 feet thick (fig. 7). More than half the Miocene section is composed of tight clay; some clay beds as thick as 100 feet occur in the lower part.

Miocene and Pliocene rocks

Yorktown Formation

The Yorktown Formation is the uppermost formation of the Miocene Series. Recent studies of the microfossils contained in the Yorktown Formation (McLean 1966, p. 28) as well as studies of the vertebrate fossils by the U. S. Geological Survey indicate that the upper part of the Yorktown is of early Pliocene age. The Yorktown Formation extends to within 50 feet or less of the land surface and is exposed in sand pits, where it can be recognized by its characteristic blue-gray color in unweathered sections and by the yellowish-orange and dark reddish-brown saprolite above the unweathered section.

The upper surface of the Yorktown Formation is an irregular erosional surface that slopes gently eastward from about 130 feet near Petersburg, Va. to below sea level in the Dismal Swamp (fig. 8). Present day drainage channels generally follow the old post-Miocene channels.

Pliocene and Pleistocene rocks

Recent detailed studies by Oaks and Coch (1973) have shown that post-Yorktown geology is much more complicated than had been supposed. Figures 4, 5, and 6 are geologic sections through the Virginia part of Dismal Swamp

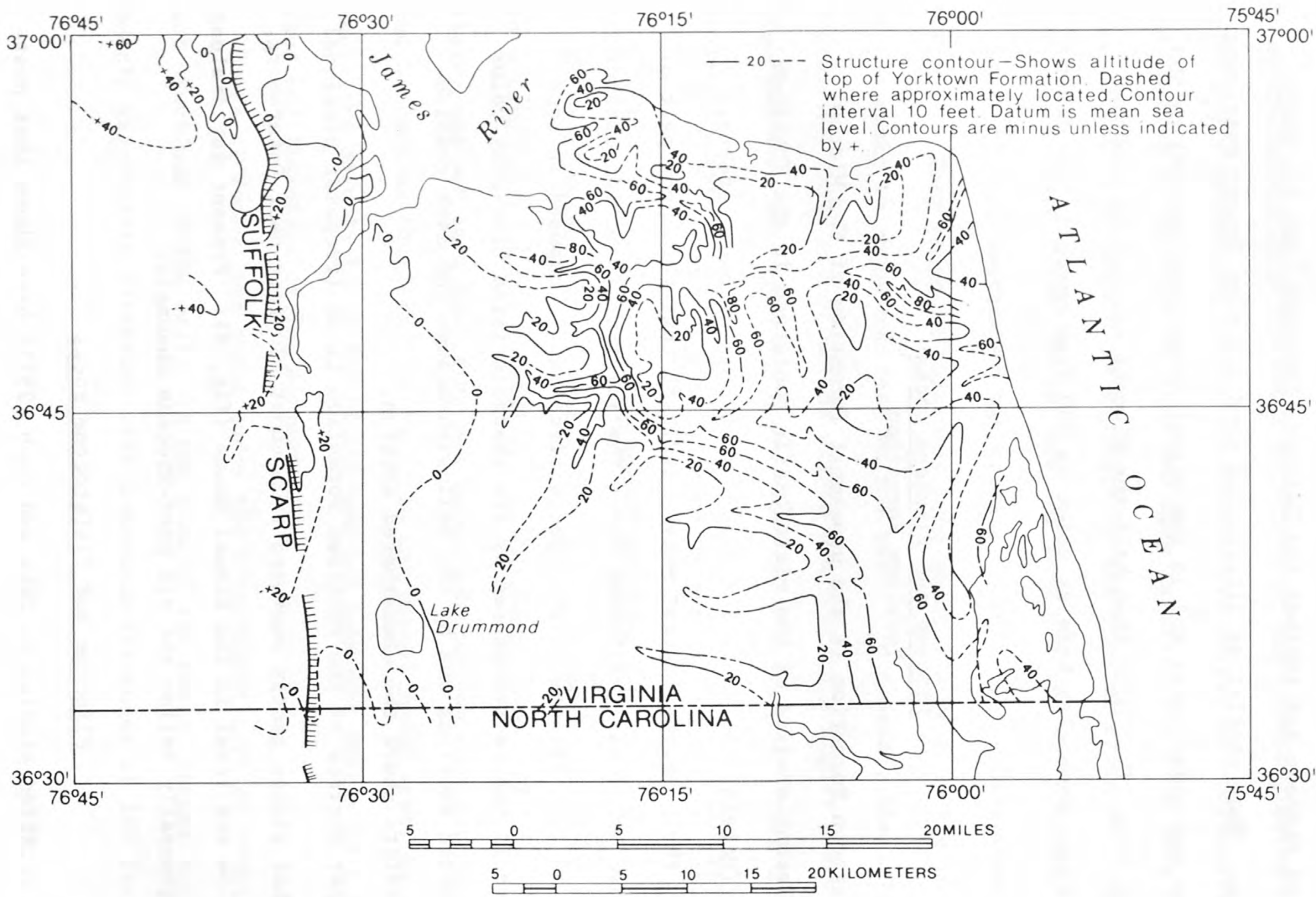


Figure 8.--Topography of top of Yorktown Formation, southeastern Virginia. After Oaks and Coch (1973).

showing post-Yorktown geologic formations as used by Oaks and Coch (1973). Detailed studies have not been made of the North Carolina part of the swamp, but it is assumed that the geology is similar to the Virginia section. Table 2 lists post-Yorktown formations as used by Oaks and Coch (1973) in southeastern Virginia. Only those formations that underlie the Dismal Swamp are discussed in this report.

Sedley Formation

The Sedley Formation probably originally extended from the present coastline to the vicinity of Petersburg, Va. However, subsequent erosion has removed the Sedley from several places, especially east of the Suffolk Scarp, where it is present only as thin, isolated remnants that extend less than a mile eastward from the scarp in the subsurface (Oaks and Coch, 1973, p. 51). The age of the Sedley Formation is uncertain, but it is probably late Pliocene and/or early Pleistocene. The Sedley unconformably overlies the Yorktown Formation and is overlain by younger formations in several small areas in the western part of the Dismal Swamp. (See figs. 4 and 6, sections EE-EE' and HH-HH'.)

Windsor Formation

The Windsor Formation extends from the Surry Scarp eastward to the Suffolk Scarp. (See fig. 3.) It is thickest (as much as 35 feet) near the Suffolk Scarp, where it unconformably overlies remnants of the Sedley Formation or the Yorktown Formation. The Windsor Formation, of middle Pleistocene age, terminates to the east rather abruptly at the Suffolk Scarp. (See figs. 4, 5, & 6.) There is evidence that a protracted period

Table 2.--Descriptions of units (modified from Oaks and Coch, 1973, Plate 2).

Holocene	<u>Qhu-Undivided sediments</u> Beach, marsh, swamp, and stream sediments.
Pleistocene	<u>Qsb-Sand Bridge Formation</u> Upper member: (faciesdesignated by numbers in geologic sections) (1) Estuarine and tidal-channel: clayey-sand facies. (2) Fluvial and lagoon: silty-sand facies. (3) Marsh and tidal-flat: silty-clay facies. (4) Barrier: sand-ridge and mud-flat complex. Lower member: Coastal sand, silty sand, and clayey sand (exposed only as narrow bands along streams; combined with upper member on map, but shown separately in cross sections as Qsbl). <u>Ql-Londonbridge Formation</u> Beach and dune sand and gravel in Oceana Ridge; lagoon clayey silt westward nearly to Suffolk Scarp. <u>Qn-Norfolk Formation</u> Upper member: (facies designated by numbers in geologic sections) (1) Beach and dune: coarse-sand facies. (3) Marsh and lagoon: silty-clay facies. (4) Brackish-marine: silty-sand facies. (5) Shoreface: medium-sand facies. (6) Shelf: silt facies. (7) Shelf: sand facies. (8) Shelf: fine-sand facies. Lower member: Beach sand and gravel (combined with upper member). <u>Qgb-Great Bridge Formation</u> Upper member: (facies designated by numbers in geologic sections) (1) Beach sand and gravel near present coast. (2) Lagoon silty clay in west. Lower member: Fluvial sand, gravel, and freshwater peat along channels in top of Yorktown Formation. <u>Qw-Windsor Formation</u> Upper member: Lagoon silty sand Lower member: Beach-and nearshore-marine sand and gravel.
Pliocene and/or Pleistocene	<u>Qts-Sedley Formation</u> Marine and estuarine clay, silt, and fine sand.
Miocene and Pliocene	<u>Ty-Yorktown Formation</u> Fossiliferous marine clay, silt, sand, and coquinite.

of subaerial erosion followed deposition of the Windsor Formation. This erosion and strong headland retreat of the Suffolk Scarp caused by wave action during submergence probably removed all traces of the Windsor Formation east of the scarp.

Great Bridge Formation

The Great Bridge Formation overlies the Yorktown Formation from the Deep Creek Swale eastward to the ocean. Its age is probably late Pleistocene, but exact dating is uncertain, as radiocarbon dating of wood fragments in the formation shows that its age is greater than the age limit (47,000 years) of radiocarbon dating.

Norfolk Formation

The Norfolk Formation unconformably overlies the Yorktown Formation beneath most of the Dismal Swamp, the southern part of the Deep Creek Swale, and the northern segment of the Fentress Rise. (See figs. 4, 5, and 6.) It probably plays an important role in the hydrology of the swamp. (See hydrology section.) In part of the Deep Creek Swale and the Fentress Rise, the Norfolk Formation conformably overlies the Great Bridge Formation. Its average thickness is 30 feet at the Fentress Rise, and it thins both to the east and the west (Oaks and Coch, 1973, p. 72). The present topography east of the Suffolk Scarp is a subdued reflection of the top of the Norfolk Formation (fig. 9). Norfolk sediments are unconformably overlain by the Londonbridge Formation in the Deep Creek Swale, in parts of the Dismal Swamp and in northern segments of the Fentress Rise, and by the Sand Bridge Formation in westernmost Dismal Swamp. Sediments of Holocene age overlie the Norfolk Formation, where other post-Norfolk units are absent (Oaks and Coch, 1973, p. 73).

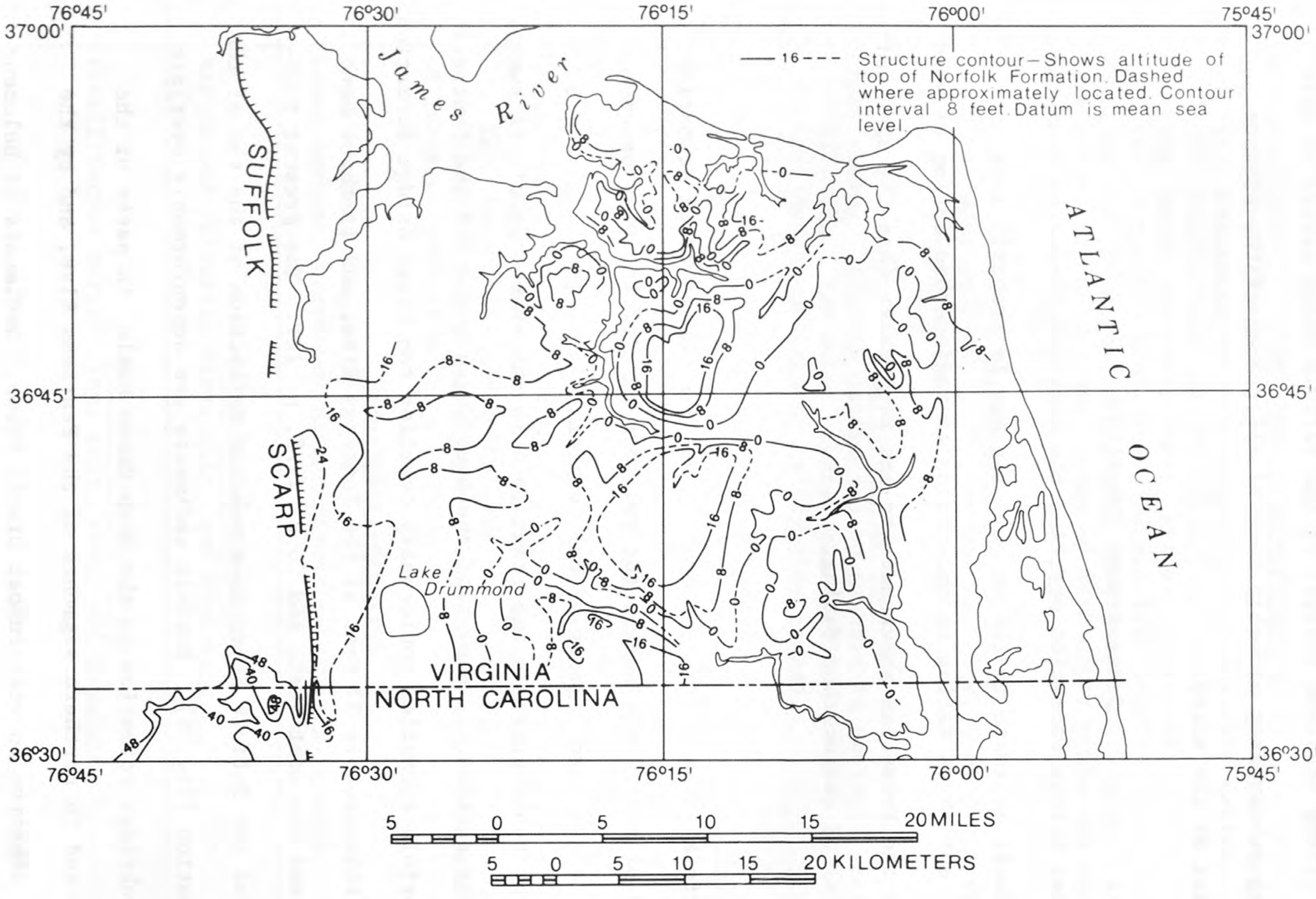


Figure 9.--Topography of top of Norfolk Formation. After Oaks and Coch (1973).

The Norfolk Formation is composed of a lower member and a highly variable upper member. The lower member consists of bluish-gray subangular to subrounded fine to very coarse quartz sand containing from a trace to 20 percent fine pebble gravel. The lower member is present through virtually the entire area of the Dismal Swamp and is a useful stratigraphic marker (Oaks and Coch, 1973, p. 73).

The upper member of the Norfolk Formation consists of eight facies. (See table 2.) The coarse-sand facies (Qn1) is present under the Suffolk Scarp and the extreme western part of Dismal Swamp, where it is the principal aquifer for domestic and other small to moderate, 5 to 20 gpm (gallons per minute), water supplies. The coarse-sand facies grades eastward under Dismal Swamp into the medium-sand facies (Qn5). (See figs. 4, 5, and 6.) The medium-sand facies underlies most of the Dismal Swamp and, in turn, grades into the fine-sand facies (Qn8) beneath most of the area east of the Dismal Swamp (fig. 10). The coarse-sand facies (Qn1) of the upper member crops out at altitudes between 25 and 70 feet in a belt less than a mile wide that trends north-south along the Suffolk Scarp (fig. 10) (Oaks and Coch, 1973, p. 73). It ranges in thickness from a veneer to 50 feet or more in undissected parts of the Suffolk Scarp. These three facies (Qn1, Qn5 and Qn8) of the Norfolk Formation probably play an important role in the hydrology of the Dismal Swamp. (See hydrology section.)

Londonbridge Formation

The Londonbridge Formation occurs in the subsurface beneath most of Deep Creek Swale and the eastern part of the Dismal Swamp. It also occurs as small remnants in breaches of the Fentress Rise, where the Norfolk

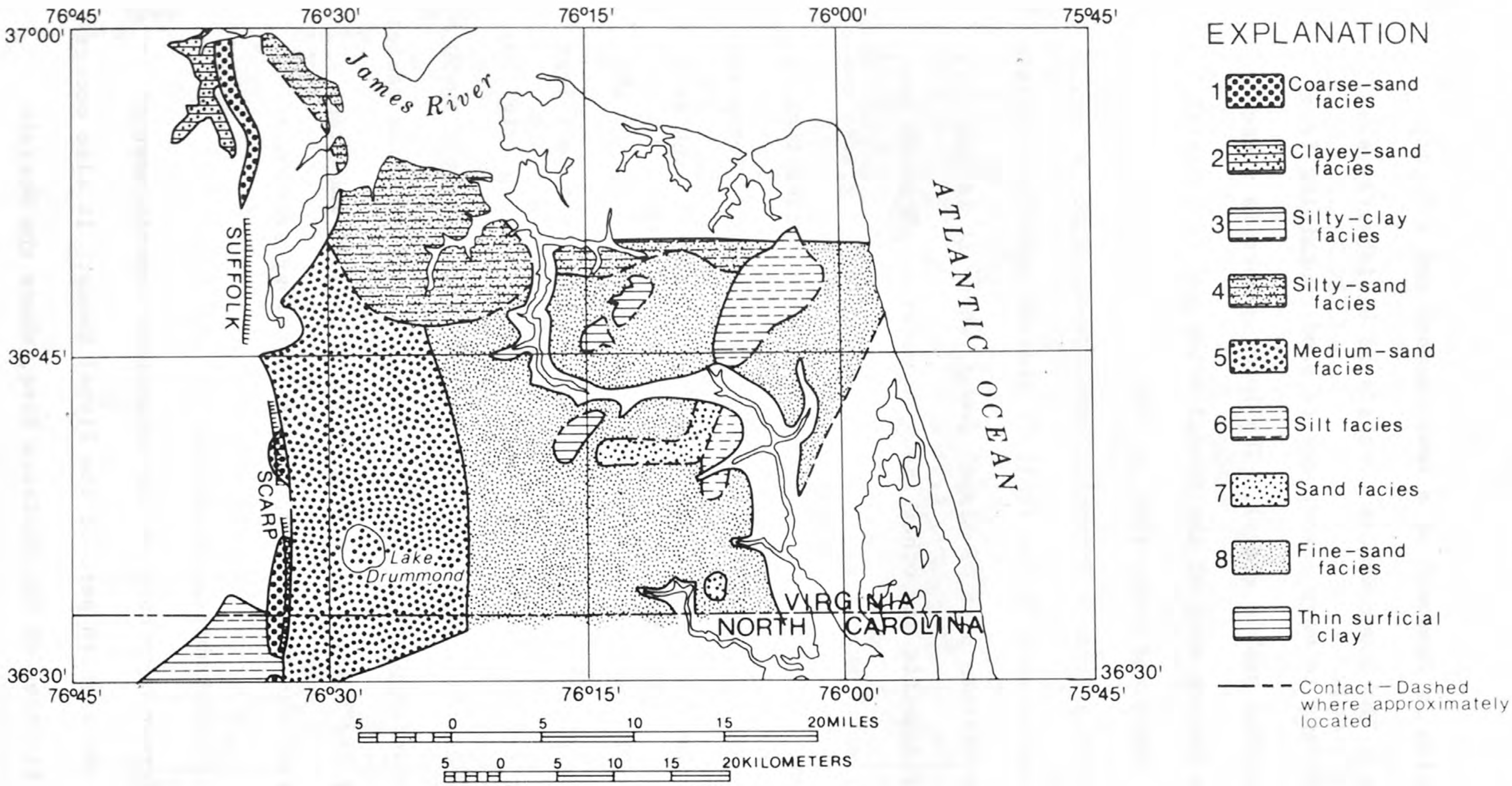


Figure 10.--Distribution of major sediment facies of Norfolk Formation, southeastern Virginia. After Oaks and Coch (1973).

Formation is high in Deep Creek Swale, and beneath most of the western part of Dismal Swamp. In the area of the Dismal Swamp, the Londonbridge Formation is a clayey silt that unconformably overlies the Norfolk Formation. The Londonbridge underlies the Sand Bridge Formation except along pre-Holocene channels in the Dismal Swamp where both formations are missing.

Sand Bridge Formation

The Sand Bridge Formation is composed of a lower member of homogeneous sand and an upper member that is variable in some areas but is fairly homogeneous in the Dismal Swamp area. The lower member forms a blanket of silty sand 2 to 8 feet thick beneath low areas east of the Suffolk Scarp and pinches out near the scarp and the Fentress Rise. It generally overlies the Londonbridge Formation, where the Londonbridge is present, or unconformably overlies the Norfolk Formation.

The upper member is a sheetlike deposit, averaging 2 to 6 feet in thickness in much of the area of the Dismal Swamp. The upper member overlaps the lower, so as to overlie the Londonbridge Formation in the southern part of Dismal Swamp and the Norfolk Formation along the western part of Fentress Rise and the western part of Dismal Swamp. Beneath the swamp and Deep Creek Swale, the upper member of the Sand Bridge Formation is composed of silty clay. (See fig. 11.) (Oaks and Coch, 1973, p. 94.) In most places, the silty clay is very light gray to dark gray, has a blockly, massive texture, and is cohesive.

The Sand Bridge Formation is late Pleistocene in age and is at least as old as mid-Wisconsin. It probably belongs to the same major submergent

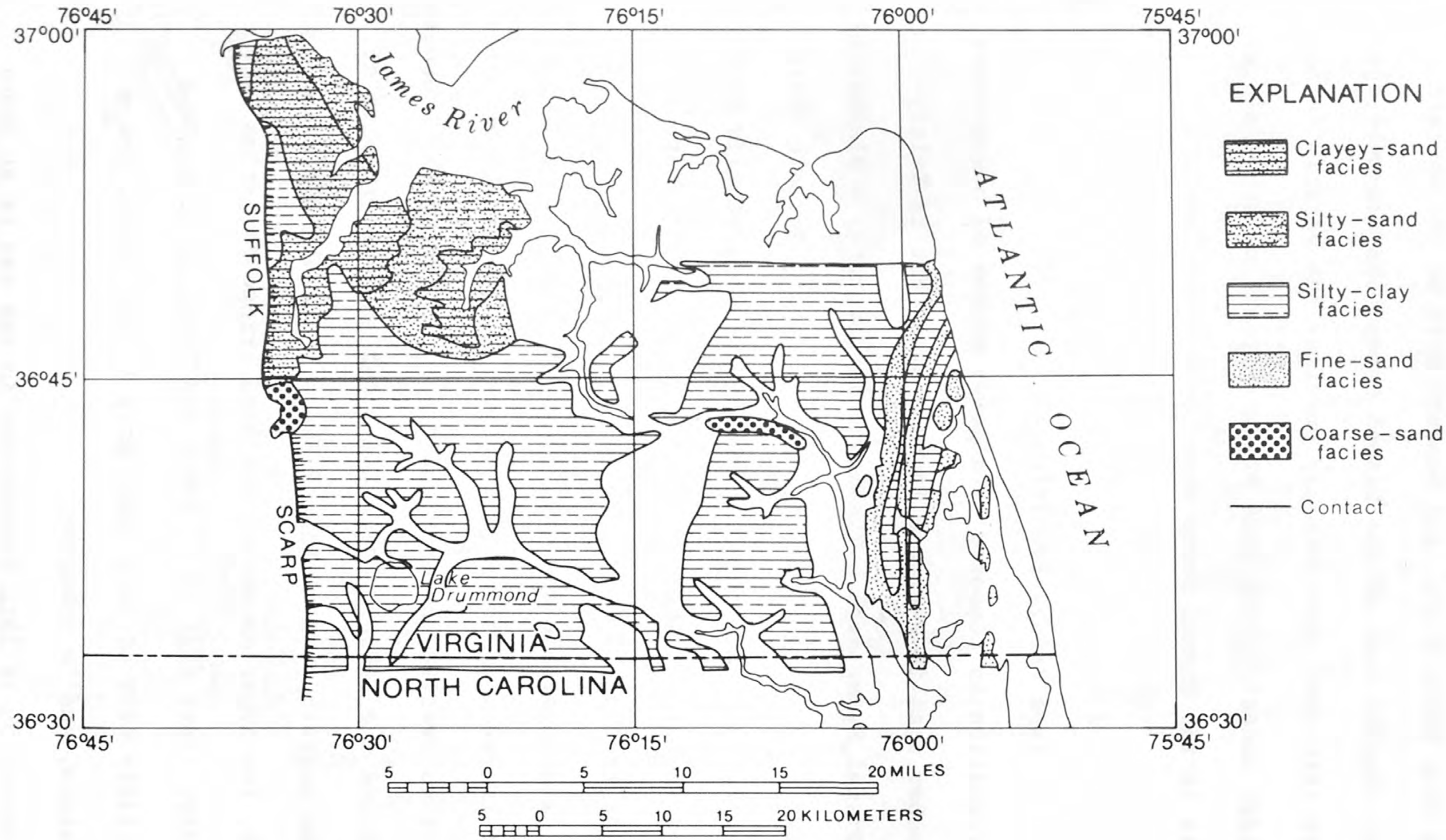


Figure 11.--Distribution of major sediment facies of upper member of Sand Bridge Formation, southeastern Virginia. After Oaks and Coch (1973).

episode as the Londonbridge Formation. A surface drainage pattern was eroded into the surface of the Sand Bridge or older formations before the emplacement of Holocene deposits. (See fig. 12.)

Holocene rocks

Holocene rocks in the Dismal Swamp consist of a basal inorganic layer, generally not more than 1 foot thick, and the overlying organic peat. The inorganic layer, which is commonly found only beneath thick peat layers, consists of white angular fine to medium sand presumably of fluvial origin. It is overlain by soft light-blue clay containing organic fragments and fresh water microfossils (Oaks and Coch, 1973, p. 105). The Dismal Swamp Peat is "a soft, wet, sponge-like mass of decaying organic material, chiefly leaves, twigs, rooted stumps and fallen logs" (Oaks and Coch, 1973, p. 106). Its color ranges from dark brown near the surface to brownish-black at depth. The thickness is highly variable within the swamp and ranges from a featheredge to more than 12 feet. The surface of the peat slopes gently eastward from an altitude of 25 feet at the base of the Suffolk Scarp to 15 feet along the west side of the Deep Creek Swale. Natural surface drainage is poor, and there are no well-developed streams.

The Dismal Swamp Peat is entirely of fresh water origin. The oldest radiocarbon age of five specimens of the peat is 8900 ± 160 years B.P. (before present) (Oaks and Coch, 1973, p. 106).

Radiocarbon ages of freshwater peat found between 70 and 89 feet below present sea level in the mouth of Chesapeake Bay ranged between 8135 ± 160 and 15,280 ± 200 years B.P. (Harrison and other, 1965, p.217-221).

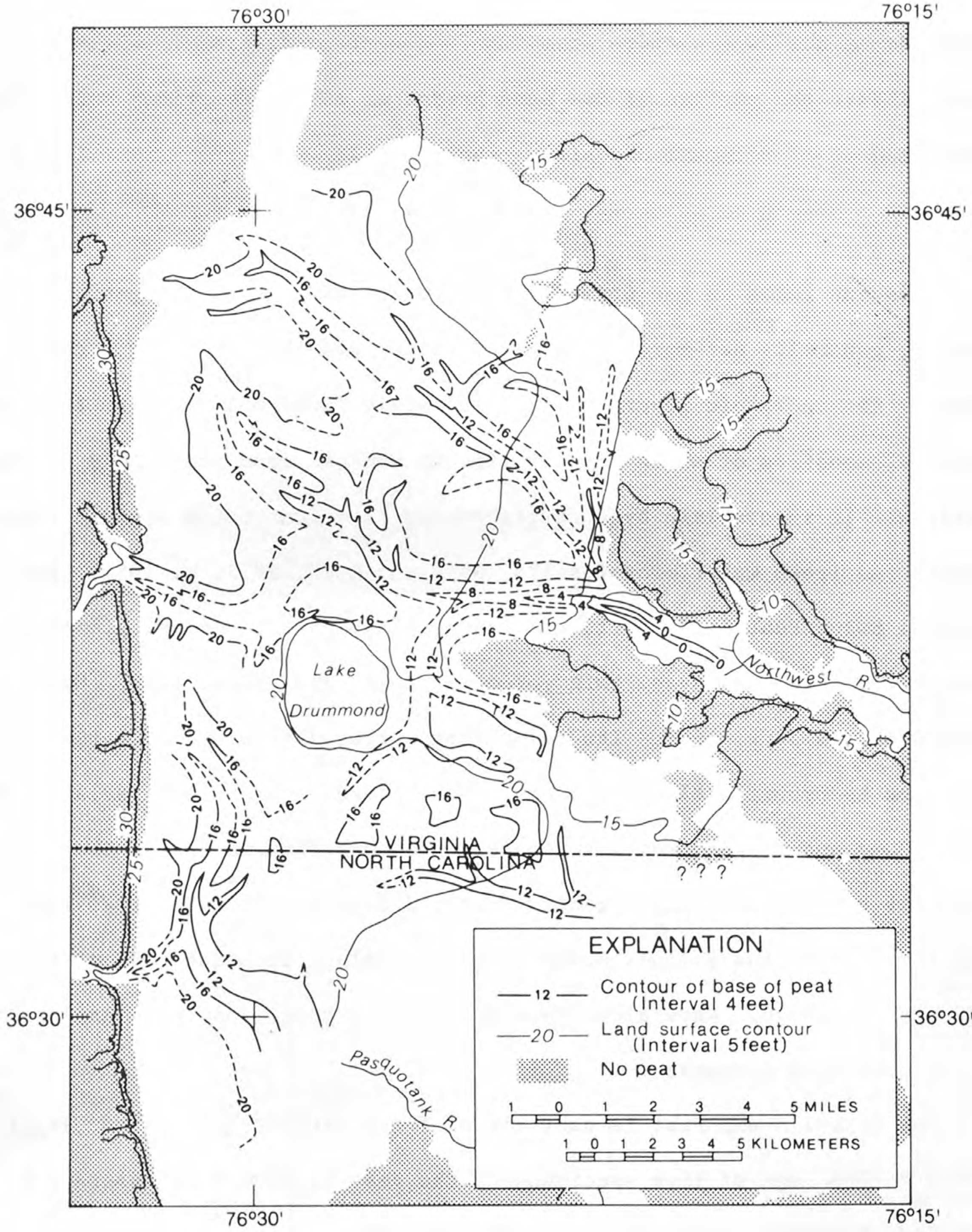


Figure 12.--Configuration of base of Dismal Swamp Peat, southern coastal Virginia and adjacent North Carolina. After Oaks and Coch (1973).

Therefore, the oldest known peat in the Dismal Swamp began forming while sea level was 60 to 70 feet or more below its present level. Sea level probably has not been significantly higher since that time than it is at present.

HYDROLOGY

The hydrology of the Dismal Swamp area has played an important role in the formation of the swamp and will obviously play an important role in its future. The climate, topography, and geology of the area, as previously discussed, are principal factors controlling the hydrology.

Theories on the Origin and Development of Dismal Swamp and Lake Drummond

The basic hydrologic requirements for the formation and development of large peat swamps are a humid climate with reasonably uniform rainfall throughout the year and restricted drainage, both surface and subsurface. The Dismal Swamp has a warm humid climate, an average annual rainfall of 45 to 50 inches, and an average annual temperature of 59° to 60°F. Average monthly rainfall ranges from 3.20 inches in October to 6.73 inches in July. Average monthly temperature ranges from 41.2°F in January to 78.8°F in July.

The thick, rather impervious clay of the Miocene and Pliocene Yorktown Formation, which underlies the entire area (figs. 4, 5, 6, and 8), is an effective seal preventing either downward or upward movement of water. The Miocene and Pliocene sediments constitute a confining bed, and water in the underlying Upper Cretaceous is under sufficient head to flow at the land surface. Therefore, if appreciable exchange of water could occur between the Upper Cretaceous aquifers and the swamp, it would be upward into the swamp rather than downward to the Upper Cretaceous aquifers.

The pre-peat surface is fairly flat. (See fig. 12.) Surface drainage is restricted by the sharp rise of the Suffolk Scarp on the west and by the Fentress Rise on the east. To the north, the flat surface of the Churchland Flat inhibits surface flow, and the flat gradient (see fig. 2) to the south also inhibits flow. Most surface drainage from the pre-peat surface of the Dismal Swamp area was apparently to the east via the ancestral Northwest River, which flowed through a gap in the Fentress Rise, and to the southeast via the Pasquotank River (fig. 12).

The general hydrologic conditions necessary for the formation of a swamp existed in the Dismal Swamp area before peat began to form. However, normal dendritic stream drainage patterns were incised on the Sand Bridge Formation before the peat began to form about 9,000 years ago. (See fig. 12.) Studies by Whitehead (1972, p. 301) show that the peat began to form in topographic lows along the stream channels. This, plus the fact that the stream channels had formed, indicates that there was not area-wide ponding in the Dismal Swamp when the peat began to form.

As previously stated, analyses of freshwater peat from the mouth of Chesapeake Bay indicate that sea level was 60 to 70 feet or more below present sea level. Therefore, the following questions arise: (1) Why did downcutting of the drainage channels of the ancestral Northwest River west of and through the Fentress Rise cease, and (2) why didn't peat form in Deep Creek Swale? This swale is in a topographic setting similar to the swamp, and surface altitudes are lower than many areas of Dismal Swamp that are covered with peat.

A plausible explanation may be found in the geology of the region, as interpreted by Oaks and Coch (1973). Figures 4, 5, and 6 show that the permeable coarse to medium sand facies of the Norfolk Formation crop out on the Suffolk Scarp (Oaks and Coch, 1973, p. 3) and dip under the Dismal Swamp. East of the swamp and under Deep Creek Swale the Norfolk Formation grades into facies that are much less permeable (fig. 4), and these facies act as a barrier to further eastward movement of water through the Norfolk Formation. Figures 4, 5, and 6 indicate that the Sand Bridge Formation, which acts as a confining layer, is absent from most of the area of the

swamp. However, figure 11 shows that the Sand Bridge actually overlies the Norfolk Formation except along topographic lows, such as broad stream channels.

Before development of the drainage pattern on the surface of the Sand Bridge Formation (fig. 12) the water in the Norfolk Formation was under artesian pressure caused by recharge in the outcrop area on top of the Suffolk Scarp but was trapped by the fine sand facies of the Norfolk Formation to the east and by the overlying silty clay facies of the Sand Bridge. As downcutting of the broad shallow valleys of the drainage system proceeded, the silty clay confining layer of the Sand Bridge was removed, thereby allowing upwelling of water from the medium sand facies of the Norfolk Formation. The addition of this water in an area of poor surface drainage may have been sufficient to trigger the accumulation of peat.

The ground water, although a small percentage of the total water budget of the area, would be especially significant because it would be a relatively constant quantity and would keep the area wet even during dry periods. Once started, the formation of peat would be self perpetuating. As the peat accumulated, it would tend to block the stream channels, slow surface drainage, cause local ponding, and hold the upwelling ground water. The ground water would be distributed by artesian pressure and by capillary action, and the area of peat would gradually spread to cover the interfluve areas.

The origin of Lake Drummond is not known. Whitehead (1972, p. 314) states that C^{14} (radiocarbon) dates from the base of the gel-mud in the lake indicate that the lake is a comparatively young feature of the swamp

(originating about 4,000 years ago), whereas the peat began to form about 9,000 years ago. The lake has no apparent relation to peat thickness or pre-peat topography (fig. 12), nor does it seem to be the remnant of a larger body of water.

Whitehead (1972, p. 314) states that the most likely explanation for the lake, based on evidence at hand, is a deep burn about 4,000 years ago, when the peat layer was thinner. Subsequent wave erosion of unburned peat would tend to smooth shoreline irregularities and account for the present almost circular shape of Lake Drummond.

It is possible that upward flow of water from the Norfolk Formation into the bottom of the lake has helped to keep fine sediments from settling in the bottom of the lake. The upwelling water would help to keep bottom sediment in suspension and allow sediment to float into the surrounding swamp when the lake extended beyond its normal shoreline. This would partly account for the clean sand bottom that was reported to exist in most of the lake before ditches were dug from the lake into the swamp. Part of the bottom of the lake has been covered by sediment, but approximately 30 percent is still sand (M. K. Garrett, oral commun., 1973).

Ground Water-Surface Water Relationships

Ground water and surface water are more closely interrelated in a swamp than in most environments. The dividing line is not always well defined. Ground water out of sight below organic litter becomes surface water when the litter is compressed by a footstep. As suggested previously, the formation of the swamp may have been initiated by seepage of water from the Norfolk Formation. This seepage has probably continued, in

modified form, to the present day. Withdrawal of water from the Norfolk Formation through wells along the Suffolk Scarp has reversed the natural potentiometric gradient in the Norfolk aquifer in some areas (fig. 13), and this may at times remove water from the swamp.

Ditches designed to remove surface water and lower the water table in the peat often intersect underlying aquifers and may deplete ground-water resources if heads in the aquifers are above water levels in the dtiches. If heads in the aquifers are below water levels in the ditches, surface water may drain into the aquifers. Rain on and near the swamp may stand on the surface before soaking into the peat and underlying formations. It then moves laterally toward areas of discharge, such as canals or ditches, and becomes surface water again.

An understanding of the interrelationships between surface water and ground water is necessary for an understanding of the hydrology of Dismal Swamp. Especially significant is the present hydrologic connection between the Norfolk Formation and the peat.

Modifications of the Hydrology

Many modifications have been made to the surface-water and ground-water systems of the swamp. The construction of canals and ditches has made the most change in the hydrology. Starting in pre-revolutionary days, ditches were dug to drain land for farming, to provide access for water-borne transportation, or to float timber from the swamp. Many wells along the Suffolk Scarp draw water from the Norfolk aquifer (water-bearing sand in the Norfolk Formation) that underlies the swamp, and this has reversed the direction of ground-water movement (fig. 13). Ground-water withdrawal from the Norfolk Formation in areas adjacent to the swamp

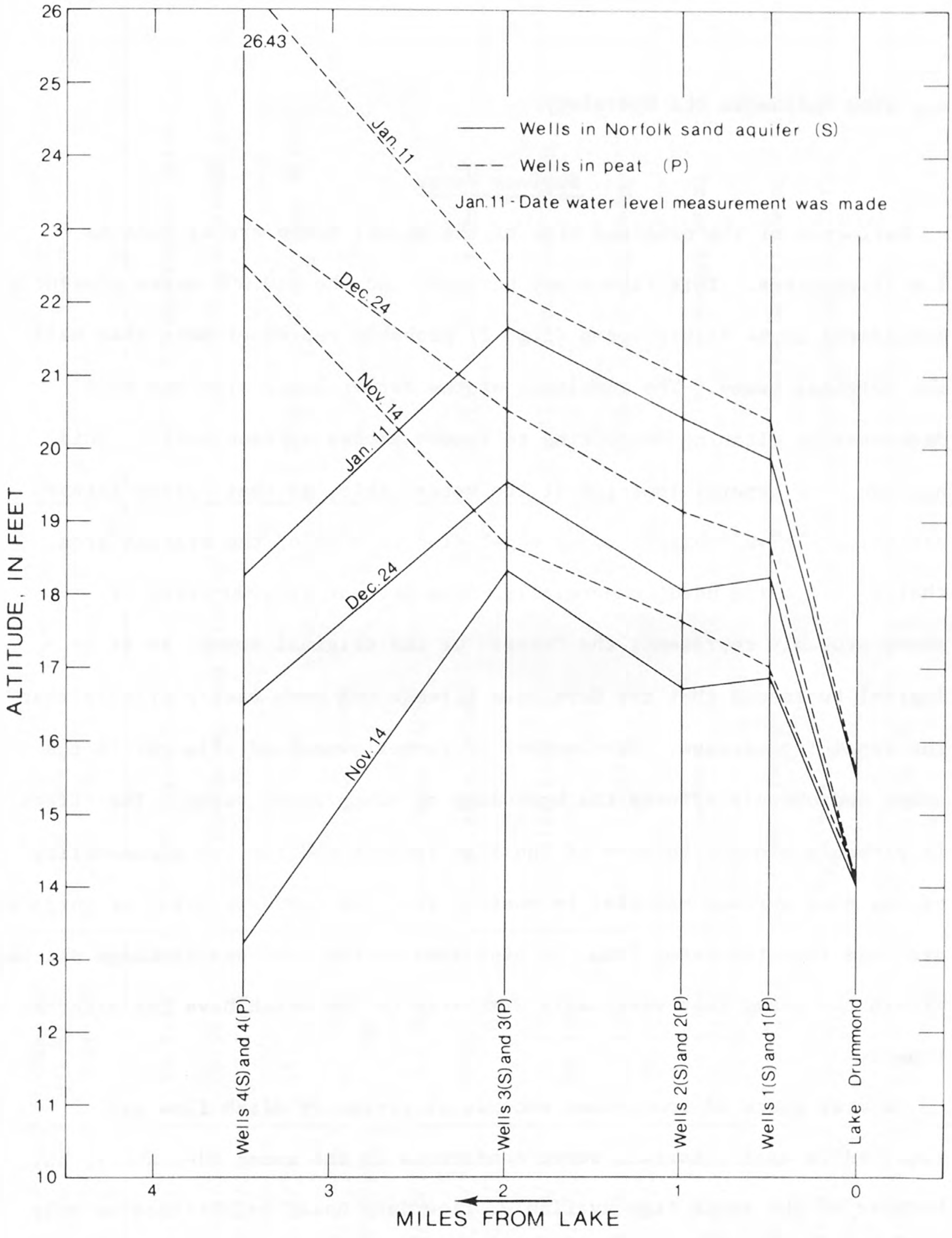


Figure 13.--Profiles of water levels near Washington ditch. Data from Main (1971). Data year late 1970 and early 1971.

may also influence the hydrology.

Surface Water

Estimates of the original size of the Dismal Swamp are as much as 1 million acres. This figure may be high, and the 210,000 acres presently considered to be viable swamp (fig. 2) probably represent more than half the original swamp. The remainder of the former swamp area has been developed by ditching and diking to remove excess surface water. This has caused a general lowering of the water table, so that upland forest assemblages have replaced swamp vegetation in much of the drained area that is not being used commercially. The present 210,000 acres of swamp probably represents the "heart" of the original swamp, as it is logical to assume that the developed acreage was more easily drained than the remaining acreage. Development of former swampland adjacent to the swamp undoubtedly affects the hydrology of the present swamp. The effect is probably minimal because of the flat terrain and the low permeability of the near surface material in most of the area. Modification of surface drainage into the swamp from the high land to the west and drainage ditches within the swamp that eventually discharge to the ocean have the greatest impact.

Several years of continuous records of stream or ditch flow are required to assess surface-water conditions in the swamp adequately, but, because of the short time available, flow data could be obtained on only two occasions--early July, and late September, 1973. Numerous sites were visited, and, where possible, estimates of flow were made (table 3). The sites where flow estimates were made are shown on figure 14. Where "no

Table 3. Estimates of surface-water flow in Dismal Swamp area.

Site Number (fig. 14)	Date	Estimated discharge (cfs)	Site	Remarks
1	7/10/73	No flow	White Marsh Road	Inflow to Washington Ditch
2	7/11/73 9/27/73	0.98 No flow	Cypress Swamp near Cypress Chapel, Va.	At site of discontinued gage
3	7/10/73	<5	Cypress Swamp	Inflow to Washington Ditch
4	7/11/73 9/26/73	0.1-0.2 0.04	Washington Ditch	
5	9/26/73	0.2-0.3	Washington Ditch	
6	7/11/73 9/26/73	5-10 0.4	Washington Ditch	Inflow to Lake Drummond
7	7/10/73 9/27/73	No flow No flow	Hoosier Road	Inflow to Railroad Ditch
8	7/10/73 9/27/73	No flow No flow	Hoosier Road	Inflow to Dismal Swamp
9	7/10/73 9/27/73	No flow No flow	Moss Swamp	Inflow to Dismal Swamp
10	7/10/73	0.02	No Name Swamp	Inflow to Dismal Swamp
11	7/10/73 9/27/73	13 0.002	Taylor Swamp	Inflow to Hamburg Ditch
12	9/27/73	0.2	Hamburg Ditch	

Table 3. Estimates of surface-water flow in Dismal Swamp area.

Site Number (fig.14)	Date	Estimated Discharge (cfs)	Site	Remarks
13	9/27/73	0.07	Sherril Ditch	Flow south to Hamburg Ditch
14	9/27/73	0.3	Hamburg Ditch	Outflow from Dismal Swamp
15	9/27/73	0.2	Sherril Ditch	Flow north to Corapeake Ditch
16	9/27/73	1	Newland Drainage Canal	Outflow from Dismal Swamp
17	7/10/73 9/27/73	30-35 2	Newland Drainage Canal	
18	9/27/73	2	Newland Drainage Canal	
19	9/27/73	Slight	Pasquotank River	Flow upstream - tidal
20	7/10/73	15-60	Pasquotank River	Tidal
21	7/10/73	No flow	Unnamed drainage ditch	Inflow to Dismal Swamp Canal
22	7/10/73	No flow	Unnamed drainage ditch	Inflow to Dismal Swamp Canal
23	7/10/73	0.8	Unnamed drainage ditch	Inflow to Dismal Swamp Canal
24	7/10/73	0.5	Unnamed drainage ditch	Inflow to Dismal Swamp Canal
25	7/10/73	< 0.1	Unnamed drainage ditch	Inflow to Dismal Swamp Canal
26	7/11/73	No flow	East Ditch	Interior drainage
27	7/11/73	0.04	East Ditch	Interior drainage
28	7/11/73	5	Hudnell Ditch	Flow to East Ditch

Table 3. Estimates of surface-water flow in Dismal Swamp area.

Site Number (fig.14)	Date	Estimated Discharge (cfs)	Site	Remarks
29	7/11/73	5-10	Cross Ditch	Flow to East Ditch
30	7/11/73	30-50	East Ditch	Inflow to Lake Drummond
31	7/11/73	20	Jericho Ditch	Flow to south
32	7/11/73	20-30	Jericho Ditch	Inflow to Lake Drummond
	9/26/73	1		
33	7/11/73	<0.1	Jericho Lane Ditch	Outflow to Shingle Creek
34	7/11/73	3-5	Jericho Ditch	Outflow to Shingle Creek
	9/26/73	1		
35	9/27/73	<0.1	Corapeake Ditch	Outflow from Dismal Swamp to Dismal Swamp Canal
36	9/27/73	0.5	Corapeake Outfall	Outflow from Dismal Swamp to Dismal Swamp Canal
37	7/18/73	72	Feeder Ditch	Measured flow, one wicket gate open
38	7/10/73	-	Dismal Swamp Canal at Deep Creek	Leakage and one wicket gate open
	9/28/73	-		Leakage; no wickets open
39	7/10/73	10	Dismal Swamp Canal at South Mills	Leakage; no wickets open
	9/27/73	-		Leakage; no wickets open

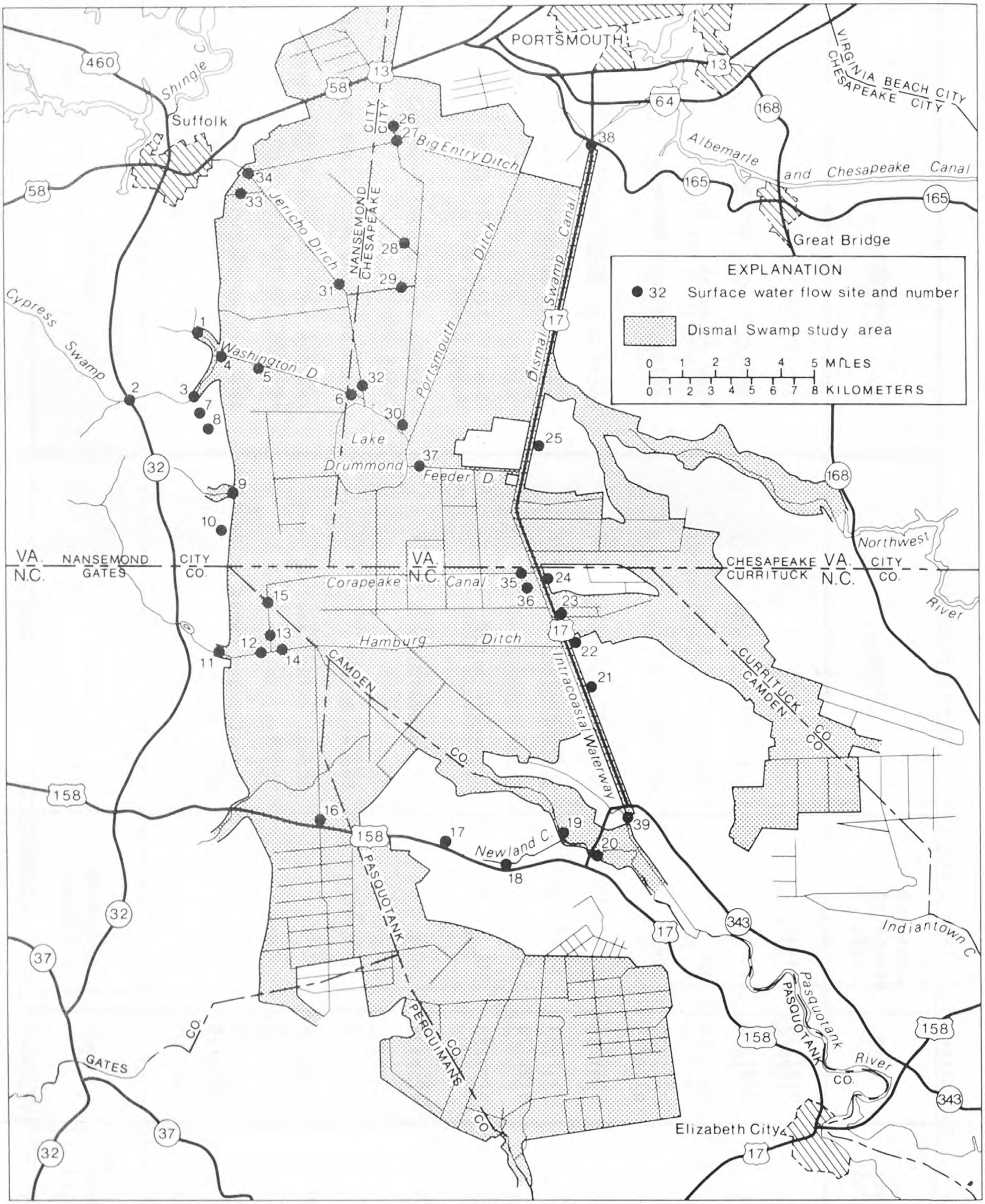


Figure 14.--Dismal Swamp study area showing where surface water flow estimates were made.

flow" is shown in table 3, a dry section of channel was observed. The estimates given in table 3 show that flow varies considerably. The estimates were made during the mid and late parts of the growing season. During other parts of the year, considerably different flow rates would probably have been observed. Figure 15 illustrates the variability in flow recorded at the gaging station on Cypress Swamp at Cypress Chapel (site 2 in table 3). It shows that during the summer, average surface inflow to the Dismal Swamp from uplands west of the Suffolk Scarp is probably very small but that average winter inflow to the swamp is probably three or four times as great.

Inflow

Surface inflow to Dismal Swamp occurs through numerous small streams and sloughs that enter from the Suffolk Scarp on the west. Most inflow enters the swamp through two watercourses, Cypress Swamp and Hamburg Ditch. Only a few discharge measurements have been made on Hamburg Ditch, but a continuous-record stream-gaging station was maintained on Cypress Swamp from October 1953 to September 1971 (U. S. Geological Survey, 1972).

The gage, Cypress Swamp near Cypress Chapel, was on State Highway 32, about 2 miles upstream from the Suffolk Scarp. The drainage area above the gage is 23 sq mi or 61 percent of the 38 sq mi of upland reported by Main 1971 (p. 7) to drain into Lake Drummond.

Streamflow records for Cypress Swamp show that runoff varies greatly from season to season and from year to year. (See fig. 15.) The minimum consecutive 12-month discharge averaged 9.32 cfs (cubic feet per

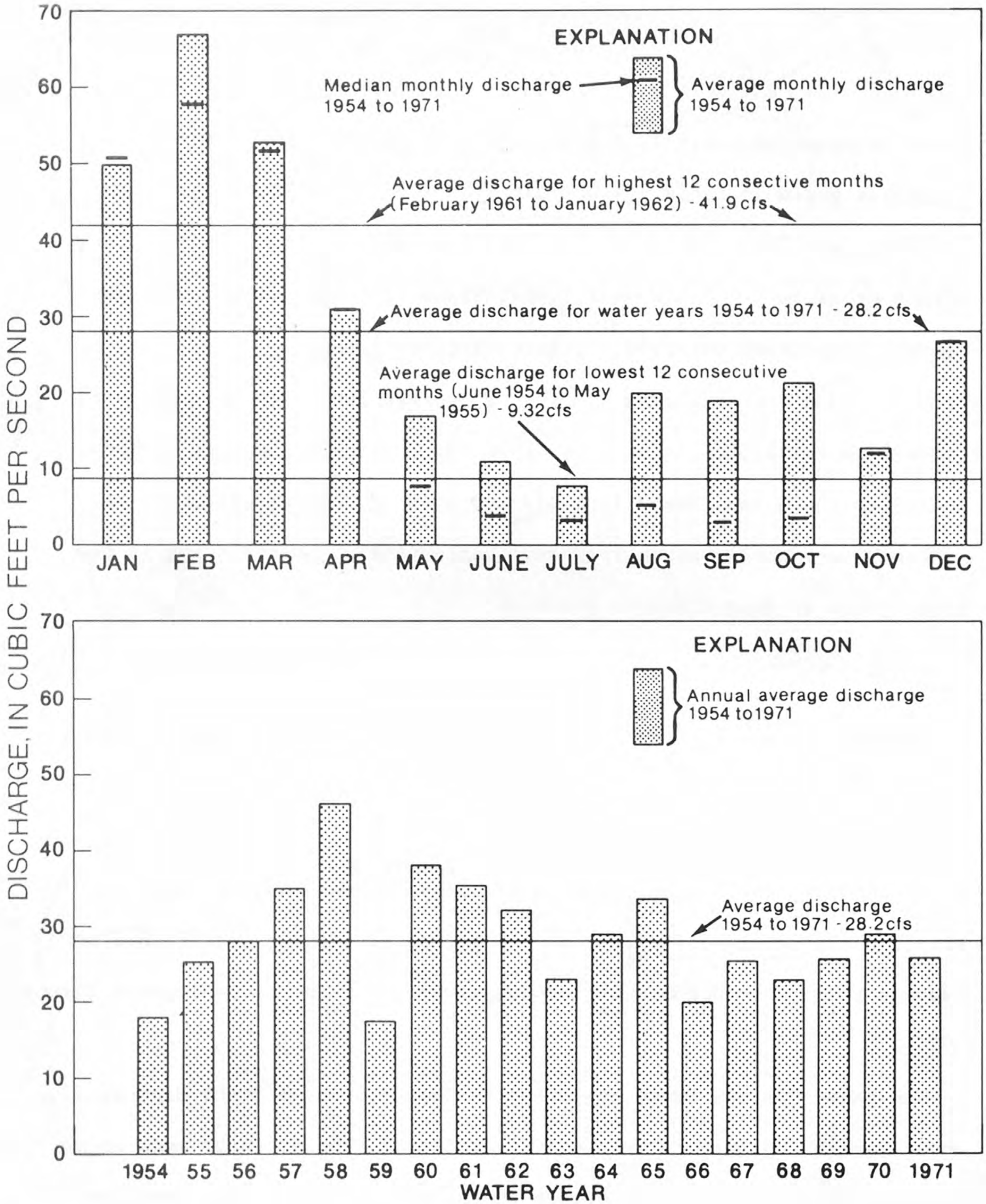


Figure 15.--Discharge of Cypress Swamp at Cypress Chapel, Va.

second), or 33 percent of the long-term average of 28.2 cfs. The maximum consecutive 12-month discharge was 41.9 cfs, or 149 percent of the long-term average.

Runoff measured at the Cypress Swamp gage is probably a good indication of runoff to Dismal Swamp from the upland area west of the Suffolk Scarp. However, study of aerial photographs shows that the other major inlet, Hamburg Ditch, runs through the swamp and drains an unknown amount of water into the Pasquotank River. Little, if any, of the runoff from the upland area drained by Hamburg Ditch is retained in the swamp or enters Lake Drummond.

About 113 sq mi of upland area is a potential source of inflow to the swamp. Using Cypress Swamp records as a base and using median flow values rather than average, this upland area could furnish about 95,000 acre-feet, about 31,000 mg (million gallons) of inflow per year. About 90 percent of this inflow could be expected during November through April, the remainder during May through October.

Presently, only about 13,100 mg of upland flow enters Lake Drummond annually (Main, 1971, p. 7). Approximately another 18,000 mg that is potentially available to the swamp is intercepted and drained away by the ditches in the southern part of the area.

Drainage ditches along the Suffolk Scarp have not affected the quantity or pattern of surface-water flow from the scarp into Dismal Swamp, except as noted. It is likely that the streams and sloughs have always dried up during even moderate droughts.

Outflow

The principal outflow of surface water from Dismal Swamp occurs through Dismal Swamp Canal. Other outlets are Jericho, Portsmouth and Hamburg (modified) Ditches (fig. 2). Many ditches within the swamp drain into Lake Drummond, which, in turn, drains to Dismal Swamp Canal through the Feeder Ditch. Jericho Ditch drains both northwest to Shingle Creek and southeast into Lake Drummond. Corapeake, Big Entry, and several smaller ditches drain into Dismal Swamp Canal. Dismal Swamp Canal and most of the ditches in the Virginia part of the study area have water-control structures that can be used to restrict outflow from the swamp; however, many ditches in the North Carolina part do not.

A significant amount of the outflow from the Dismal Swamp is used for operation of the Dismal Swamp Canal Locks at South Mills and Deep Creek. During an average year there is a total of 2,600 lockages. Each lockage requires 1.25 mg of water. Most lockages are during May through October (85 to 90 percent), which is the period of lowest inflow (Main, 1971, p. 5). Main (1971, p. 6) estimates that lockages required about 3,250 mg annually, based on 1.25 mg per lockage, and that total annual water use by the canal was 5,190 mg.

A large amount of water leaves the southern part of the swamp via a network of canals. As pointed out previously, the Hamburg Ditch inflow is channeled through the swamp, eventually to flow into the Pasquotank River. Newland Canal along the south edge of the swamp provides an efficient drainageway for outflow from the heavily ditched southern part.

Outflow rates from the swamp follow general seasonal patterns similar to inflow patterns except for release of water from Lake Drummond to support canal operations. Outflow depends in part on the setting of the individual control structures and to a certain extent on the pattern of precipitation. For example, a heavy rainstorm in one part of the swamp may cause a reversal in the direction of flow in various ditches.

Quality

The surface water in Dismal Swamp is generally of good quality except for very high color (160-1000 units, table 4) and low pH (3.5-6.7, table 4). Although it has a distinct taste, most people consider it potable after they become accustomed to its taste. The low pH tends to inhibit growth of organisms. This characteristic made Dismal Swamp water especially desirable for long ocean voyages in the days of sailing ships. Water samples have been collected from Jericho Ditch near the fire tower, from Lake Drummond, and from Dismal Swamp Canal. Representative analyses are shown in table 4.

Ground Water

Inflow

Ground-water inflow to Dismal Swamp is mostly from the west through the Norfolk aquifer and the surficial sand that overlies the Sand Bridge confining layer. The flow within the Norfolk aquifer has been modified (fig. 13) by withdrawal of water for domestic, stock, and irrigation uses. Ditches that intersect the Norfolk aquifer and are inadequately controlled drain ground water to Lake Drummond or out of the swamp.

Table 4.--Chemical quality of surface water from the Dismal Swamp.
(Results in milligrams per liter except as indicated)

No. used on fig. 2 A	Location of sampling site	Date of collection	Temperature (°C)	Dissolved silica (SiO_2)	Iron (Fe)	Dissolved calcium (Ca)	Dissolved magnesium (Mg)	Dissolved sodium (Na)	Dissolved potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Dissolved sulfate (SO_4)	Dissolved chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphate (PO_4)	Dissolved solids (residue at 180°C)	Hardness: Calcium, magnesium	Hardness: Non-carbonate	Specific conductance (micromhos at 25°C)	Laboratory pH	Color (platinum-cobalt units)
1	Dismal Swamp Canal	7-27-70	-	3.8	0.94	7.2	3.2	15	2.4	10	-	18	23	0.2	0.5	0.69	151	31	23	122	6.7	160
2	Dismal Swamp Canal	7-27-70	-	4.2	.81	5.2	.7	10	5.8	2	-	12	8.7	1.2	.0	4.4	127	16	14	71	4.9	240
3	Lake Drummond	7-28-70	-	7.5	.80	8.0	2.4	6.5	5.3	6	-	16	8.7	.4	.0	5.0	162	30	25	90	5.2	270
3	Lake Drummond	10-02-70	22	.3	.48	5.4	1.1	6.0	1.1	2	-	13	9.5	.1	.8	.37	95	18	16	81	4.6	180
4	Jericho Ditch	4-12-73	-	4.1	.70	1.3	.7	4.2	1.3	0	0	-	6.0	.6	3.0	.20	175	6	6	110	3.5	1000
4	Jericho Ditch	9-28-73	-	6.7	1.9	3.3	1.1	9.5	1.4	0	0	12	17	.4	4.0	.21	232	12	12	146	3.7	1000

Ground water moving laterally through the surficial sand overlying the confining bed seeps into the peat of the swamp. The movement of water through the peat has not been studied. Most of the peat is sapric (well decomposed) (Main, 1971, p. 13) and has a low hydraulic conductivity below the top few inches. However, desiccation cracks extend 1 1/2 to 2 feet below the surface in many parts of the swamp. The extent of interconnection of these cracks has not been studied, but it is likely that the interconnection is fairly good in at least the top 1 to 1 1/2 feet.

When the water table is at or near the surface of the peat, water probably flows through the interconnected desiccation cracks. As the water table is lowered to 1 to 2 feet below the peat surface, the flow probably decreases drastically. Horizontal ground-water movement through the lower parts of the sapric peat is probably very slow. Except near the ditches, most of the movement is probably in a vertical direction by capillary action.

Outflow

Ground-water discharge in Dismal Swamp is from the Norfolk aquifer and from the peat and muck. Discharge from the Norfolk aquifer is by upward seepage into Lake Drummond, by seepage through the overlying peat, where the confining beds of the Sand Bridge Formation are permeable or absent, by direct seepage into canals and ditches that intersect the aquifer and by pumping along the Suffolk Scarp. The amount of water discharged is probably large, but no direct measurements have been made.

Discharge from the peat is by evapotranspiration and by seepage into ditches, canals, and streams. A detailed analysis of the seepage has not been made, but evapotranspiration withdraws by far the largest quantity of water from the peat.

Pumpage along the scarp is estimated to be 100,000 gallons per day. This withdrawal has apparently reversed the gradient in the Norfolk aquifer for part of the year in part of the Suffolk Scarp. (See fig. 13.)

Quality

Samples of ground water were collected from a shallow flowing well in Feeder Ditch near the Dismal Swamp Canal, from a deep flowing well at the abandoned Canal Bank Motel, from a shallow domestic well on the Suffolk Scarp, and from shallow auger holes near Washington Ditch. The analyses are shown in table 5. The concentrations of the various chemical constituents vary considerably from well to well.

The color is high (80-350 units) in water from the auger holes on Washington ditch, because the water was contaminated by the overlying peat. The chloride content of the Canal Bank Motel well water is slightly above the U. S. Public Health limit of 250 mg/l, (U. S. Public Health Service, 1962), but it is not harmful.

FEASIBILITY OF PRESERVING THE DISMAL SWAMP

It is obviously feasible to preserve the Dismal Swamp from direct development by man. This can be done by government acquisition of the land, by legislation governing activities within the swamp, by cooperation of landowners, or by any combination of the above. A major factor involved in preserving the swamp and Dismal Swamp Canal is financial support.

The Dismal Swamp has changed since Colonial Times, and it is likely that American Indians modified the swamp by burning and other means long before Europeans ever saw it. Since George Washington's time, drainage canals, ditches, and their accompanying spoilbanks have changed surface-water

Table 5.--Chemical quality of ground water from Dismal Swamp area.
(Results in milligrams per liter except as indicated)

No. used on fig. 2 A	Location of Sampling site	Date of collection	Temperature (°C)	Dissolved silica (SiO_2)	Iron (Fe)	Dissolved calcium (Ca)	Dissolved magnesium (Mg)	Dissolved sodium (Na)	Dissolved potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Dissolved sulfate (SO_4)	Dissolved chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphate (PO_4)	Dissolved solids (residue at 180°C)	Hardness: Calcium, magnesium	Hardness: Non-carbonate	Specific conductance (micromhos at 25°C)	Laboratory pH	Color (platinum-cobalt
5	Flowing well in Feeder Ditch	7-19-73	15	50	0.47	140	5.5	170	28	624	0.0	3.7	170	0.3	0.3	0.16	221	370	0	1490	7.1	30
6	Flowing well at Canal Bank Motel	7-10-73	19	9.8	.14	3.5	3.4	580	70	1010	.0	75	260	3.5	.3	.22	147	22	0	2500	8.0	10
7	Auger hole near Washington Ditch	7-28-73	-	24	.41	3.2	1.6	40	3.1	53	.0	29	30	.5	1.6	.13	250	14	0	205	5.9	350
8	Auger hole near Washington Ditch	7-28-73	-	23	.09	7.9	.7	26	1.9	19	.0	33	20	.2	.4	.04	173	22	7	170	5.5	80
9	Shallow domestic well on White Marsh Road	9-27-73	-	6.2	.01	6.4	2.7	31	4.1	5	.0	53	15	.1	34	34	154	27	23	245	5.4	5

levels and flow patterns. In at least parts of the swamp, roads built on spoilbanks have provided high ground and sunlit areas. Such changes and repeated lumbering have caused different flora and fauna to evolve. If present trends continue, the swamp of the future will be more like an upland forest than it is at present (Gerald Levy, oral commun., 1973).

Water levels in the swamp can be raised by sealing the locks or restricting pumping from the Norfolk aquifer. Data are insufficient, at present, to predict the hydrologic effect of various possible control measures, but if water levels are abruptly raised too high, many trees will be unable to adapt rapidly and will be killed (M. K. Garrett, oral commun., 1973).

Restoring the swamp to its original condition is impossible because that condition is unknown. The swamp has been and is still evolving, even without human interference; therefore, perhaps it would be best to manage the swamp for its best uses within the framework of conservation, rather than try to return it to some previous condition. This would probably involve maintaining a variety of ecosystems, which would, in turn, involve a variety of hydrologic conditions.

SUGGESTED FOLLOW-UP ACTIONS

Hydrologic studies needed to provide data to aid in managing the Dismal Swamp include:

1. Defining the present role of the Norfolk aquifer. Scattered borings indicate that some parts of the swamp remain wet, even during droughts because of upward seepage of ground water. Determination of the extent and amounts of upward seepage are essential.

2. Determining how withdrawal of water from the Norfolk aquifer has changed ground-water flow patterns and the effect future withdrawal may have on the swamp.
3. Identifying those parts of the swamp best suited to wetter types of ecosystems and those best suited to dryer types.
4. Determining surface inflow to the swamp from the Suffolk Scarp.
5. Determining surface outflow from the swamp.
6. Determining the number and type of structures necessary to control surface-water movement in the swamp.
7. Determining the water budget of the swamp.
8. Monitoring seasonal and long-term changes in the chemical quality of both surface water and ground water.

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