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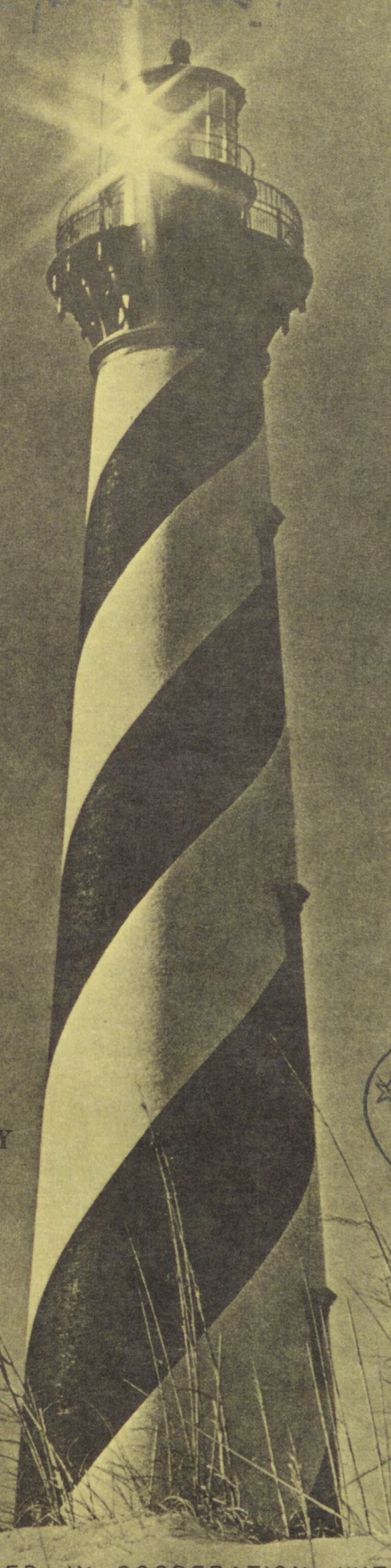
WATER RESOURCES OF NORTHEAST NORTH CAROLINA



U.S. DEPARTMENT OF THE INTERIOR
MARCH 3, 1849

U. S. GEOLOGICAL SURVEY
WATER RESOURCES
INVESTIGATIONS 77-81

PREPARED IN COOPERATION WITH THE
U. S. ARMY CORPS OF ENGINNERS

BIBLIOGRAPHIC DATA SHEET	1. Report No.	2.	3. Recipient's Accession No.
4. Title and Subtitle Water Resources of Northeast North Carolina			5. Report Date May 1978 6.
7. Author(s) H. B. Wilder, T. M. Robison, and K. L. Lindskov			8. Performing Organization Rept. No. USGS/WRI 77-81
9. Performing Organization Name and Address U. S. Geological Survey Water Resources Division P. O. Box 2857 Raleigh, N. C. 27602			10. Project/Task/Work Unit No. 11. Contract/Grant No.
12. Sponsoring Organization Name and Address U. S. Geological Survey Water Resources Division P. O. Box 2857 Raleigh, N. C. 27602			13. Type of Report & Period Covered Final 14.

15. Supplementary Notes
Prepared in cooperation with the U. S. Army Corps of Engineers.

16. Abstracts Associated with economic development of northeast North Carolina are several water-related problems. The solution to these problems depends in part on adequate knowledge of the hydrology of this 8,930 square mile coastal area. Although it is hydrologically the least studied area of North Carolina, enough is known to present this reconnaissance-level picture of its water resources.

Average annual precipitation on the area is about 50 inches. Of this amount, about 34 inches returns to the atmosphere via evapotranspiration, about 15 inches leaves the area as runoff, and about one inch leaves through ground-water outflow.

No large streams originate within the area, but major streams entering from the north and west bring in three times as much streamflow as originates within the study area. The flat, low-lying terrane does not offer opportunities for extensive development of surface-water supplies through the use of reservoirs. Much of the surface water is contaminated by saltwater from the ocean. Ground water occurs in three major aquifers, all of which contain both freshwater and saltwater.

17. Key Words and Document Analysis. 17a. Descriptors

Water Resources, North Carolina, Water balance, Coastal Plains, Estuaries, Aquifers, Ground water, Water quality, Channel improvement.

17b. Identifiers/Open-Ended Terms

Castle Hayne limestone, freshwater-saltwater relations, Corporate farms, Lake Phelps, Lake Mattamuskeet, Albemarle Sound, Pamlico Sound, Outer Banks.

17c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
No restriction on distribution	UNCLASSIFIED	123
	20. Security Class (This Page) UNCLASSIFIED	22. Price

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WATER-RESOURCES INVESTIGATIONS 77-81

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U.S. Army Corps of Engineers

1978

UNITED STATES DEPARTMENT OF THE INTERIOR

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GEOLOGICAL SURVEY

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May 1978

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INTERNATIONAL SYSTEM UNITS

The following factors may be used to convert the English units published herein to the International System of Units (SI).

Multiply English units	By	To obtain SI units
Length:		
inches (in)	25.4	millimeters (mm)
feet (ft)	.3048	meters (m)
miles (mi)	1.609	kilometers (km)
Area:		
square feet (ft^2)	0.0929	square meters (m^2)
acres	4047	square meters (m^2)
	.4047	hectares (ha)
	.4047	square hectometers (hm^2)
	.004047	square kilometers (km^2)
square miles (mi^2)	2.590	square kilometers (km^2)
Volume:		
gallons (gal)	3.785	liters (L)
	3.785×10^{-3}	cubic meters (m^3)
million gallons (Mgal)	3785	cubic meters (m^3)
	3.785×10^{-3}	cubic hectometers (hm^3)
cubic feet (ft^3)	.02832	cubic meters (m^3)
million gallons per square mile ($Mgal/mi^2$)	1461	cubic meters per square kilometer (m^3/km^2)
Flow:		
cubic feet per second (ft^3/s)	28.32	liters per second (L/s)
	.02832	cubic meters per second (m^3/s)
gallons per minute (gal/min)	.06309	liters per second (L/s)
	6.309×10^{-5}	cubic meters per second (m^3/s)
million gallons per day (Mgal/d)	43.81	liters per second (L/s)
	.04381	cubic meters per second (m^3/s)
	3800.	cubic meters per day (m^3/d)
gallons per day per square mile $(gal/d)/mi^2$	.0015	cubic meters per day per square kilometer $(m^3/d)/km^2$

Multiply English units	By	To obtain SI units
million gallons per day per square mile (Mgal/d)/mi^2	1461	cubic meters per day per square kilometer (m^3/d)/km^2
cubic feet per second per square mile (ft^3/s)/mi^2	.01093	cubic meters per second per square kilometer (m^3/s)/km^2
	10.93	liters per second per square kilometer (L/s)/km^2
gallons per day per foot (gal/d)/ft	.041	cubic meters per day per meter (m^3/d)/m
Gradient:		
feet per mile (ft/mi)	1894	meters per kilometer (m/km)

WATER RESOURCES OF NORTHEAST NORTH CAROLINA

By H. B. Wilder, T. M. Robison, and K. L. Lindskov

ABSTRACT

Northeast North Carolina is experiencing what many feel is the leading edge of an economic boom. Associated with the development of this 8,930 square mile coastal area are several water-related problems. Among them are (1) the possibility of saltwater encroachment into surface-water and ground-water supplies due to heavy pumping or flooding from wind-driven ocean tides; (2) artificial drainage from large corporate farms is changing the runoff patterns in the area, (3) channelization of existing streams to reduce spring flooding of farmlands may adversely affect stream ecology.

The solution to these problems depends in part on adequate knowledge of the hydrology of northeast North Carolina. Although it is hydrologically the least studied area of North Carolina, enough is known to present a reconnaissance-level description of its water resources.

Average annual precipitation on the area is about 50 inches. Of this amount, about 34 inches returns to the atmosphere via evapotranspiration, about 15 inches leaves the area as runoff, and about 1 inch leaves through ground-water outflow.

Large streams flowing into the area include the Chowan, Roanoke, Tar, and Neuse River. These convey an average flow of 17,500 cubic feet per second from an outside drainage area of nearly 20,000 square miles. This is about three times as much runoff as originates within the study area if precipitation falling directly on large bodies of salty open water is not considered.

The chemical quality of the fresh surface waters of northeast North Carolina is generally good where it is not mixed with seawater. The freshwater does not contain objectionable amounts of any dissolved mineral constituents, except that some streams draining the Castle Hayne Limestone outcrops may contain moderately hard water. The only undesirable characteristics of the fresh surface waters of the study area is that water drained from swampy areas may be colored enough to stain laundry, paper, and so forth, and be esthetically objectionable for drinking.

The major rivers of the study area become estuaries in their lower reaches; these in turn open up into large sounds, which are partly cut off from the ocean by the Outer Banks. Although some authorities have classified some of these sounds as freshwater bodies, potential users should understand that nowhere in the sounds are freshwater supplies available. They contain enough seawater everywhere to be unsuitable for water supplies.

There are three major aquifers in northeast North Carolina--an upper aquifer consisting primarily of sands and clays, a middle limestone aquifer, and a lower aquifer consisting of complexly interbedded layers of sand, silt, clay and shale, and limestone and dolomite.

The average thickness of the upper aquifer is about 460 feet and ranges from less than 100 feet thick near the western part of the region to more than 1,300 feet thick on parts of the Outer Banks. Typical yields of the upper aquifer to small-diameter screened wells is 5 to 10 gallons per minute, and in some places can be as much as 100 gallons per minute. Water from the upper aquifer tends to be low in dissolved solids, but in some locations may need to be treated for excessive iron or hardness. In addition, saltwater is present in the upper aquifer in much of the eastern part of the area, rendering the water unfit for many uses.

The limestone aquifer has an average thickness of about 510 feet; it thickens to the east and southeast, reaching a maximum thickness of about 1,200 feet near Cape Hatteras. Yields to wells tapping the limestone aquifer are typically several hundred to as much as 2,000 gallons per minute. The limestone aquifer contains only freshwater in the western border of the area; to the east, freshwater in the aquifer is underlain by saltwater.

The quality of water from the limestone aquifer is typical of waters from limestone formations. It is hard, high in alkalinity, and tends to form scale. It may also contain objectionable amounts of silica and iron.

The lower aquifer also dips and thickens to the east and southeast; its average thickness is 2,780 feet and it is over 7,000 feet thick at Cape Hatteras. In areas where the aquifer contains freshwater, yields to individual wells may be several hundred to as much as 1,000 gallons per minute. Such high yields are due to the lower aquifer's great thickness--its hydraulic conductivity is much lower than the limestone aquifer.

The lower aquifer contains exclusively freshwater only in the northwest part and the western fringe of the study area. Within a 20-mile wide strip east of the completely freshwater areas, freshwater overlies saltwater in this aquifer. Farther east, the aquifer yields only saltwater. Where the water is fresh, it is the best quality water of any of the major aquifers. It is a soft, alkaline water that requires little or no treatment for most uses. The only serious potential quality drawback is that the water may contain excessive fluoride in some locations.

There is a close interdependency among the various components of the hydrologic system in northeast North Carolina and planning for land and water management should consider this carefully. Large-scale agricultural drainage projects are altering the hydrology of the area; heavy pumping of the limestone aquifer is taking place in parts of the area in connection with phosphate mining operations. These and other operations may have profound effects on the hydrology of the area and should be more thoroughly examined to insure an orderly development of the water resources of northeast North Carolina.

INTRODUCTION

Northeastern North Carolina has been one of the largest economically underdeveloped areas along the southeastern seaboard. (See fig. 1.) The potential for recreational, agricultural, and commercial development in the 8,230 mi^2 area far exceeds what has actually taken place. Beaches, sounds, estuaries, and lakes provide abundant opportunities for water-related recreation. Timber, phosphate, and limestone are available in commercial amounts. The rich peat soil found in many areas is a type highly prized for farming. What many call the leading edge of an economic boom is now taking place and the area's underdeveloped status is rapidly changing.

The Outer Banks are now being rapidly developed for recreation particularly in the Nags Head area. Plans to pave roads in the extreme northern part of the Outer Banks could lead to even more rapid development of that area, especially in terms of beach cottages and service establishments. The coastal area on the north side of Albemarle Sound is relatively undeveloped, and its location is convenient for recreational development to serve not only North Carolinians, but also the huge Washington-Baltimore metropolitan area.

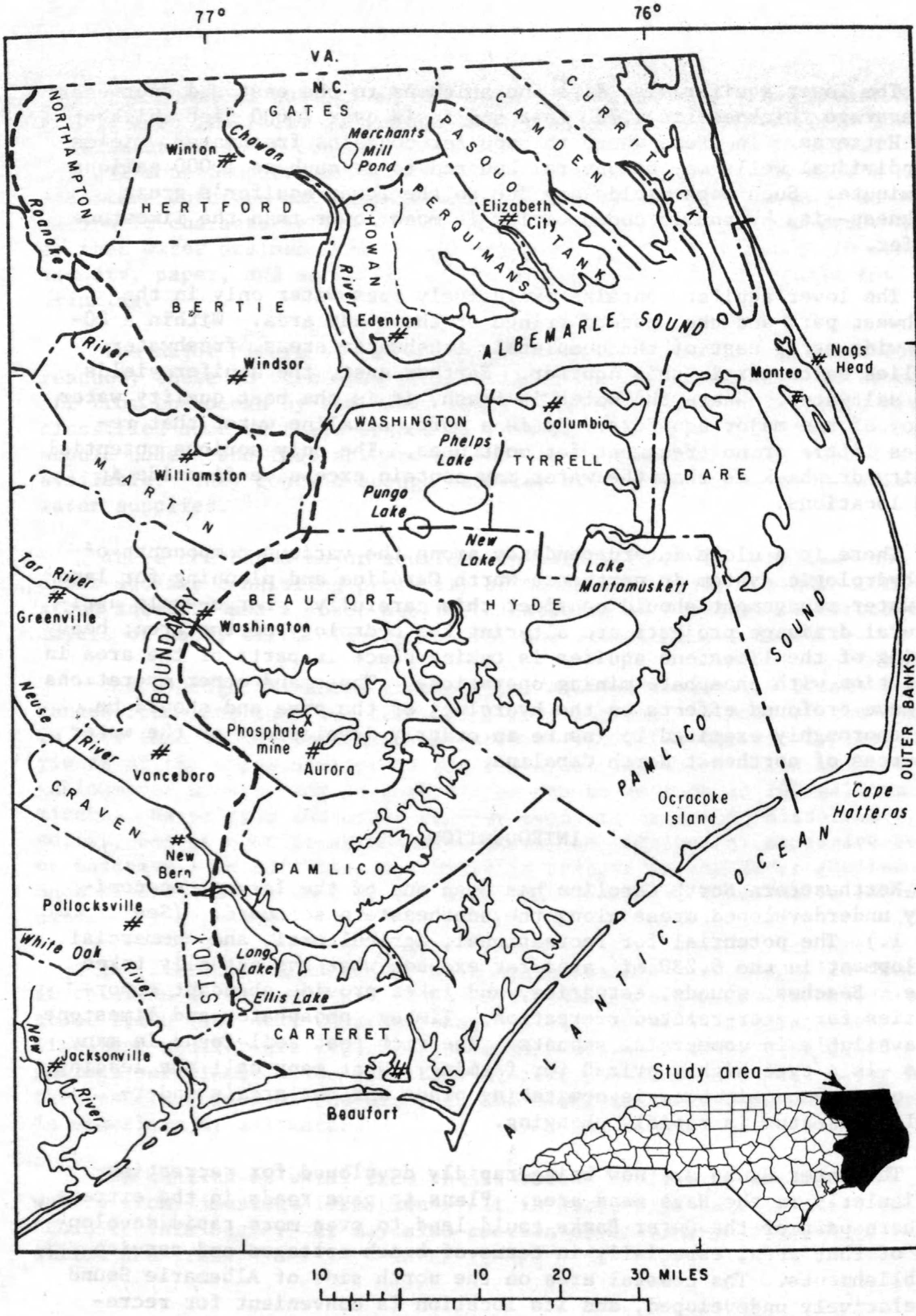


Figure 1.--Northeast North Carolina.

Since 1965, large-scale phosphate mining operations have been taking place in Beaufort County and plans are now (spring 1976) being formulated to expand these operations. Other industries, particularly in the textile and wood products fields, have shown increased interest in expanding operations in the area.

Water Problems

Attendant with these developments, there are and there likely will continue to be problems of water supply and water quality. Some are problems common wherever development occurs, and others are rather unique to the northeast North Carolina area.

Development of water supplies requires careful attention to the possibility of saltwater encroachment into surface- and ground-water bodies in large areas of northeast North Carolina. Extensive coastal areas are less than 5 ft above mean sea level and wind-driven ocean tides sometimes drive brackish or salty water upstream into lakes and rivers that are normally fresh. Pumping from wells anywhere in the study area can induce brackish water (which occurs naturally at depths ranging from less than 100 ft to more than 600 ft) to move into naturally freshwater-bearing zones. Heavy pumping averaging 65 Mgal/d is taking place in Beaufort County in connection with phosphate mining, and locally saltwater intrusion into the Castle Hayne Limestone is now taking place.

Finally, massive drainage and land-clearing operations by large corporate farms have recently taken place and are continuing in the area; perhaps more than 500 mi^2 in northeast North Carolina will be affected by 1980. There are several water problems related to these agricultural developments. Artificial drainage projects for large corporate farms are changing the hydrology of large areas, according to Heath (1975). Increased runoff from drainage ditches at times may adversely affect the fishery resources in the study area. Efforts to reduce spring flooding of farmlands by channelization of existing streams have raised serious questions about the effects of channelization on stream ecology. The answers to these and other questions are needed to ensure proper development of the water resources of northeast North Carolina.

Purpose and Scope

The purpose of this reconnaissance-level report is to present baseline knowledge of the hydrology of northeast North Carolina for use in identifying and solving water-related problems associated with accelerating economic and recreational development of the area. The report was done by the U.S. Geological Survey in cooperation with the U.S. Army Corps of Engineers. It provides information about the occurrence, quality, and variability of surface and ground waters in the region.

Previous Investigations

There have been no past water-resources studies of northeast North Carolina which cover the entire area and all major aspects of hydrology. Nevertheless, many useful studies have been done which cover parts of the area or which relate to one or more aspects of its hydrology. Many of these are reported by Lindskov (1973) in the form of an annotated bibliography and will not be repeated here. Since then, several investigations have added to knowledge of the hydrology of the area and have been added to Selected References at the back of the report. The North Carolina Water Resources Research Institute has recently completed several studies of the effects of fertilizer nutrients on the waters of the Coastal Plain [Gambrell and others (1974), and Hobbie (1974)]. The North Carolina Department of Natural and Economic Resources has also completed several important studies relating to ground-water use in the Coastal Plain [Peek and others (1972), North Carolina Groundwater Section (1974), and Peek and Nelson (1975)]. Finally, the U.S. Geological Survey has recently published a preliminary report on the impact of agricultural developments on the hydrology of the Albemarle-Pamlico region (Heath, 1975). The Geological Survey also has studied the potential effects of channelization on the Creeping Swamp watershed (Winner and Simmons, 1977) and is expanding work on the study of the hydrologic effects of land clearing in the Albemarle-Pamlico region.

PHYSICAL SETTING

Northeast North Carolina lies within the Coastal Plain Province as described by Fenneman (1938). The average annual temperature is about 60°F (15.6°C), with a frost-free period usually lasting from late March to early November. The area includes all or parts of the 17 most northeastern counties in North Carolina. The land generally is flat and low lying; much of it is swampy. In fact, almost the entire area is less than 25 ft above mean sea level. (See figure 2.) Of the 8,930 mi^2 area of northeast North Carolina, about 2,400 mi^2 is open water in sounds and estuaries.

The two largest bodies of water in the area are Albemarle Sound and Pamlico Sound, which are partly cut off from the ocean by the Outer Banks. The three largest estuaries are those of the Neuse, Tar, and Chowan Rivers. These are also three of the four largest rivers in the area; the other being the Roanoke River. None of these major rivers originates within the study area, but they carry the drainage from

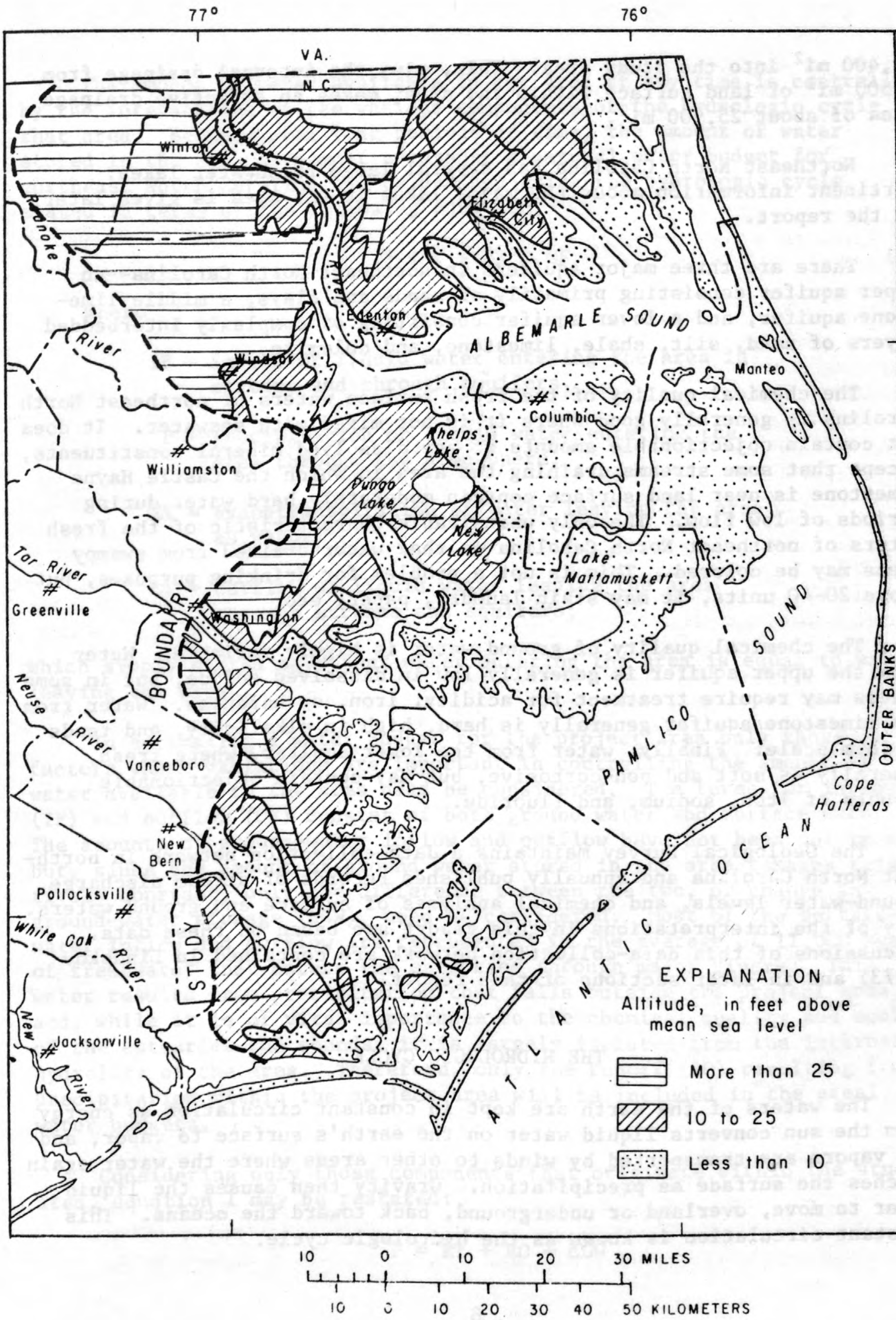


Figure 2.--Generalized land-surface altitude.

19,400 mi^2 into the study area. This, plus the internal drainage from 6,500 mi^2 of land surface within the area, makes an effective drainage area of about 25,900 mi^2.

Northeast North Carolina has several large freshwater lakes. Pertinent information about the major lakes in the area is given later in the report.

There are three major aquifers in northeast North Carolina--an upper aquifer consisting primarily of sands and clays, a middle limestone aquifer, and a lower aquifer consisting of complexly interbedded layers of sand, silt, shale, limestone, and dolomite.

The chemical quality of the fresh surface waters of northeast North Carolina is generally good where it is not mixed with seawater. It does not contain objectionable amounts of any dissolved mineral constituents, except that some streams draining the area in which the Castle Hayne Limestone is near land surface contain moderately hard water during periods of low flow. The only undesirable characteristic of the fresh waters of northeast North Carolina is that water drained from swampy areas may be colored. This is not a problem for drinking purposes, but above 20-40 units, it may stain laundry, paper, etc.

The chemical quality of ground water is highly variable. Water from the upper aquifer is generally low in dissolved solids, but in some places may require treatment for acidity, iron, or hardness. Water from the limestone aquifer generally is hard, high in alkalinity, and tends to form scale. Finally, water from the lower aquifer, where fresh, generally is soft and non-corrosive, but may contain objectionable amounts of iron, sodium, and fluoride.

The Geological Survey maintains a data-collection network in northeast North Carolina and annually publishes records of stream discharge, ground-water levels, and chemical analyses of surface and ground waters. Many of the interpretations in this report are based on these data. Discussions of this data-collection network are contained in Lindskov (1973) and in later sections of this report.

THE HYDROLOGIC CYCLE

The waters of the earth are kept in constant circulation as energy from the sun converts liquid water on the earth's surface to vapor, and the vapors are transported by winds to other areas where the water again reaches the surface as precipitation. Gravity then causes the liquid water to move, overland or underground, back toward the oceans. This constant circulation is known as the hydrologic cycle.

The amount of water available in any area at any time is controlled by the interactions of the various components of the hydrologic cycle in that area. Because over long periods of time, the amount of water stored in the area is almost constant; a natural water budget for northeast North Carolina can be defined using the hydrologic cycle stated in terms of the following equation:

$$IF + P = ET + OF \tag{1}$$

Where

IF = inflow or liquid water entering the area in streams and through aquifers,

P = precipitation or liquid water entering the area through the atmosphere,

ET = evapotranspiration or water leaving the area as vapor,

OF = outflow or liquid water leaving the area through streams and aquifers;

which simply stated says that water entering the area is equal to water leaving the area.

In estimating a water budget for the project area only those factors whose variations are important in controlling the amount of water available to the area need be considered. The terms for inflow (IF) and outflow (OF) consist of both ground water and surface water. The amounts of ground-water inflow and outflow have not been determined but, since the amount of ground water stored in the area remains relatively constant, only the difference between the two, or change in ground-water storage (ΔGW), need be considered. Most of the surface-water inflow and outflow are represented in the average of 11,000 Mgal/d of freshwater that enters the estuaries through major rivers. This water results from precipitation that falls outside the project area, and, while it is of vital importance to the chemical quality and ecology of the estuaries and sounds, it is largely isolated from the internal hydrology of the area. Therefore, only the runoff (RO) resulting from precipitation within the project area will be included in the areal water budgets.

Considering only those components that originate within the study area, equation 1 may be restated:

$$P = ET + RO + \Delta GW \tag{2}$$

where P and ET remain the same as in equation 1 and:

RO = runoff resulting from precipitation within the area

ΔGW = change in ground-water storage, or the difference between ground-water inflow and ground-water outflow through aquifers.

Each of these elements will be discussed in the following sections.

Precipitation

Ultimately, the supply of water available to northeast North Carolina is derived from atmospheric precipitation. The mean annual precipitation throughout the area is about 50 in/yr. Converted to volume this represents 870 (Mgal/mi^2)/yr or an annual average of about 8 trillion gallons of rainfall per year for the entire area. These average figures can vary greatly however, both from place to place and from time to time. As shown on figure 3, precipitation ranges from about 48 in/yr or 840 (Mgal/mi^2)/yr in the northern part of the area to about 56 in/yr or 980 (Mgal/mi^2)/yr in the southern part of the area. Figure 4 shows the expected distribution of total annual precipitation over long periods at New Bern, N.C. During very dry years, precipitation may be as low as 35 in and, in extremely wet years, as high as 80 in. Precipitation frequency curves similar to those of figure 4 could be constructed for other stations in northeast North Carolina.

As shown on figure 5, the average precipitation in this part of the state is distributed fairly evenly throughout the year. The average monthly precipitation is usually higher during July, August, and September. In a given year, however, any month can be either excessively wet or excessively dry. These patterns are typical of the study area.

The information shown on figures 3-5 emphasize the variability in the amount of new water that reaches the area from year to year. These variations will take on increasing significance as we consider what happens to the precipitation once it reaches land surface.

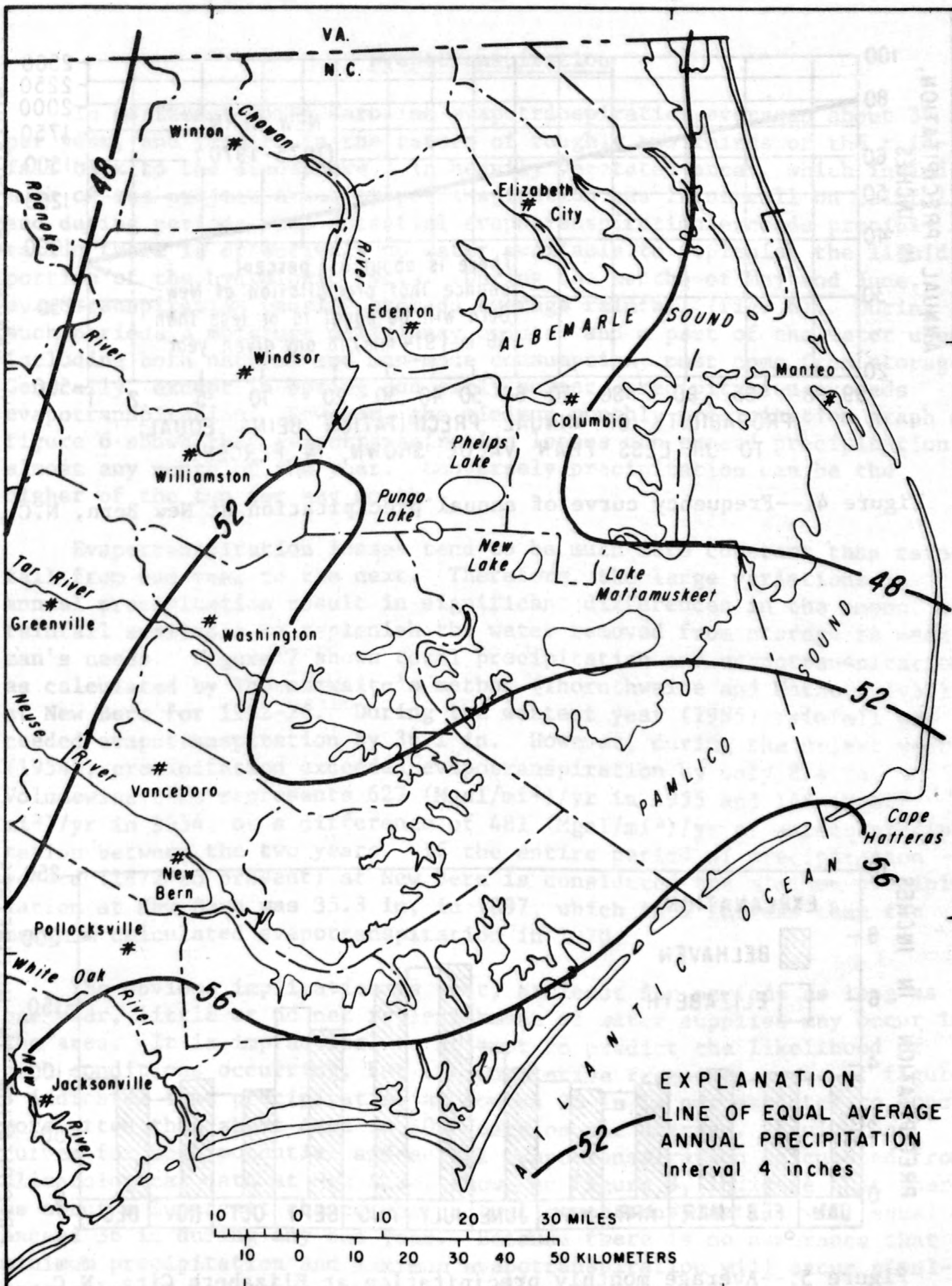


Figure 3.--Average annual precipitation for northeast North Carolina. (From Hardy and Hardy, 1971.)

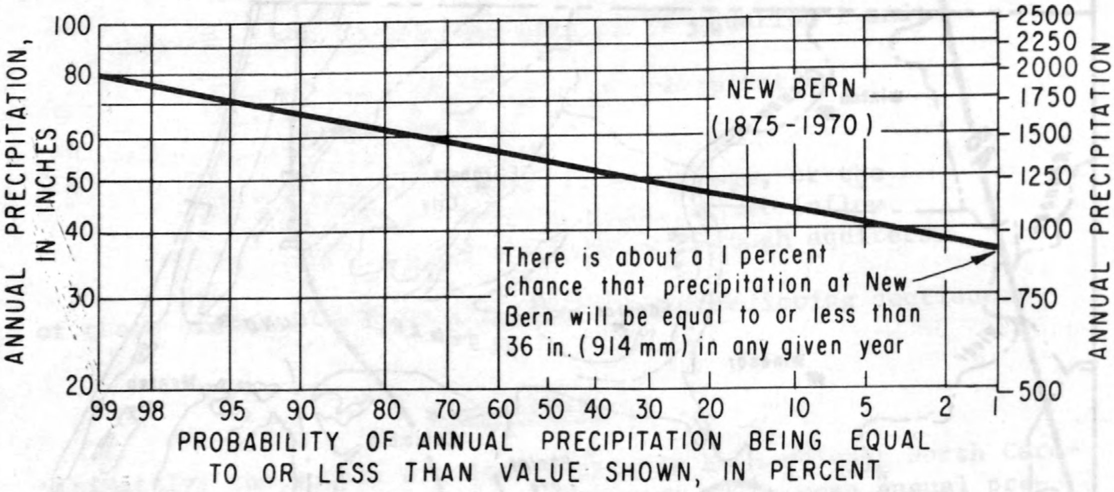


Figure 4.--Frequency curve of annual precipitation at New Bern, N.C.

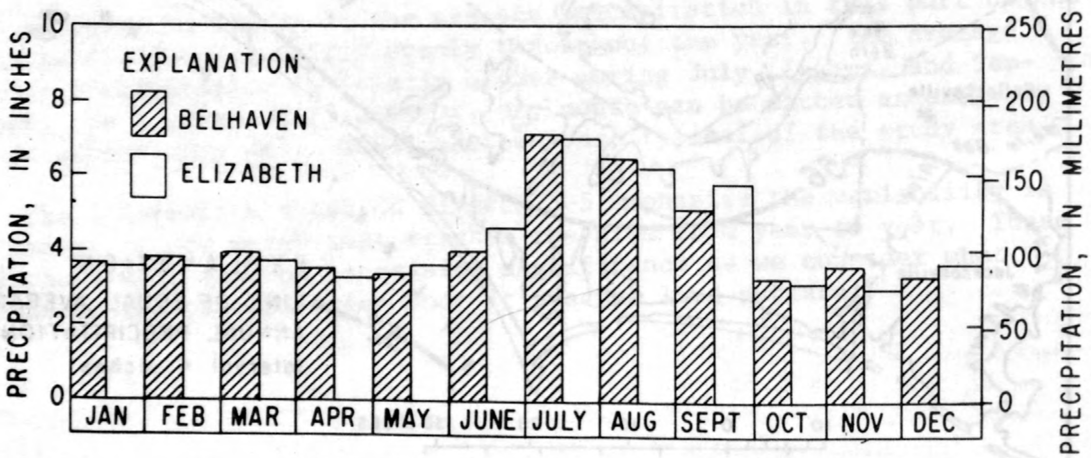


Figure 5.--Average monthly precipitation at Elizabeth City, N.C., and Belhaven, N.C., 1910-60.

Evapotranspiration

In northeast North Carolina evapotranspiration averages about 34 in per year, and results in the return of roughly two thirds of the rainfall back to the atmosphere. In heavily vegetated areas, which include much of the project area, evapotranspiration has first-call on rainfall, and during periods when potential evapotranspiration exceeds precipitation there is effectively no water available to replenish the liquid portion of the hydrologic cycle. During the months of May and June, evapotranspiration usually exceeds average rainfall (fig. 6). During such periods a moisture deficiency exists, and a part of the water used, including both natural and man-made consumption, must come from storage. Generally, except in spring and early summer, precipitation exceeds evapotranspiration. However, the minimum monthly precipitation graph on figure 6 shows that evapotranspiration losses can exceed precipitation almost any month of the year. Conversely precipitation can be the higher of the two for any month.

Evapotranspiration losses tend to be much more constant than rainfall from one year to the next. Therefore, the large variations in annual precipitation result in significant differences in the amount of rainfall available to replenish the water removed from storage to meet man's needs. Figure 7 shows total precipitation and evapotranspiration, as calculated by Thornthwaite's method (Thornthwaite and Mather, 1957), at New Bern for 1952-70. During the wettest year (1955) rainfall exceeded evapotranspiration by 36.1 in. However, during the driest year (1954), precipitation exceeded evapotranspiration by only 8.4 in. Volumewise this represents 627 ($Mgal/mi^2$)/yr in 1955 and 146 ($Mgal/mi^2$)/yr in 1954, or a difference of 481 ($Mgal/mi^2$)/yr of excess precipitation between the two years. If the entire period of precipitation record (1872 to present) at New Bern is considered the minimum precipitation at New Bern was 35.3 in, in 1897, which is 1 in less than the maximum calculated evapotranspiration in 1970.

The obvious implication is that, at least for periods as long as one year, little or no net replenishment of water supplies may occur in the area. It is impractical to attempt to predict the likelihood of such conditions occurring, but the cumulative frequency curve of figure 4 indicates that precipitation as low as 35 in is not expected to occur more often than about once in 100 years on the average. Equivalent curves for both potential and actual evapotranspiration calculated from climatological data at New Bern, shown on figure 8, indicate that there is about a 3 percent chance that actual evapotranspiration will equal or exceed 36 in during any one year. Because there is no assurance that minimum precipitation and maximum evapotranspiration will occur simultaneously, it is not possible to predict the frequency of an annual moisture deficiency, but it is expected to be less frequent than once each 100 years on the average.

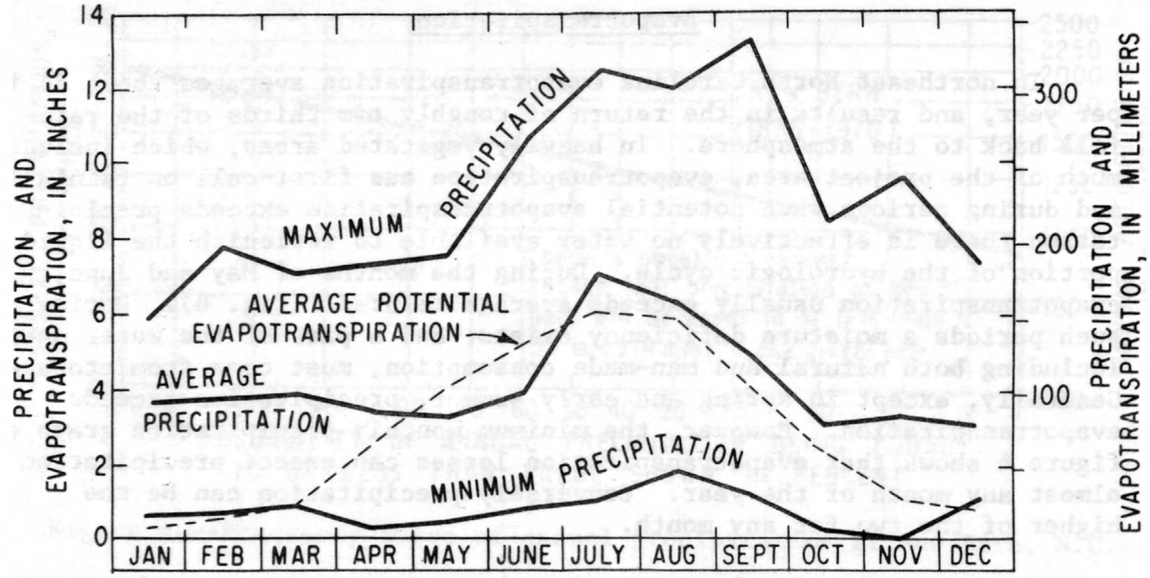


Figure 6.--Maximum, average, and minimum monthly precipitation and calculated average evapotranspiration at Elizabeth City, N.C., 1931-60.

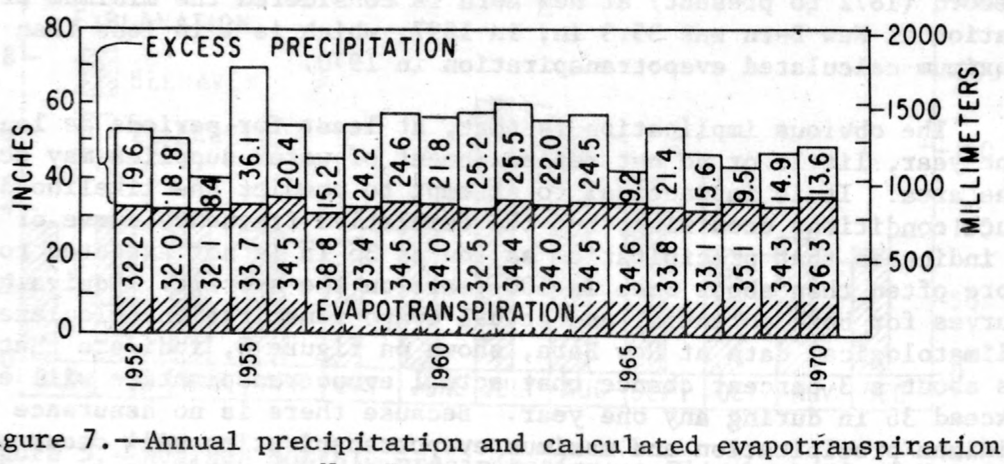


Figure 7.--Annual precipitation and calculated evapotranspiration at New Bern, N.C., 1952-70.

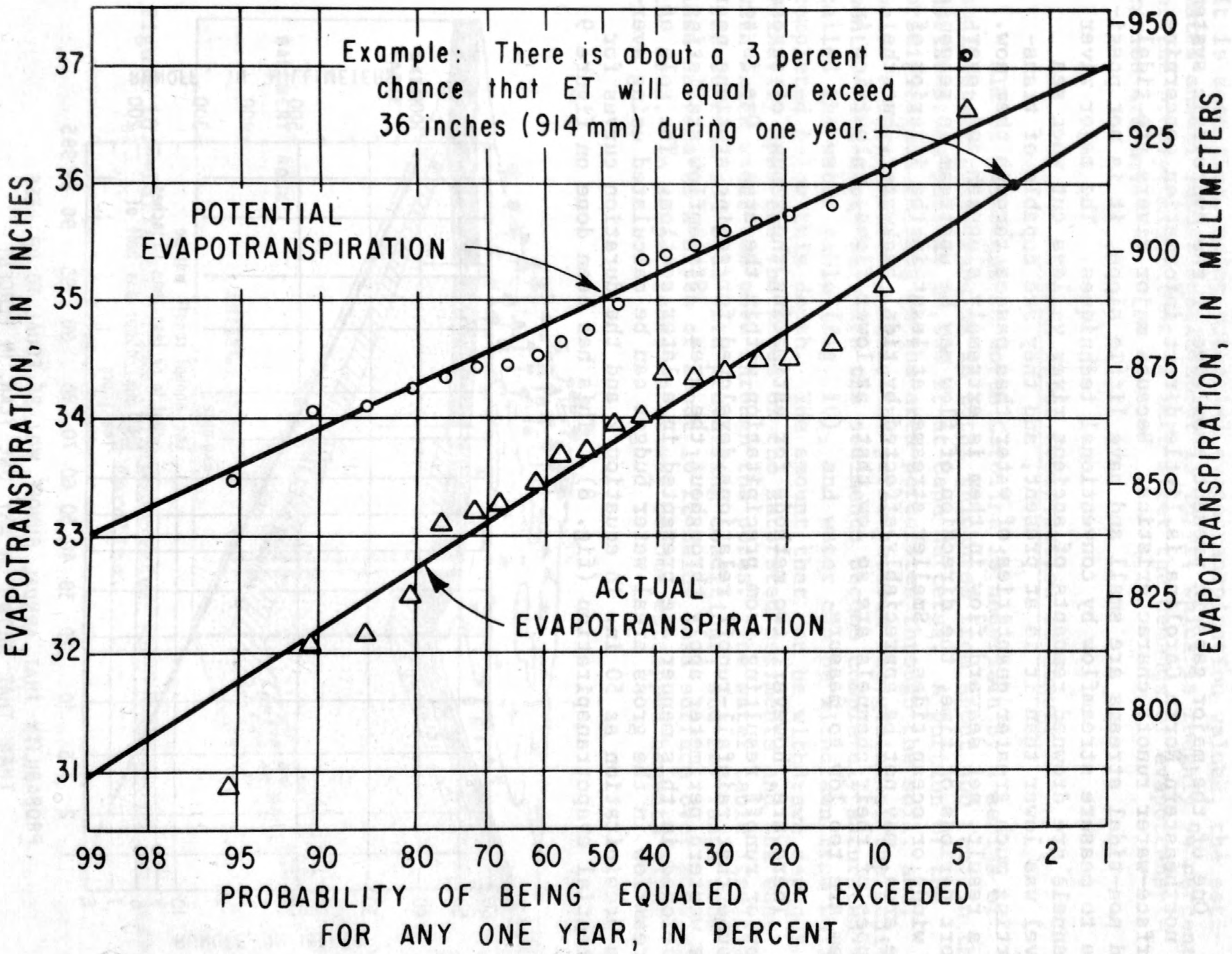


Figure 8.--Duration curves of evapotranspiration based on climatological data at New Bern, N.C.

Surface-Water Runoff

One of the major gaps in present knowledge of the hydrologic system in northeastern North Carolina is little direct information concerning surface-water runoff characteristics. Because major rivers are tidal and non-tidal streams are small and have little slope, it is not possible to measure streamflow by conventional techniques. The major river channels are drowned remnants of ancient river valleys cut when sea level was lower than it is at present, and they are capable of transporting much greater quantities of water than passes through them now. As a result, net seaward flow in them is extremely sluggish and, over short periods of time, the direction of flow may be upstream in response to winds or ocean tides. Smaller streams, at least in the interior of the area, may not be appreciably affected by tidal backwater, but the slopes of their channels are so low that, at lower flows, velocities in them are too low to measure.

There are, however, two methods for estimating the amount of streamflow or runoff resulting from precipitation within the area. One is to assume that rainfall-runoff relations developed for gaging stations near the western perimeter apply throughout the area. Streamflow statistics developed in this manner are presented in a later section. The role of streamflow in the gross areal water budget can be calculated using average precipitation as 50 in. in equation 2 and the duration curves for potential evapotranspiration (fig. 8). This has been done on figure 9

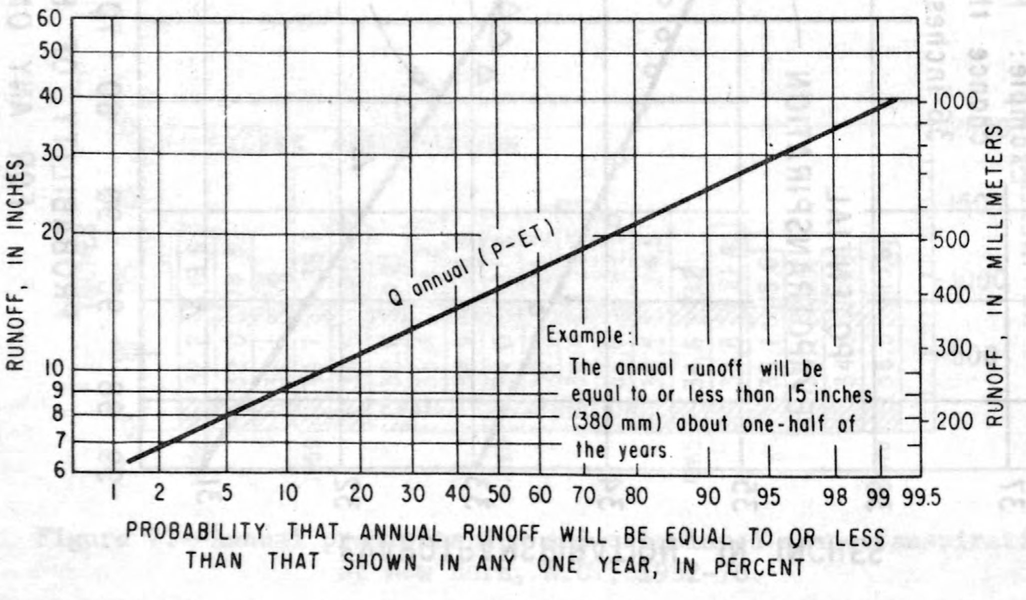


Figure 9.--Duration of annual runoff for small streams in northeast North Carolina.

which shows the frequency with which annual streamflow, shown as runoff in inches, may be expected to be equal to or less than certain values. It is seen that, using potential evapotranspiration values, the estimated annual runoff equals about 15 in/yr, which is roughly 94 percent of the precipitation that is left after the demands of evapotranspiration are met.

Ground-Water Contribution to Runoff

All of northeastern North Carolina is underlain by a series of sedimentary rocks ranging in total thickness from about 400 feet in the northwestern part to 10,000 ft at Cape Hatteras. A portion of the precipitation falling on the area percolates through the soil, and, below a certain level, fills the pores between the grains of the sediments. The depth at which the sediments become completely saturated is called the water table (fig. 10), and water can be withdrawn from wells completed below this depth. The amount that can be withdrawn depends primarily upon the thickness of the saturated sediments and the ease with which water can move through the pores. The water table itself is free to rise and fall with prevailing conditions, and may range from land surface to a depth of about 10 ft below land surface over most of the area. In deeper zones water may become entrapped beneath tight

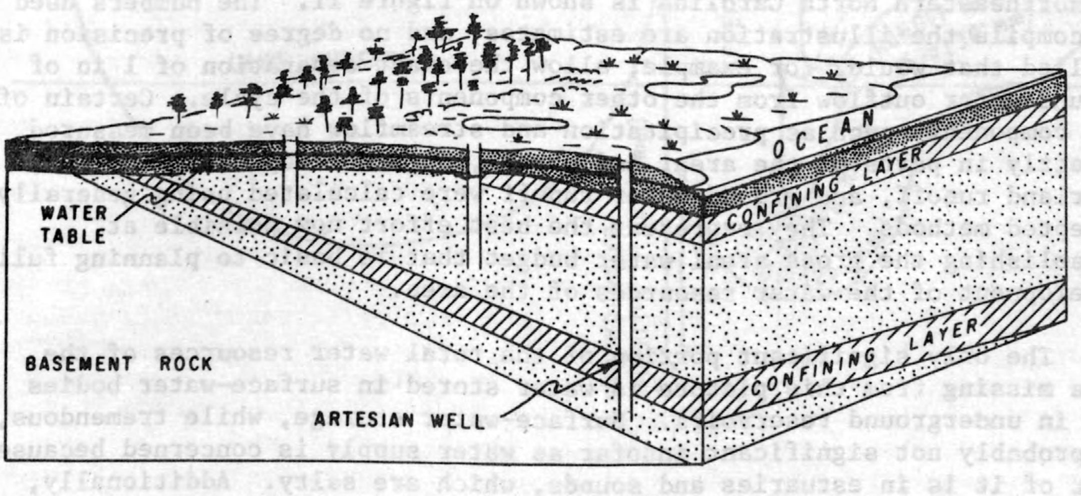


Figure 10.--Different types of ground-water environments in northeast North Carolina.

layers of clay or silt and be confined under pressure. Water levels in wells penetrating these pressurized zones may rise anywhere from a few feet above the bottom of the confining bed to several feet above land surface; but in either case such wells are called artesian wells.

Movement of water underground is very much slower than movement over the surface. Even in the deeper aquifers, however, water is in constant motion and, through various routes, is making its way to the sea. It is estimated that the total recharge to the water table averages about 11 in, or 190 (Mgal/mi^2)/yr. Under natural conditions about 10 in of this recharge rapidly seeps into nearby streams and drainage channels and leaves the area as base runoff.

An additional amount of water enters and leaves the area underground as ground-water inflow and outflow. At present, there is no way of directly estimating the magnitude of either ground-water inflow or outflow, but it is possible to include them in the areal water budget as the excess of outflow over inflow (ΔGW) as calculated from equation 2. The resulting value is 1 in or 17.4 (Mgal/mi^2)/yr.

Areal Water Budget

A schematic representation of the operation of the hydrologic cycle in northeastern North Carolina is shown on figure 11. The numbers used to compile the illustration are estimates, and no degree of precision is implied that would, for example, allow the exact separation of 1 in of ground-water outflow from the other components of the cycle. Certain of the components such as precipitation and streamflow have been measured directly in parts of the area; and others, such as evapotranspiration, overland runoff, and ground-water runoff were calculated using generally accepted methods. They represent the best effort now possible at establishing the gross areal water budget that is basic to planning full development of the water resources of the area.

The only significant portion of the total water resources of the area missing from this picture is water stored in surface-water bodies and in underground reservoirs. Surface-water storage, while tremendous, is probably not significant insofar as water supply is concerned because most of it is in estuaries and sounds, which are salty. Additionally, there is a relatively small amount of freshwater stored in natural lakes that may be significant for local supplies but not to the overall water budget. Ground-water storage is also tremendous, and will be discussed quantitatively in later sections devoted to individual aquifer systems.

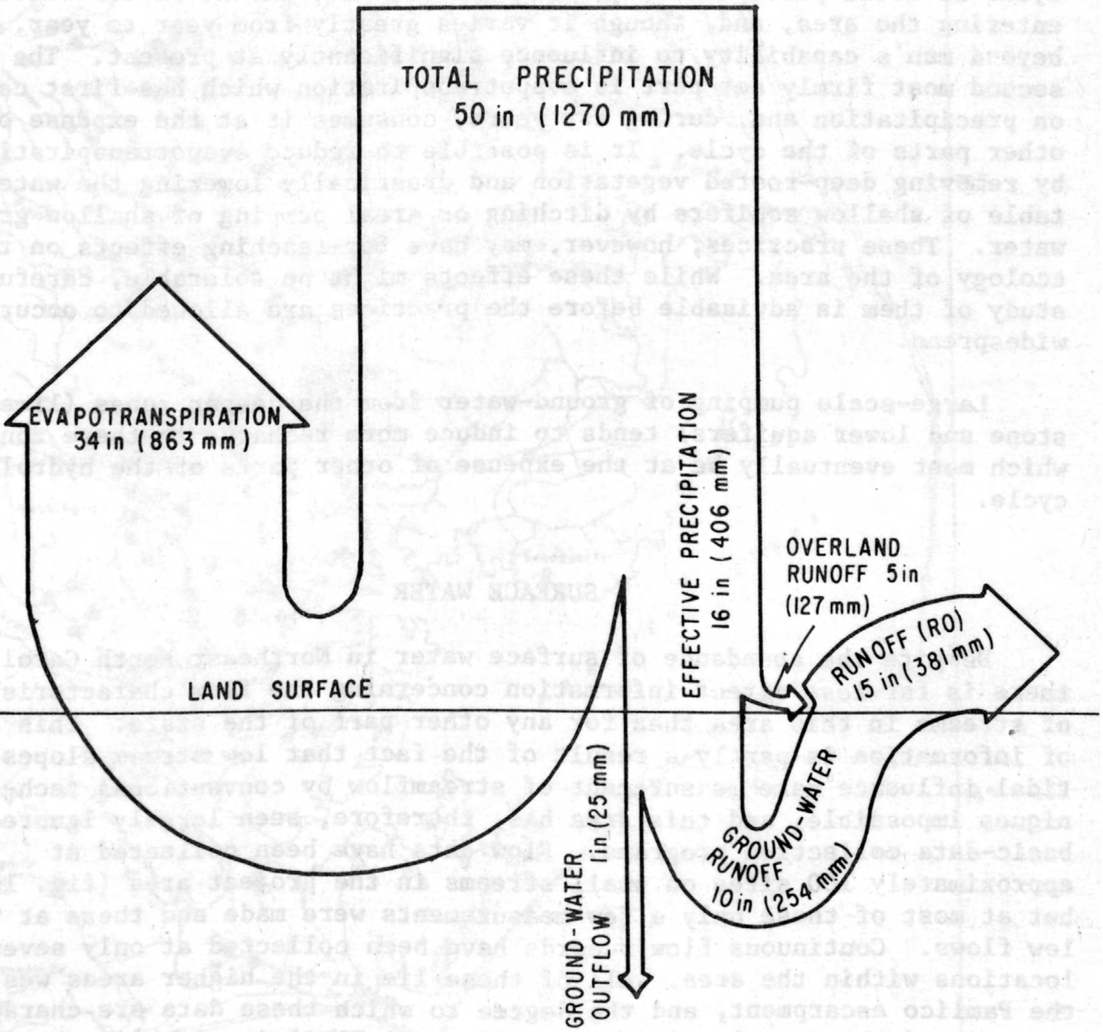


Figure 11.--The components of the hydrologic cycle in northeast North Carolina.

Figure 11 also illustrates the interdependency of all aspects of the areal water budget, and clearly suggests that, when man alters the natural operation of the cycle by large withdrawals of water, he must consider the overall consequences. The one unalterable part of the cycle is total precipitation, which controls the amount of new water entering the area, and, though it varies greatly from year to year, is beyond man's capability to influence significantly at present. The second most firmly set part is evapotranspiration which has first call on precipitation and, during dry years, consumes it at the expense of other parts of the cycle. It is possible to reduce evapotranspiration by removing deep-rooted vegetation and drastically lowering the water-table of shallow aquifers by ditching or areal pumping of shallow ground water. These practices, however, may have far-reaching effects on the ecology of the area. While these effects might be tolerable, careful study of them is advisable before the practices are allowed to occur widespread.

Large-scale pumping of ground-water from the deeper zones (limestone and lower aquifers) tends to induce more recharge to these zones which must eventually be at the expense of other parts of the hydrologic cycle.

SURFACE WATER

Despite the abundance of surface water in Northeast North Carolina, there is far less direct information concerning the flow characteristics of streams in this area than for any other part of the state. This lack of information is partly a result of the fact that low stream slopes and tidal influence make measurement of streamflow by conventional techniques impossible, and this area has, therefore, been largely ignored in basic-data collection programs. Flow data have been collected at approximately 100 sites on small streams in the project area (fig. 12), but at most of these only a few measurements were made and these at very low flows. Continuous flow records have been collected at only seven locations within the area. All of these lie in the higher areas west of the Pamlico escarpment, and the degree to which these data are characteristic of the more low-lying outer Coastal Plain is not known. Recognizing the uncertainty involved, the data that are available have been extrapolated to provide estimates of the characteristics of surface waters throughout the area. These characteristics are described in following sections of the report.

Although large estuaries and sounds, that mostly drain areas outside the project area, dominate the topography of northeast North Carolina, surface drainage originating within the area is most important insofar as the areal hydrology is concerned. Detailed maps show that internal natural drainage is accomplished by two distinctly different

Figure 12.--Location of stream-gaging sites in northeast North Carolina.

systems. In the western part of the area, where land surface is more than 25 ft above mean sea level (fig. 2), the well defined dendritic stream system common to the inner Coastal Plain and Piedmont terrains provides for distinctly channeled surface runoff. Farther east, where the land surface is less than 10 ft above mean sea level, the stream system diminishes to a few short channels that tend to drain perpendicularly into the larger rivers and sounds. The number of miles of natural stream channel per square mile of drainage area here is only a small fraction of that found farther inland.

There are two possible implications of this lack of a well-defined drainage pattern. The first is that there is not enough local runoff to require a natural drainage system of the same magnitude as that required farther inland. The gross areal water budget equation (equation 2) shows that this assumption is tenable only if evapotranspiration is sufficiently greater in the outer Coastal Plain to consume much of the water that elsewhere becomes streamflow. The second possible implication is that the amount of surface drainage is consistent with what might be expected from the amount of precipitation, but the nature of the runoff is different in the outer Coastal Plain from that in the inner Coastal Plain.

The exact nature of the drainage is, to a degree, speculative. Visual observations indicate that, during periods of heavy rainfall, the few natural streams expand to great widths and cover large areas of the land surface with what amounts to sheet flow or "swamp drainage." Because of the very low land slopes, this flow consistently does not reach velocities high enough to cut well defined stream channels, except in places where indentions in shorelines of estuaries and sounds allow the flow to concentrate and escape from the land mass. Once flood flows have subsided, the drainage is continued in the form of seepage from the swamps to the shoreline channels. These channels are inundated remnants of ancient channels carved by erosion at a time when sea level was much lower than it is now. Their capacity to transport water is so great in proportion to the amount that presently seeps into them during low-flow periods that net downstream velocities are too low to be measured by conventional techniques.

Average Streamflow

Major Rivers

Large rivers, including the Chowan, Roanoke, Tar, and Neuse Rivers, convey freshwater from a total of nearly 20,000 mi^2 into the project area. The total average flow of all of these rivers is 17,500 ft^3/s which probably amounts to about three times as much streamflow as originates within the area itself.

None of the major rivers have been gaged within the project area, but flow is well defined for 60 to 90 percent of the drainage area outside the project limits. Flow data from the most downstream gage on each stream have been expressed as discharge per square mile, and in this form can be used to estimate flow into the area. On a long-term basis, average flows on a unit basis through all of the major rivers are within narrow limits, ranging from 0.80 $(ft^3/s)/mi^2$ for the Roanoke River to 1.05 $(ft^3/s)/mi^2$ for the Neuse River. These differences are largely a result of differences in rainfall over the various river basins. For shorter periods, however, flow can vary considerably from average values. Figures 13-16 show frequency curves for annual average discharges for each of the four major rivers. These curves define the probability of the annual discharge being equal to or less than, a specified value during any year. For example, the frequency curve for Neuse River, shown on figure 16, shows that in any one year the probability of the annual average discharge being less than 0.4 $(ft^3/s)/mi^2$ is 1 percent. Also from figure 6, the probability that the flow will exceed 2.1 $(ft^3/s)/mi^2$ in any one year is 1 percent.

These discharge statistics for major rivers show the variability of average natural inflows of freshwater into the study area. The next section discusses average flows of streams originating within the area.

Intra-Area Streams

In the absence of direct information concerning the variations in surface runoff over much of the area, flow characteristics can only be estimated from data collected at the higher elevations. For periods of time as long as a year, these estimates are probably valid. Because evapotranspiration is fairly constant from year to year and we have assumed it to be constant across the study area, then annual flow variations should be dependent upon variations in precipitation. Figure 17 is a plot of annual runoff for all gaging stations in, or near, the project area and annual rainfall recorded at the National Weather Service gage nearest each individual site. The correlation coefficient for the relationship is 0.78, and seems to support the assumption that annual runoff can be estimated by subtracting average annual evapotranspiration from annual precipitation. Figure 18 shows annual runoff across the area estimated from rainfall and the curve of figure 17. The calculated runoff was checked against measured runoff at five gaging stations in or near the study area. Each of the gaging stations had at least five years of record and measured runoff from at least 20 mi^2. The values of calculated and measured runoff were nearly identical. Figure 17 can also be used in conjunction with figure 4 to estimate the range in yearly runoff. For example, figure 4 shows that there is about a 4 percent chance that precipitation at New Bern will be equal to or less than 40 in for a given year. Figure 17 shows that when rainfall is

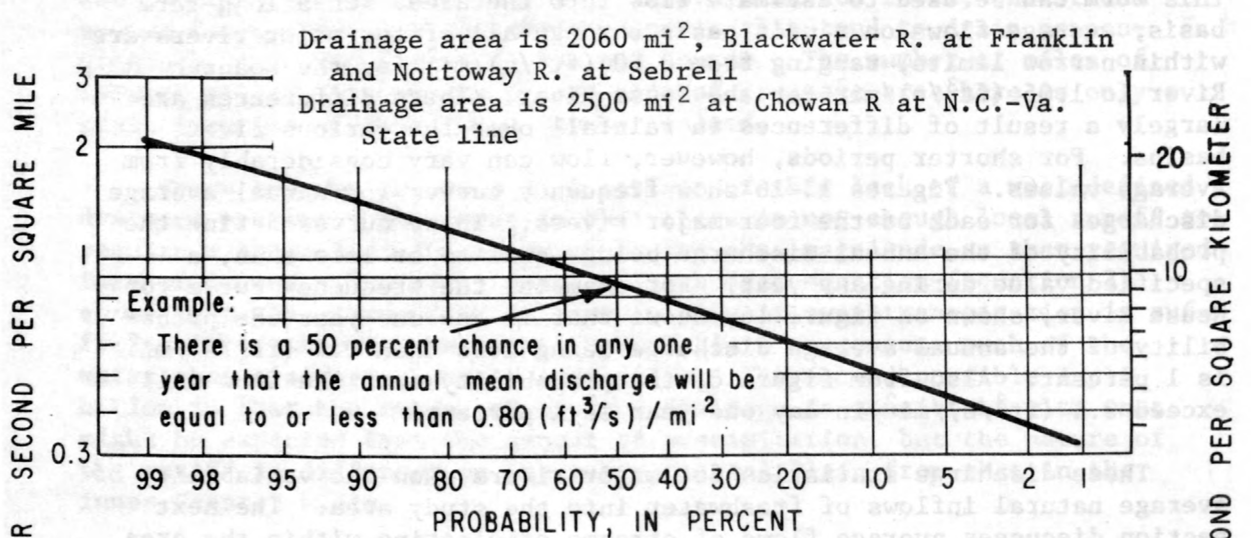


Figure 13.--Frequency curve of annual mean discharges, combination of Blackwater River at Franklin, Va., and Nottoway River near Sebrell, Va.

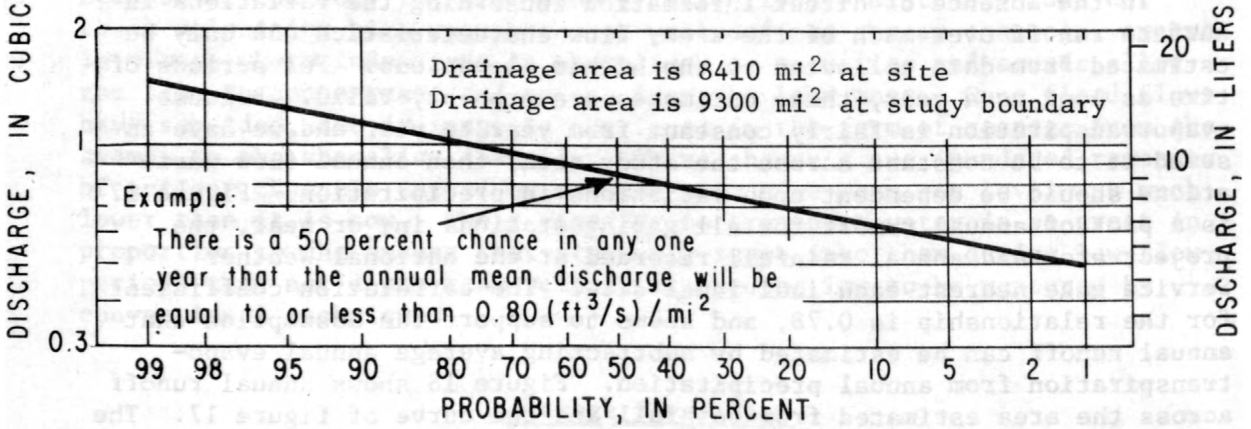


Figure 14.--Frequency curve of annual mean discharge of Roanoke River at Roanoke Rapids, N. C.

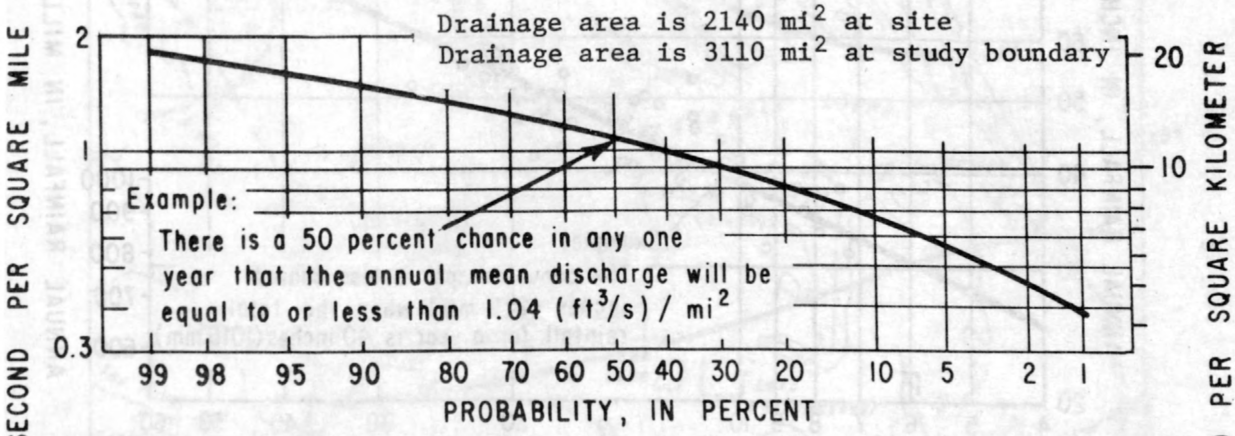


Figure 15.--Frequency curve of annual mean discharge of Tar River at Tarboro, N. C.

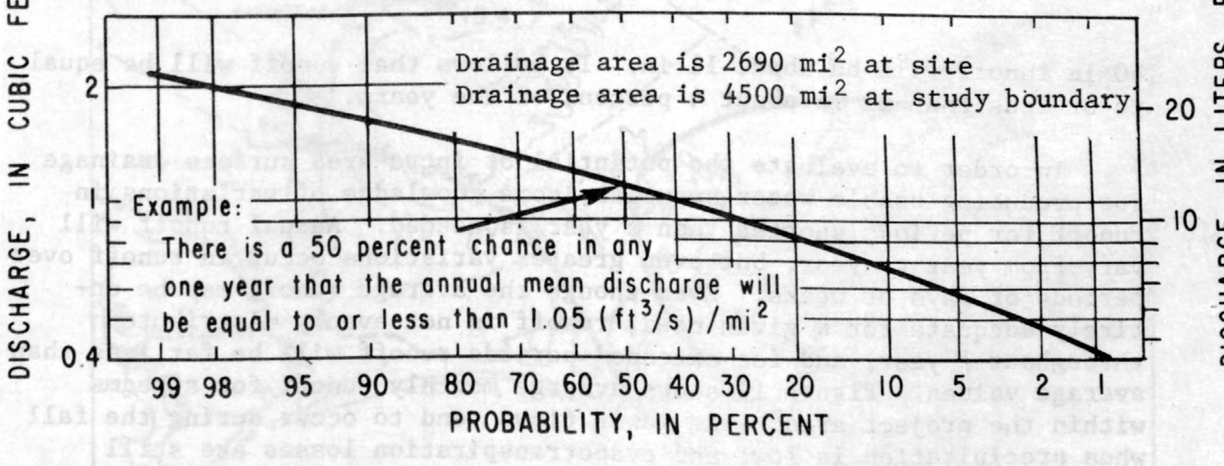


Figure 16.--Frequency curve of annual mean discharge of Neuse River near Kinston, N. C.

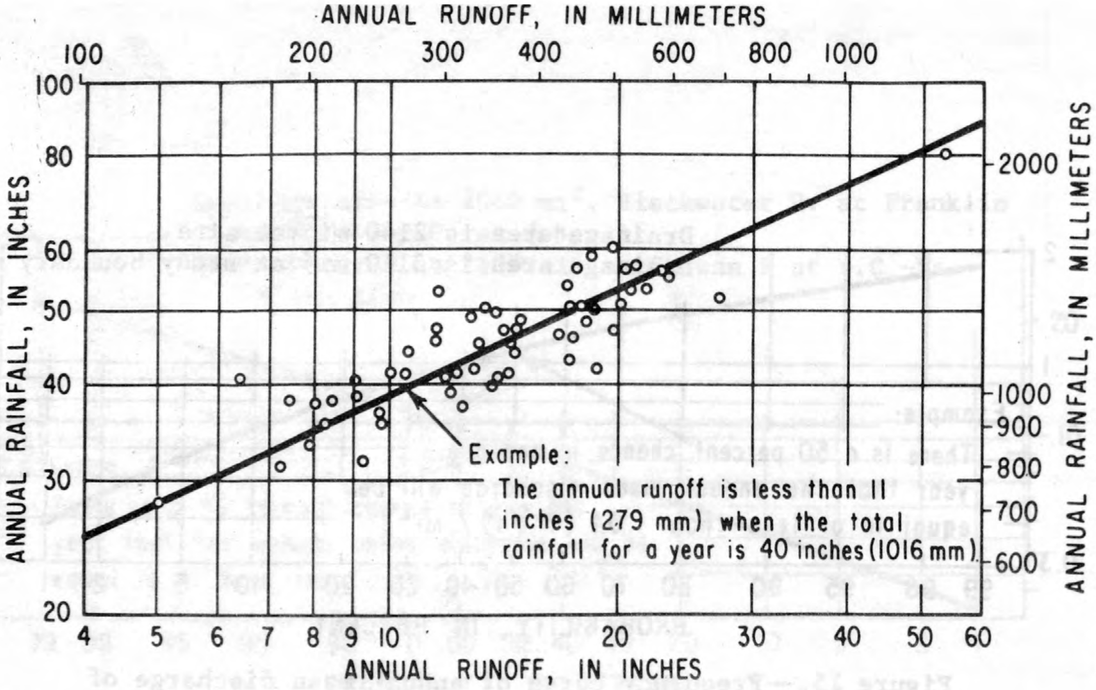
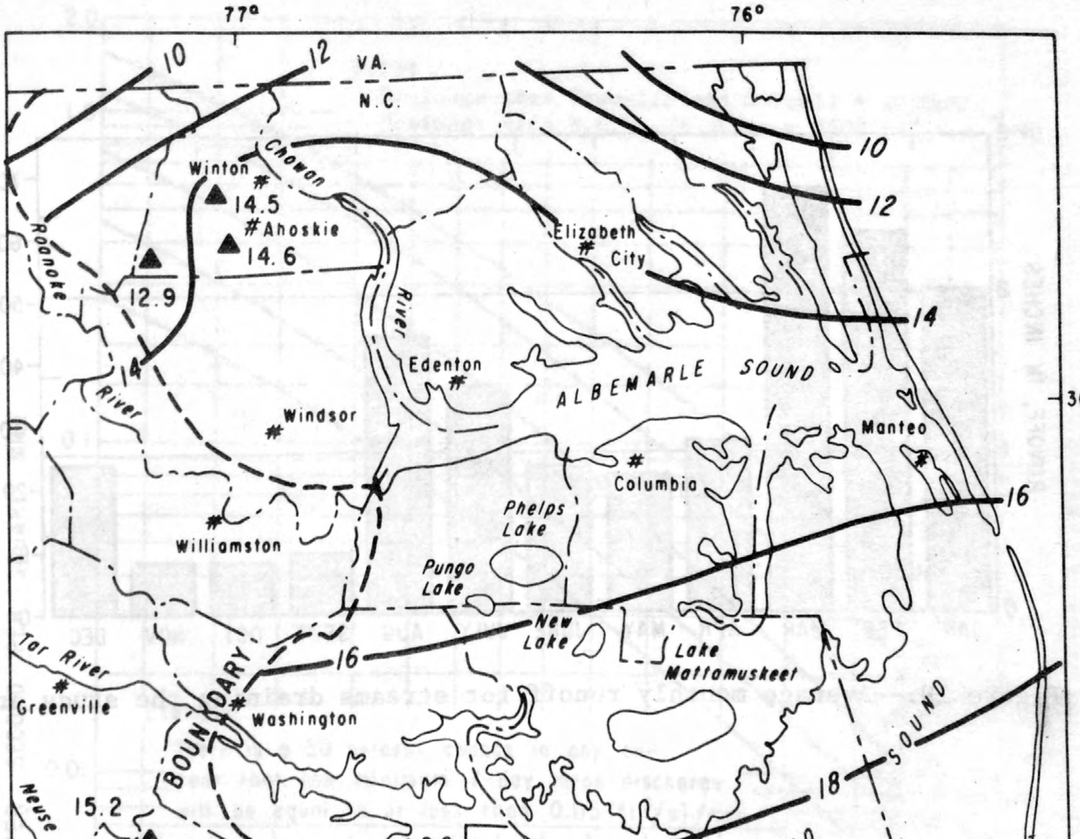


Figure 17.--Relation of annual runoff at gaging sites in eastern North Carolina to annual precipitation at the nearest National Weather Service gage.

40 in runoff will be about 11 in. It follows that runoff will be equal to or less than 11 in about 4 percent of the years.

In order to evaluate the potential of intra-area surface drainage for producing usable water supplies, some knowledge of variations in runoff for periods shorter than a year is needed. Annual runoff will vary from year to year, but even greater variations occur in runoff over periods of days or weeks. Even though the average runoff may be entirely adequate for a given need, runoff is not evenly distributed throughout a year, and for extended periods runoff will be far less than average values. Figure 19 shows average monthly runoff for streams within the project area. The lower flows tend to occur during the fall when precipitation is low, and evapotranspiration losses are still relatively high. Higher flows occur in winter when evapotranspiration is at a minimum. The monthly values shown are based upon data collected at gaging stations that generally have less than ten years of continuous record, and may not be strictly representative of long-term averages. They do, however, indicate the general seasonal variations that might be expected. Even average monthly values do not entirely define the flow variations that must be accounted for, because these values represent the average discharge for a particular month over a period of several years. Obviously, as is shown by the precipitation curves on figure 6, any given month will be much drier some years than it is in other years.



EXPLANATION

18.4 ▲ Gaging station. Number is average annual runoff in inches (1965-70).

—20— Line of equal average annual runoff. Interval 2 inches.

Figure 18.--Average annual runoff calculated from rainfall-runoff relationships, and measured runoff at gaged sites, 1965-70.

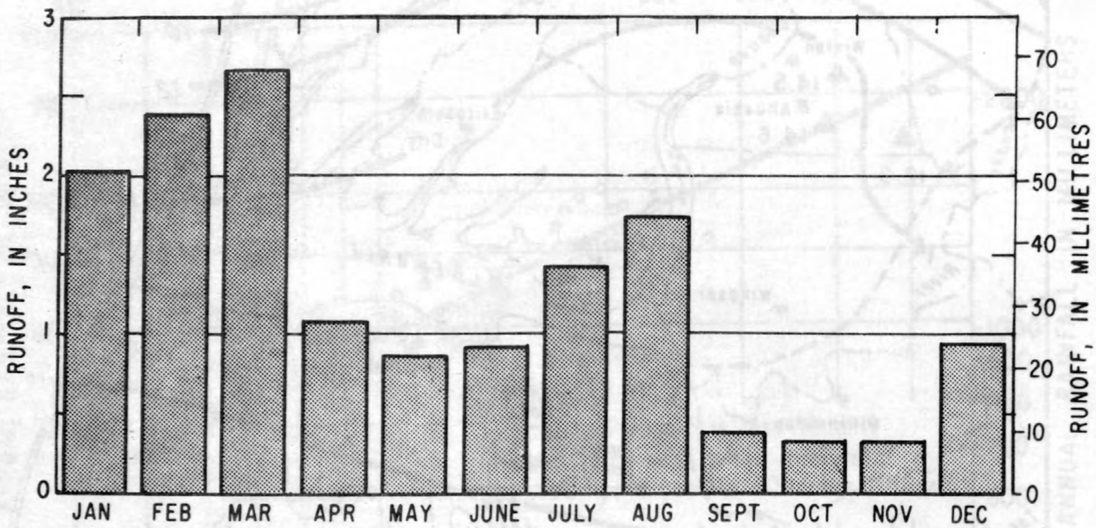


Figure 19.--Average monthly runoff for streams draining the study area.

Low Flows

Major Rivers

The estimates of variations in average-annual discharges shown on figures 13-16 are useful for evaluating general variations in fresh-water inflow into northeast North Carolina or into the estuaries and sounds; but, for most management purposes, flow characteristics that might prevail over shorter periods are more important. Usually the most critical periods are those of prolonged low flow, when salinities in the estuaries and sounds are likely to be highest, and circulation and flushing rates within these tidal waters are at a minimum.

Low-flow characteristics of major rivers entering the area may be evaluated by use of low-flow frequency curves which show the probability of flows being equal to or less than a given value for a specified number of consecutive days. Figures 20-23 show low-flow frequency curves for 7, 30, 60, 120, and 183 days for each of the four major rivers. These curves are compiled from data gathered at the most down-stream gaging station on each stream, except for the Chowan River which is based upon combined flows from Blackwater River at Franklin, Va., and Nottoway River near Sebrell, Va. So that inflow from different areas

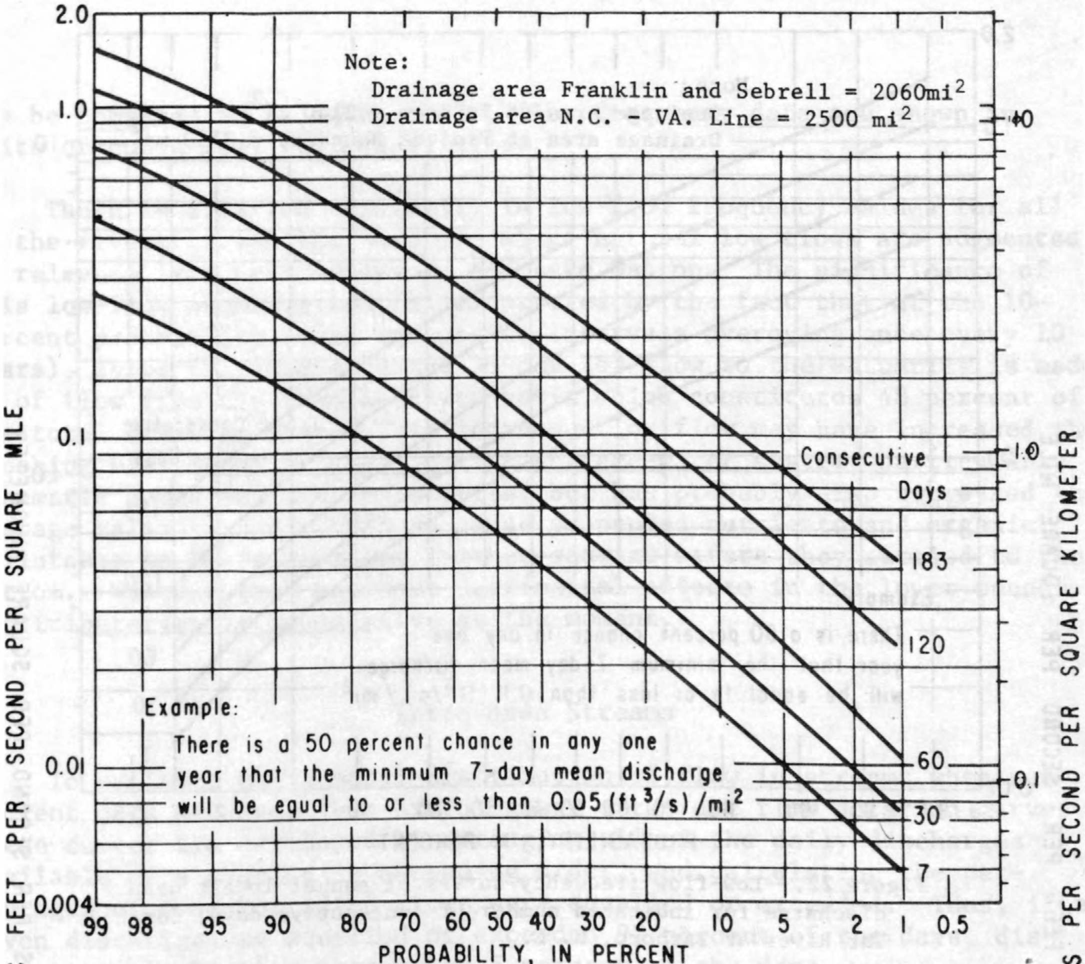


Figure 20.--Low-flow frequency curves of annual lowest mean discharge for indicated number of consecutive days, combination of Blackwater River at Franklin, Va., and Nottoway River at Sebrell, Va.

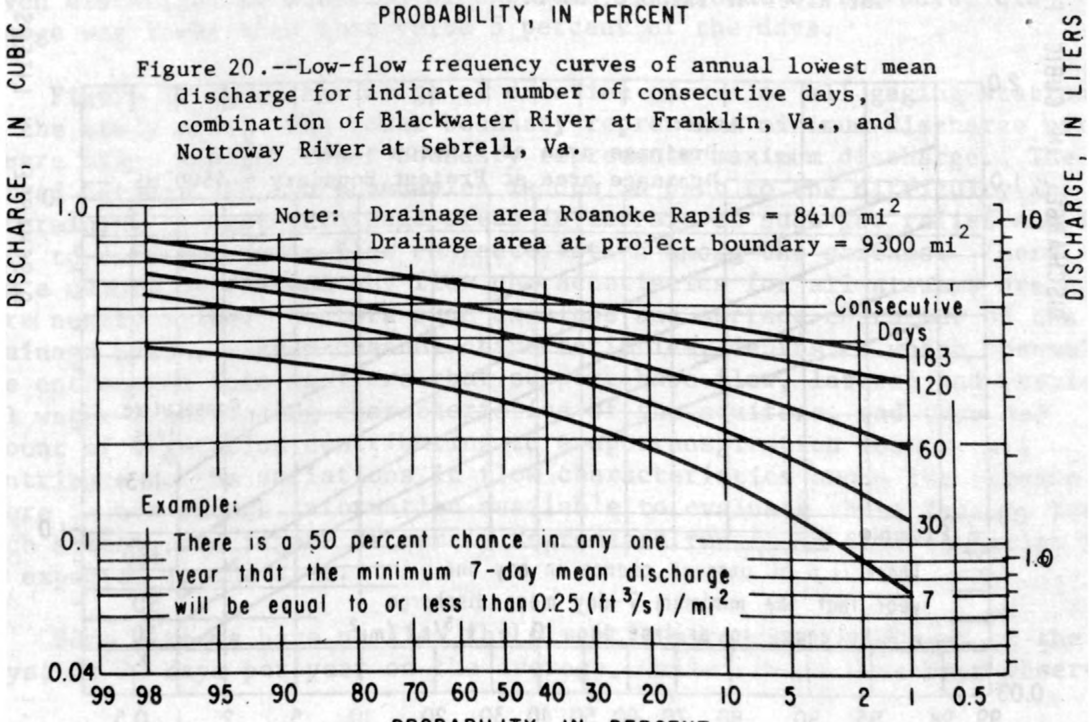


Figure 21.--Low-flow frequency curves of annual lowest mean discharge for indicated number of consecutive days, for Roanoke River at Roanoke Rapids, N. C.

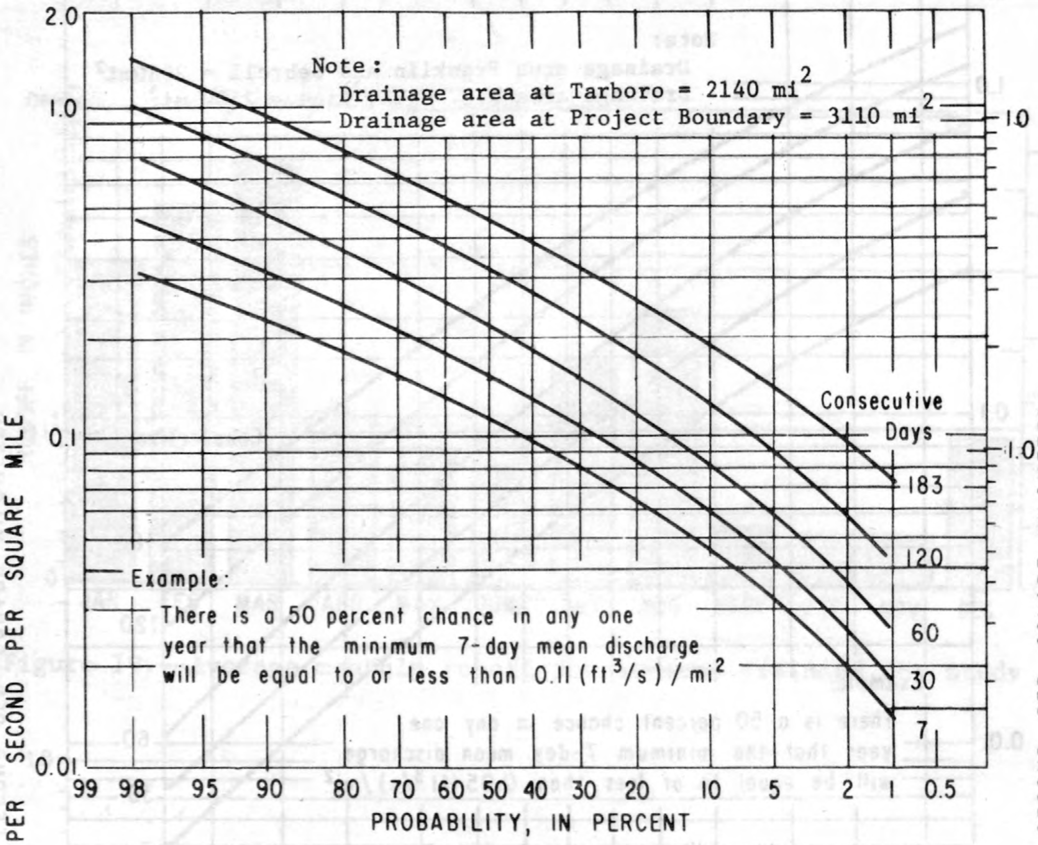


Figure 22.--Low-flow frequency curves of annual lowest mean discharge for indicated number of consecutive days, for Tar River at Tarboro, N. C.

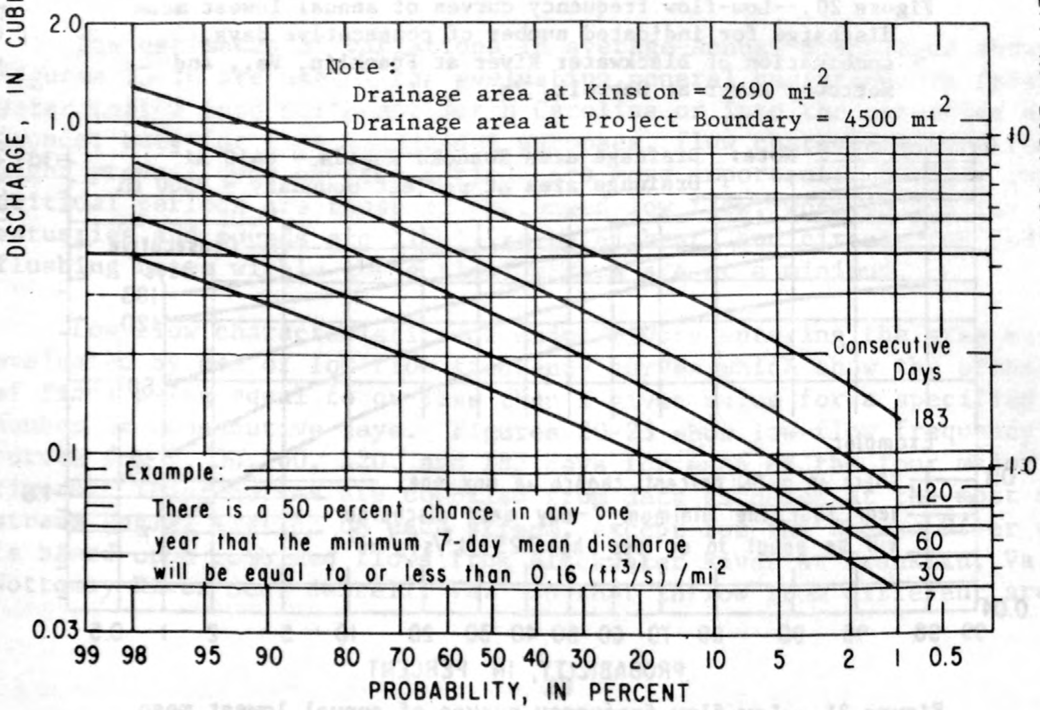


Figure 23.--Low-flow frequency curves of annual lowest mean discharge for indicated number of consecutive days, for Neuse River near Kinston, N. C.

may be compared on an equal basis, flow frequency data are shown in units of cubic feet per square mile.

There is a marked similarity in low-flow frequency values for all of the rivers except the Roanoke, where natural low flows are augmented by releases from Kerr Reservoir and Lake Gaston. The significance of this low-flow augmentation is illustrated by the fact that at the 10-percent probability level (occurs at intervals averaging once every 10 years), about 75 percent of the 30-day low flow to the estuaries is made up of flow from the Roanoke River basin which constitutes 48 percent of the total drainage area. This increased low flow may have increased the flushing efficiency of the brackish surface-water system, particularly Albemarle Sound and its tributaries, but has probably also decreased the average salinity and tended to cause suspended nutrients and organic pollutants to be transported farther seaward before they settled to the bottom. Whether this may have detrimental effects in the lower sounds and tributaries is speculative at the moment.

Intra-Area Streams

To evaluate the general distribution of flow in streams when sufficient data are available hydrologists often use flow duration curves. These curves are developed by arranging all of the daily discharges available at a station in ascending order, and calculating the percentages of days specified flows were equalled or exceeded. Thus, if a given discharge was equalled or exceeded 95 percent of the days, discharge was lower than that value 5 percent of the days.

Figure 24 shows the range of duration curves at all gaging stations in the study area. The lower boundary represents minimum discharge per square mile, and the upper boundary represents maximum discharge. The spread between the two boundaries is due in part to the difficulty in determining accurate drainage areas in terrain of such low relief and in part to differences in flow characteristics among the streams. There are a number of reasons why flow characteristics for all streams are not more nearly alike. Factors such as slope and surface character of the drainage basin, stream-channel characteristics, depths to which channels are entrenched into aquifers that support base flow, lateral and vertical water-transmitting characteristics of the aquifers, and type and amount of vegetation contributing to evapotranspiration losses, all contribute to the variations in flow characteristics among the streams. There is not enough information available to evaluate these factors for each stream, and figure 24 merely represents ranges in flow variation to be expected in the area.

Some streams have no flow for slightly more than 5 percent of the days, or 20 days per year on the average, while others have been observed

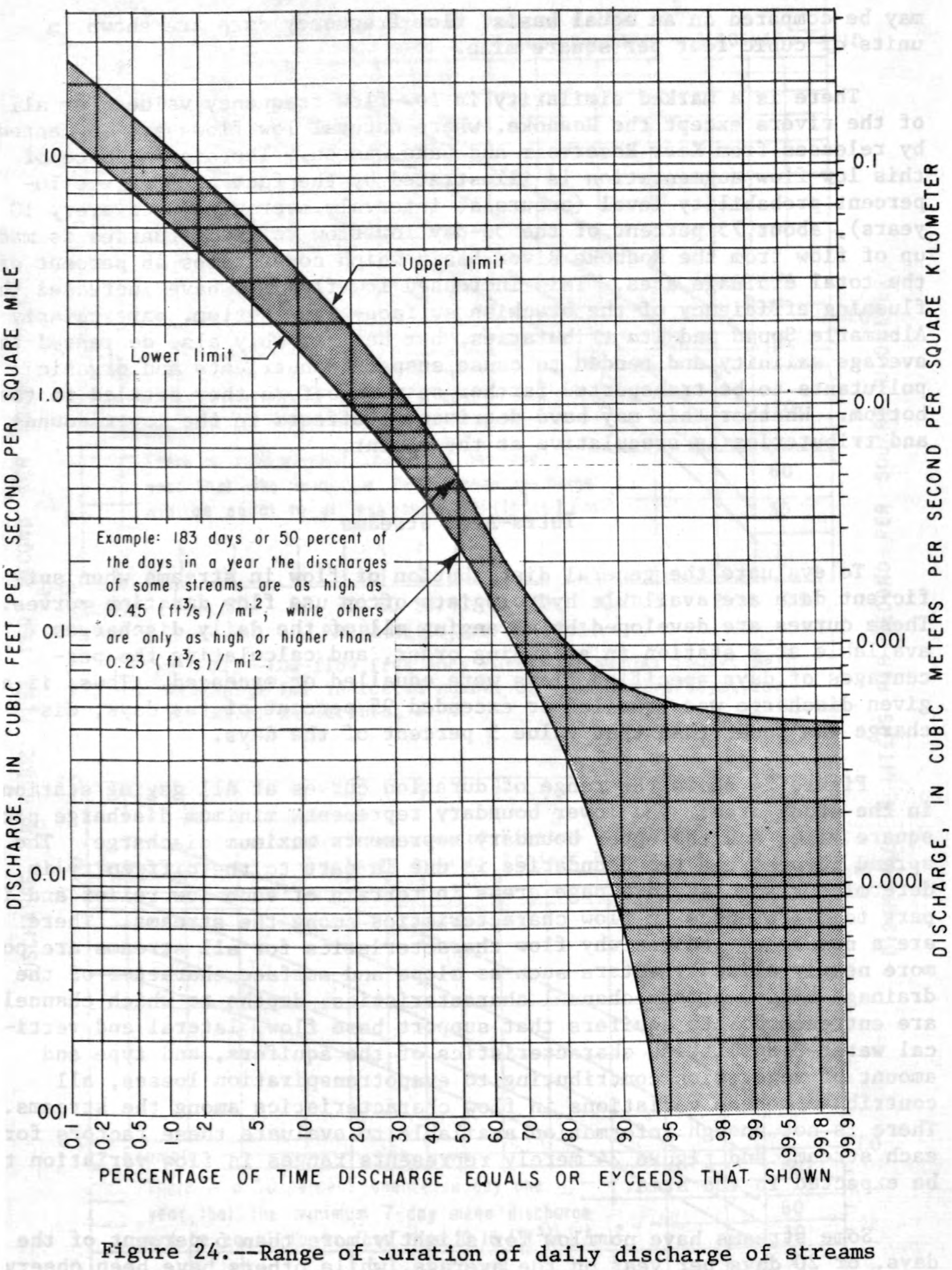


Figure 24.--Range of duration of daily discharge of streams in the study area.

to reach zero flow for shorter periods or not at all. As discussed later in the report, large differences in the distribution of flows equalled or exceeded about 75 percent of the time are probably caused by increased base flow resulting from artificially deepening stream channels for improved drainage.

Surface-Water Ground-Water Relations

A major key to successful management of the water resources of the study area is an understanding of the relation between surface water and ground water, because base flow of perennial streams is derived from ground-water seepage. In northeast North Carolina the relation is so intimate that it is impractical to consider surface water and ground water in any manner except as two phases of the same system. The natural water table is at or near land surface throughout much of the area. Small stream channels, where they exist, are quite shallow, and most of the time flow in them is maintained from stored water contributed chiefly by the top few feet of the uppermost aquifer. Consequently any management practices that affect the water table would be reflected rapidly in stream discharge.

The portion of total streamflow that comes from the ground-water system may be estimated by separating the discharge hydrographs of a stream into the ground-water contribution to runoff and overland runoff. Ground-water runoff was determined by a hydrograph separation technique described by Rasmussen and Andreasen (1959, p. 63). This technique was used to establish a relation between ground-water runoff in Creeping Swamp near Vanceboro, North Carolina, and the average ground-water level in a water-table observation well 0.4 mi from the gage on Creeping Swamp during times when all the streamflow is ground-water discharge. The relation is shown in figure 25. Daily average water levels in the well were plotted against the daily average discharge of Creeping Swamp at times during October 1971 to September 1972 preceding rises in the stream when base flow conditions prevailed.

The relation in figure 25 shows how ground-water runoff to Creeping Swamp may be estimated for all conditions, including periods when overland runoff is also occurring. The ground-water runoff component of streamflow in Creeping Swamp is compared with total streamflow on figure 26.

Base flow was about 65 percent of the total flow for the period shown in figure 26. The 1972 water year was chosen because a record of good quality and continuity was available. This was an exceptionally wet year, however, with the total runoff being 31 in as compared to the average of about 16 in. During more normal years the amount of overland runoff would be less, and the percentage of base flow would be higher.

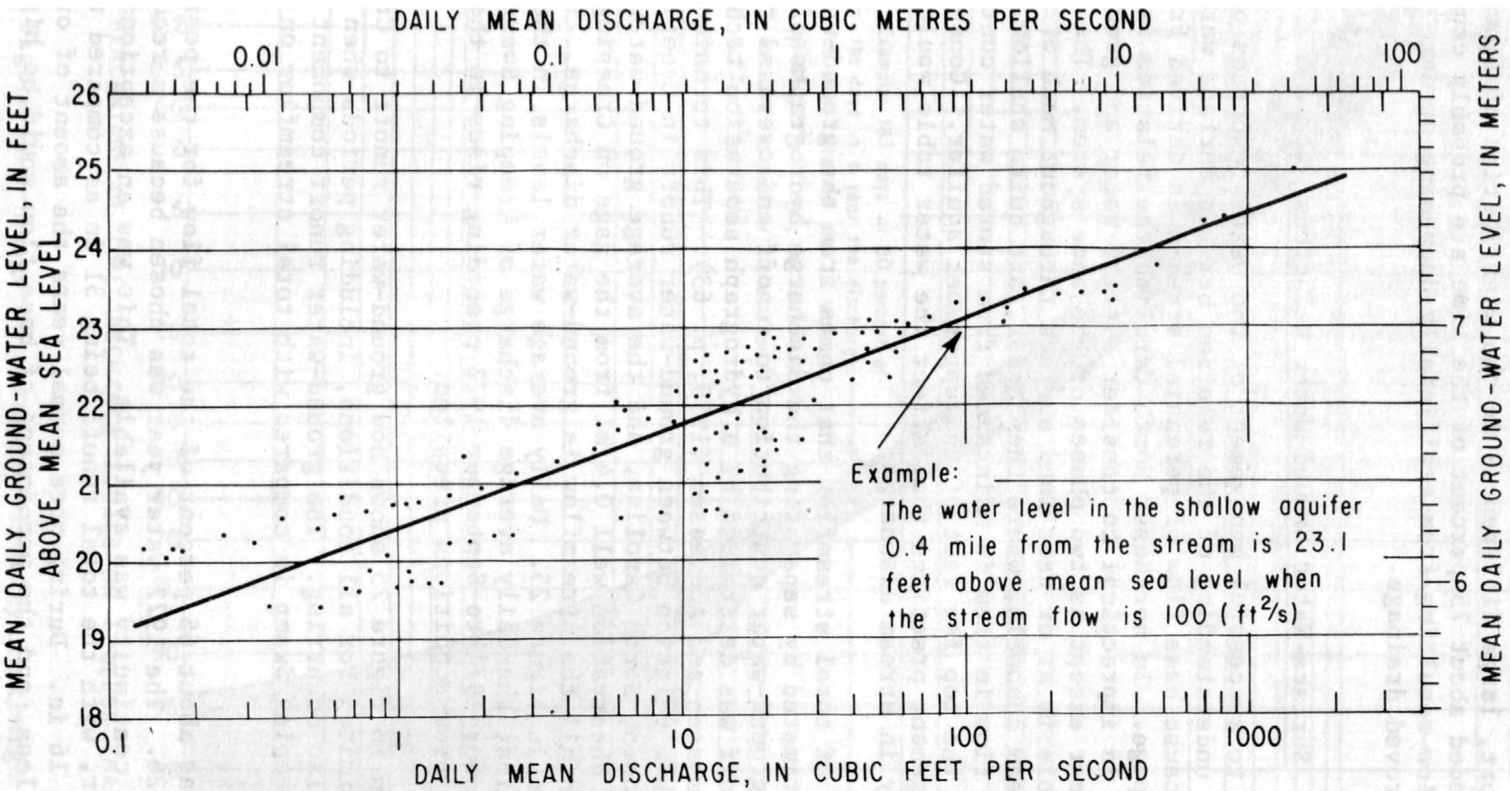


Figure 25.--Relation between water levels in a shallow well 0.4 mi (0.6 km) from stream and discharge at gaging station, Creeping Swamp near Vanceboro, N.C., October 1971-September 1972.

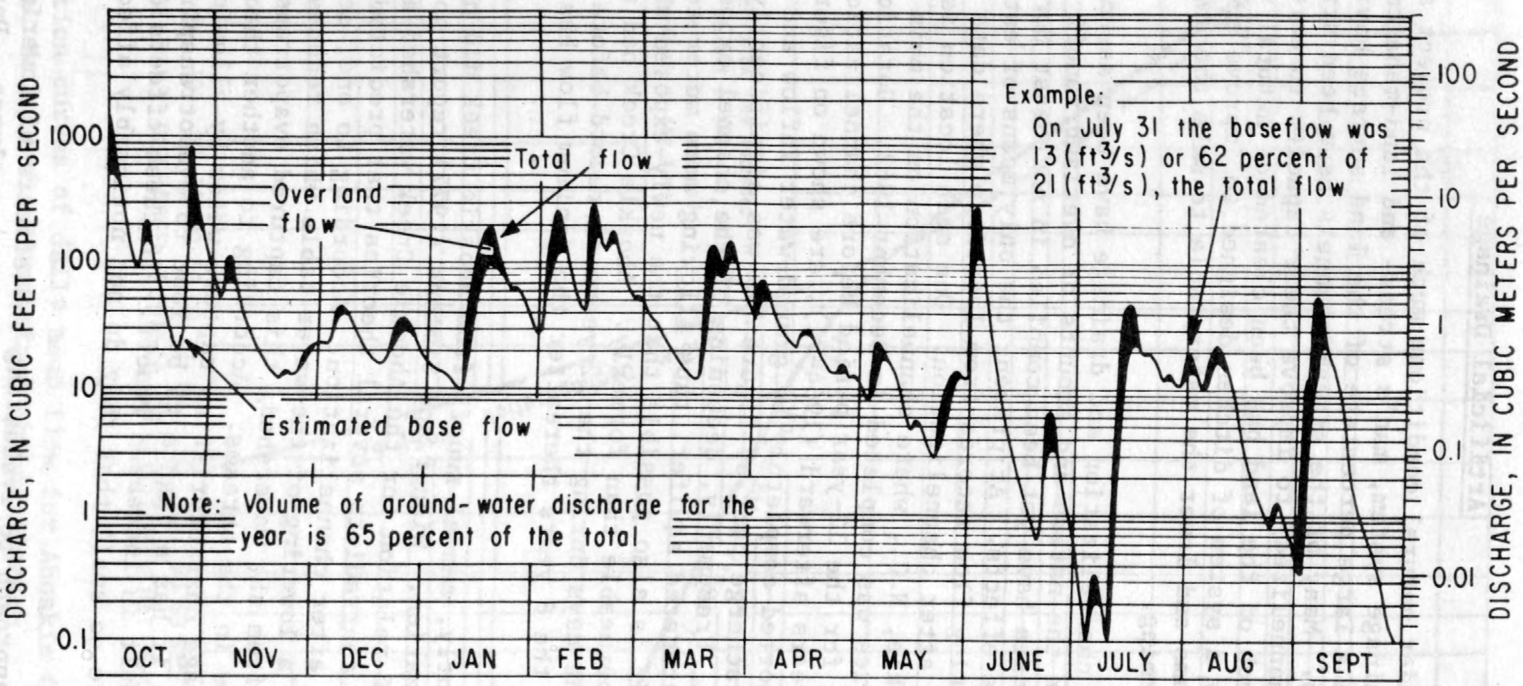


Figure 26.--Discharge at Creeping Swamp near Vanceboro, N.C., showing base flow October 1971-September 1972.

Artificial Drainage

Although under natural conditions much of the project area has no well-defined drainage system, man's stream- and land-management practices have resulted in a large percentage of the land surface having efficient drainage systems. Many of the stream channels have been straightened and deepened (channelized) to improve their capacity to carry high flows. Also, much of the land has been cleared of natural vegetation and dissected by a system of ditches designed to improve surface drainage to the streams and lower the water table to make the swampy areas suitable for farming.

Artificial channelization and drainage have been assumed to significantly alter the nature and amounts of overland runoff in coastal areas; but few data have yet been compiled in northeast North Carolina to measure these effects. At present the only means of estimating them is by extrapolating flow records from locations where data are available both before and after channelization. One such location is Ahoskie Creek near Ahoskie, N.C., where channelization on the main stem and some of its tributaries was completed in December 1962. Duration curves of daily discharge for the 12-year period before channelization (1951-62), and for the 8 years afterward (1964-71), are shown on figure 27. Base flow--that supported completely by ground-water inflow and represented on the lower discharge part of figure 27--was significantly higher after channelization. Presumably, deepening of the channel exposed a greater thickness of saturated aquifer, thus allowing more water to seep into the channel. It is also possible that the newly-exposed channel boundaries are more permeable than formerly. Ahoskie Creek had no flow about 5 percent of the days during the 12 years of record before channelization, but in the 8 years thereafter the minimum flow has been 2 and 3 ft^3/s.

Significantly, annual runoff from Ahoskie Creek did not increase after channelization. Winner and Simmons (1977) report no change in the rainfall-runoff relation for the Ahoskie Creek watershed after channelization. This contradicts several theories that predicted annual runoff would increase after channelization. According to one, deepening the channel causes a lowering of the water table which reduces evapotranspiration losses from the watershed; this captured evapotranspiration becomes base flow in the streams. According to another theory, the improved drainage characteristics capture water by allowing it to enter streams before it has a chance to be lost to evapotranspiration. This would also result in increased runoff. If these effects do in fact occur, they are so small that they do not noticeably affect the water budget.

Another approach to evaluating the effects of lowering the bed of the channel is by use of low-flow frequency analyses. Duration curves,

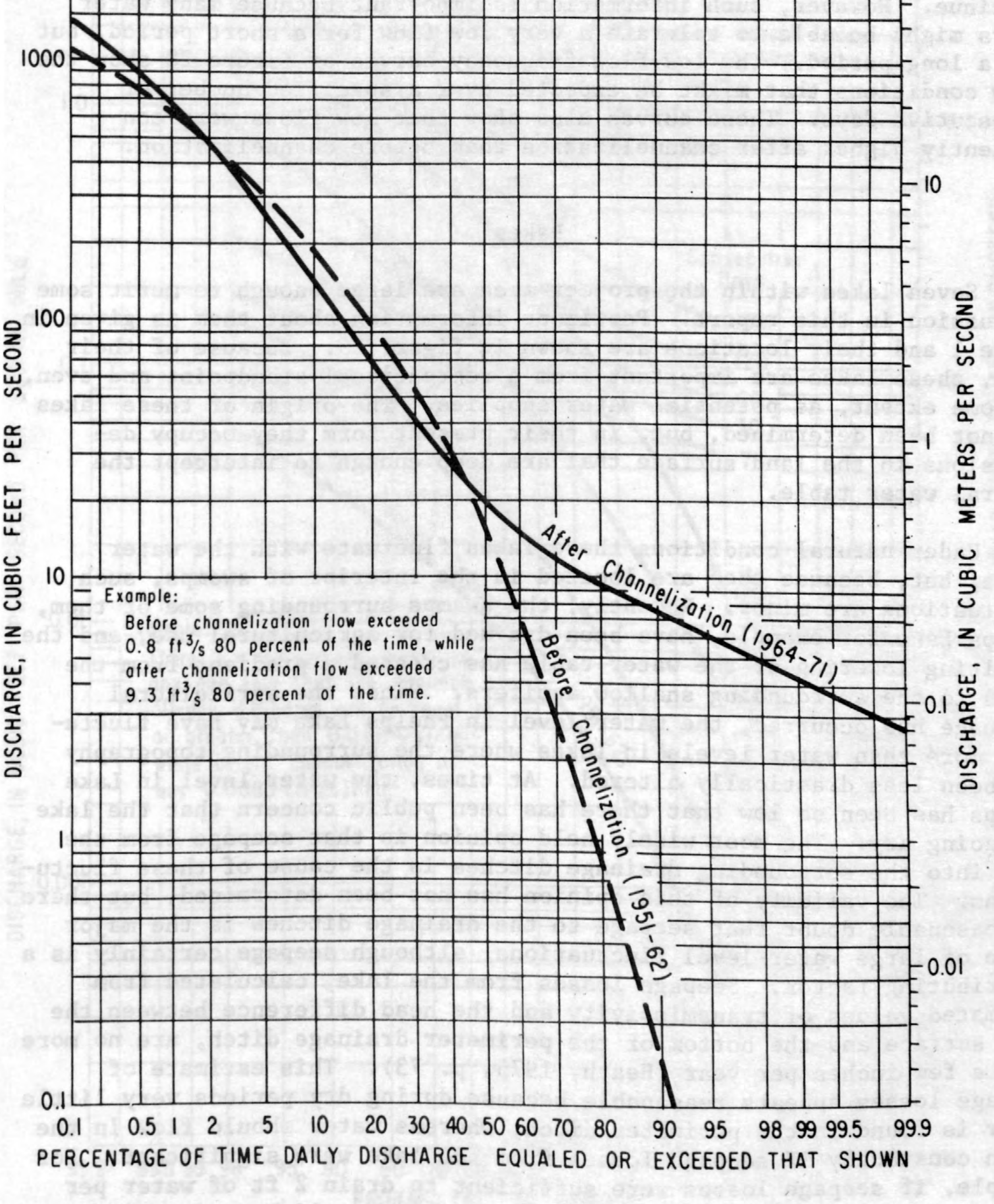


Figure 27.--Duration curves of daily mean flow for Ahoskie Creek at Ahoskie, N.C., before and after channelization.

such as figure 27, show the distribution of daily discharges, but give no indication of the length of time a given flow might be expected to continue. However, such information is important because many water users might be able to tolerate a very low flow for a short period, but not a long period. The low-flow frequency curves of figure 28 show the flow conditions that might be expected over a specified number of consecutive days. These curves also show that low flows were consistently higher after channelization than before channelization.

Lakes

Seven lakes within the project area are large enough to merit some discussion in this report. Pertinent information about them is given in table 1 and their locations are shown in figure 29. Because of their size, these lakes are important from a recreational standpoint and even, to some extent, as potential water supplies. The origin of these lakes has not been determined, but, in their present form they occupy depressions in the land surface that are deep enough to intercept the natural water table.

Under natural conditions these lakes fluctuate with the water table; but, because they are located in the interior of swamps, such fluctuations are minor. Recently, the swamps surrounding some of them, Phelps Lake for example, have been drained for agricultural use, and the resulting lowering of the water table has created a gradient from the lakes to the surrounding shallow aquifers. Since the agricultural drainage has occurred, the water level in Phelps Lake may have fluctuated more than water levels in lakes where the surrounding topography has been less drastically altered. At times, the water level in Lake Phelps has been so low that there has been public concern that the lake was going dry. The most widely held opinion is that seepage from the lake into the surrounding drainage ditches is the cause of these fluctuations. The validity of this opinion has not been determined, but there is reasonable doubt that seepage to the drainage ditches is the major cause of large water-level fluctuations, although seepage certainly is a contributing factor. Seepage losses from the lake, calculated from estimated values of transmissivity and the head difference between the lake surface and the bottom of the perimeter drainage ditch, are no more than a few inches per year (Heath, 1975, p. 73). This estimate of seepage losses appears reasonable because during dry periods very little water is found in the perimeter ditch, whereas water should flow in the ditch constantly if seepage losses from the lake were significant. For example, if seepage losses were sufficient to drain 2 ft of water per year from the lake, a constant flow of 45 ft^3/s would be maintained in the ditch. Even if this flow were to leave the ditch at a velocity of 2 ft/s, which is an unrealistically high velocity for this area, the ditch would be about 80 percent full of flowing water at all times from

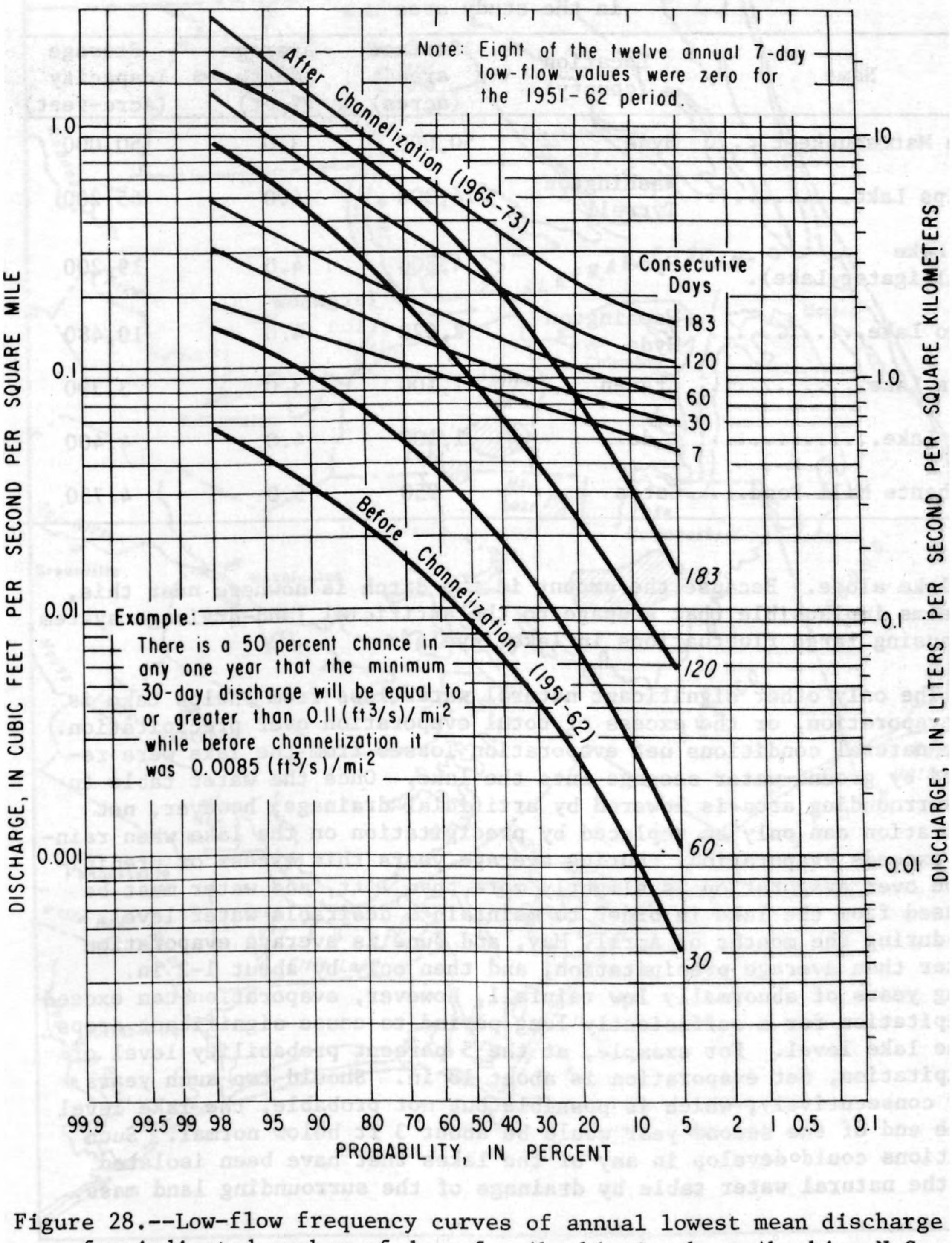


Figure 28.--Low-flow frequency curves of annual lowest mean discharge for indicated number of days for Ahoskie Creek at Ahoskie, N.C., before and after channelization.

Table 1.--Physical characteristics of the seven largest lakes in the study area

Name	Location (county)	Surface area (acres)	Average depth (feet)	Storage capacity (acre-feet)
Lake Mattamuskeet.....	Hyde	50,000	3.0	150,000
Phelps Lake..........	Washington Tyrrell	16,300	4.0	65,200
New Lake (Alligator Lake).	Hyde	4,800	4.0	19,200
Pungo Lake...........	Washington Hyde	2,620	4.0	10,480
Ellis Lake...........	Craven	1,100	3.0	3,300
Long Lake............	do.	1,100	4.0	4,400
Merchants Mill Pond...	Gates	950	5.0	4,750

the lake alone. Because the amount in the ditch is nowhere near this, it seems implausible that seepage to the artificial land-drainage system is causing large fluctuations in lake levels.

The only other significant natural water loss from Phelps Lake is net evaporation, or the excess of total evaporation over precipitation. Under natural conditions net evaporation losses from the lake were replaced by ground-water seepage into the lake. Once the water table in the surrounding area is lowered by artificial drainage; however, net evaporation can only be replaced by precipitation on the lake when rainfall exceeds evaporation. During average years this excess of precipitation over evaporation is slightly more than 1 ft, and water must be released from the lake in order to maintain a desirable water level. Only during the months of April, May, and June is average evaporation greater than average precipitation, and then only by about 1-2 in. During years of abnormally low rainfall, however, evaporation can exceed precipitation for a sufficiently long period to cause significant drops in the lake level. For example, at the 5 percent probability level of precipitation, net evaporation is about 18 in. Should two such years occur consecutively, which is possible but not probable, the lake level at the end of the second year would be about 3 ft below normal. Such conditions could develop in any of the lakes that have been isolated from the natural water table by drainage of the surrounding land mass.

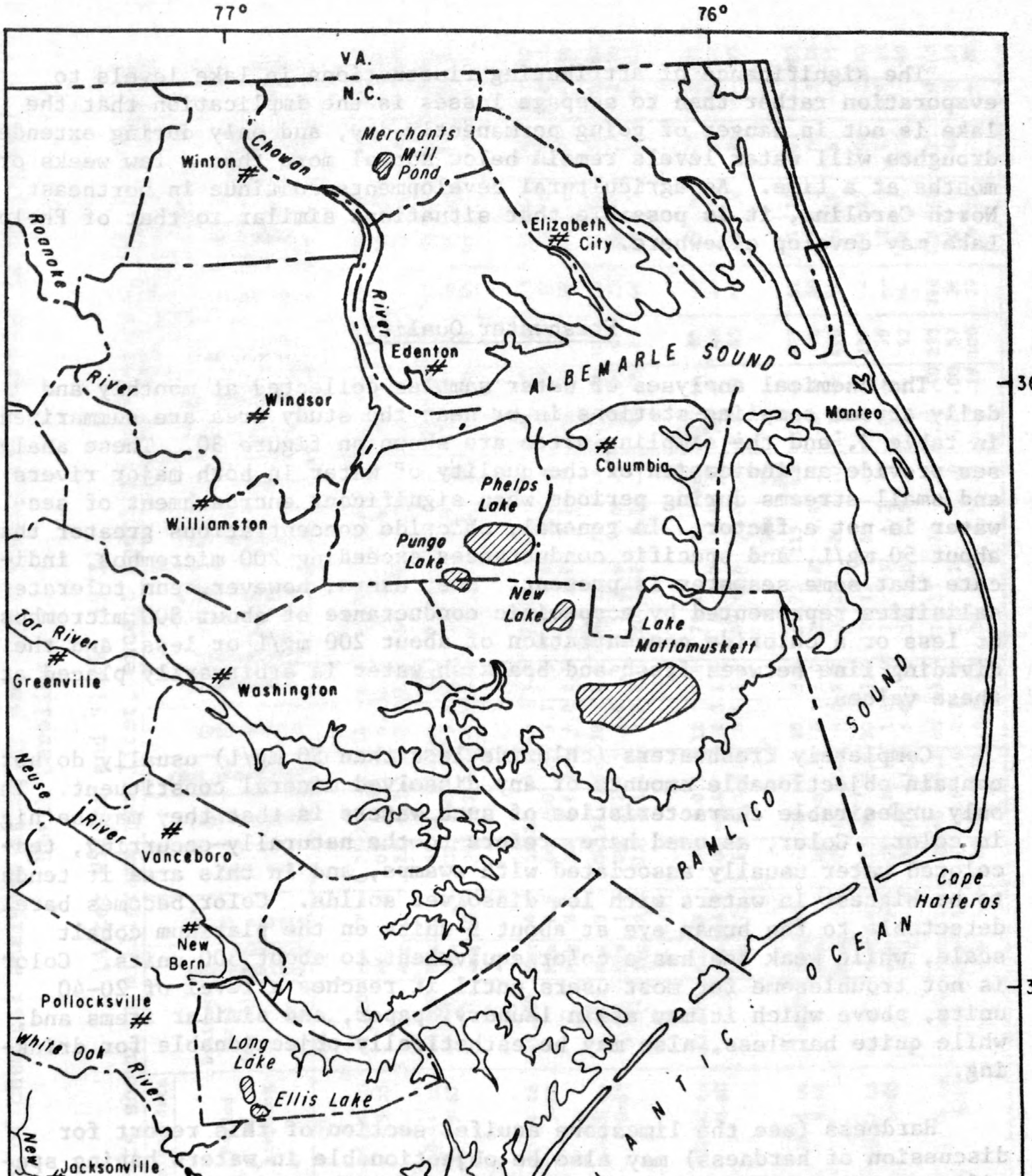


Figure 29.--Location of large lakes in northeast North Carolina.

The significance of attributing fluctuations in lake levels to evaporation rather than to seepage losses is the implication that the lake is not in danger of going permanently dry, and only during extended droughts will water levels remain below normal more than a few weeks or months at a time. As agricultural developments continue in northeast North Carolina, it is possible that situations similar to that of Phelps Lake may develop elsewhere.

Freshwater Quality

The chemical analyses of water samples collected at monthly and daily stream sampling stations in or near the study area are summarized in table 2, and the sampling sites are shown on figure 30. These analyses provide an indication of the quality of water in both major rivers and small streams during periods when significant encroachment of seawater is not a factor. In general, chloride concentrations greater than about 50 mg/L, and specific conductances exceeding 200 micromhos, indicate that some seawater is present. Most users, however, can tolerate salinities represented by a specific conductance of about 800 micromhos or less or a chloride concentration of about 200 mg/L or less, and the dividing line between fresh and brackish water is arbitrarily placed at these values.

Completely freshwaters (chloride less than 50 mg/L) usually do not contain objectionable amounts of any dissolved mineral constituent. The only undesirable characteristics of such waters is that they may be high in color. Color, as used here, refers to the naturally-occurring, tea-colored water usually associated with swamps, and in this area it tends to be highest in waters with low dissolved solids. Color becomes barely detectable to the human eye at about 5 units on the platinum cobalt scale, while weak tea has a color equivalent to about 300 units. Color is not troublesome for most users until it reaches a level of 20-40 units, above which it may stain laundry, paper, and similar items and, while quite harmless, also may be esthetically objectionable for drinking.

Hardness (see the limestone aquifer section of this report for discussion of hardness) may also be objectionable in waters having specific conductance much greater than 200 micromhos. The waters in most rivers and streams of northeastern North Carolina are soft if no seawater is intermixed with them. Because magnesium is the second most abundant dissolved constituent in seawater, hardness increases rapidly when seawater encroachment occurs.

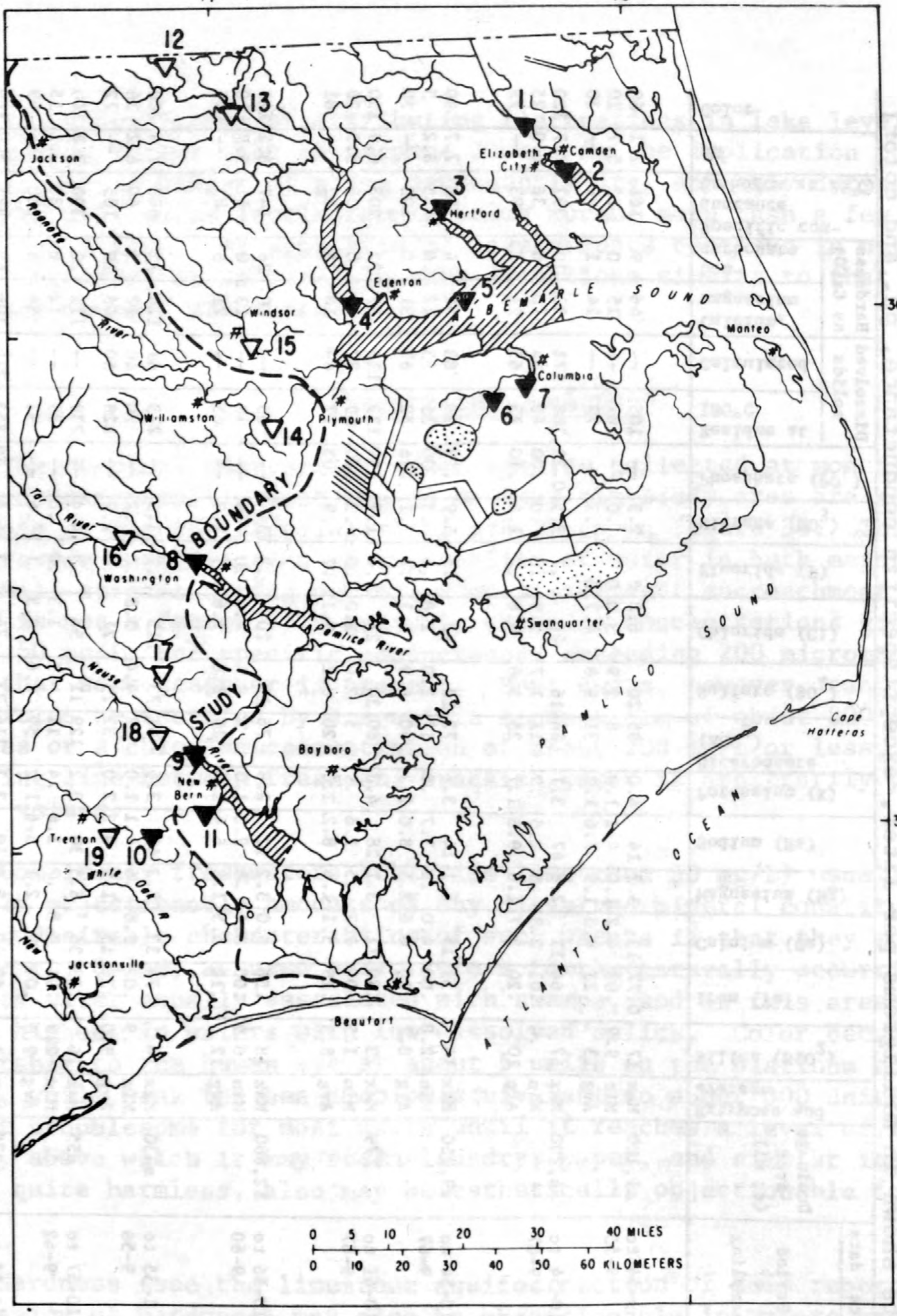
Table 2.--Summary of chemical analyses at daily and monthly sampling stations in northeast North Carolina

[After Wilder and Slack, 1971]

[Chemical constituents shown in milligrams per liter, except specific conductance, pH, and color]

Map No.	Station name	Chemical data: Sampling frequency [b]	Chemical data: Period of sampling	Drainage area (sq mi)	Extremes and average	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphate (PO_4)	Dissolved solids: Residue at 180°C	Dissolved solids: Calculated	Hardness as $CaCO_3$: Calcium, magnesium	Hardness as $CaCO_3$: Non-carbonate	Specific conductance (µmho/cm at 25°C)	pH	Color
	CHOWAN RIVER BASIN																							
12	Meherrin River near Severn, N.C.	M	9-54 to 9-55	[a]1,120	Max	17	0.77	13	3.2	14	4.0	83	20	6.8	0	2.3	--	105	--	46	9	166	7.1	60
					Min	9.9	.03	4.2	1.0	4.1	1.3	8	2.9	3.0	0	.0	--	61	--	15	0	62	5.7	10
					Avg	13	.22	6.3	1.9	7.6	1.9	31	9.8	4.7	0	.7	--	73	--	24	1	96	--	30
13	Chowan River at Winton, N.C.	D	10-54 to 9-67	[a]4,200	Max	17	.64	11	2.8	47	3.1	84	16	46	.7	3.5	0.20	188	171	36	10	297	7.7	320
					Min	.4	.01	2.9	.5	2.5	.9	11	1.7	2.9	.0	.0	.00	40	34	10	0	36	6.0	25
					Avg	10	.20	5.7	1.6	9.3	1.7	25	5.6	9.6	.2	1.4	.10	73	65	21	2	93	--	73
	ROANOKE RIVER BASIN																							
14	Roanoke River at Jamesville, N.C.	D	10-54 to 9-67	[a]9,250	Max	14	.59	15	4.1	14	3.6	72	12	12	.5	5.9	.23	98	83	52	4	188	7.7	90
					Min	2.8	.00	4.0	.5	3.7	.6	17	2.0	2.8	.0	.3	.00	35	33	12	0	55	6.2	5
					Avg	8.7	.10	8.6	2.5	8.0	2.1	40	6.9	6.1	.1	2.1	.06	72	67	31	0	105	--	30
15	Cashie River at Windsor, N.C.	M	10-61 to 9-67	179	Max	23	.80	11	3.1	28	4.8	60	34	23	.4	1.7	.50	129	115	37	32	203	6.9	160
					Min	1.5	.00	2.2	.5	1.6	.9	5	2.6	2.0	.0	.3	.00	49	22	10	0	34	5.3	20
					Avg	8.3	.19	5.1	1.4	8.2	2.0	20	8.2	9.1	.2	.9	.05	77	49	18	5	82	--	81
	PAMLICO RIVER BASIN																							
16	Tar River near Pactolus, N.C.	D	10-56 to 9-60	[a]2,680	Max	18	.56	9.0	3.2	12	2.8	76	19	20	.3	13	--	85	--	60	26	147	8.1	120
					Min	6.9	.00	3.4	.8	2.3	1.0	8	2.7	4.4	.0	.6	--	48	--	13	0	51	5.9	10
					Avg	12	.14	5.5	1.8	6.4	1.8	19	6.8	7.6	.1	2.3	--	65	--	21	5	81	--	45
	NEUSE RIVER BASIN																							
17	Swift Creek at Vanceboro, N.C.	D	1-55 to 9-56	[a]230	Max	16	.74	33	8.3	40	3.6	61	73	115	.2	3.3	--	273	61	114	72	603	7.4	200
					Min	.9	.02	5.6	.6	4.1	1.0	12	4.4	5.8	.0	.2	--	70	40	17	3	60	6.2	16
					Avg	9.0	.28	15	1.9	9.2	2.0	32	23	21	.0	1.7	--	128	50	46	19	185	--	72
18	Batchelders Creek near Streets Ferry, N.C.	M	10-57 to 9-62	[a]55	Max	16	.33	36	6.5	30	3.2	129	11	58	.3	4.4	--	239	--	111	22	390	7.8	140
					Min	2.9	.01	3.8	.7	1.6	.4	11	.5	1.3	.0	.0	--	39	--	12	0	35	6.1	15
					Avg	9.0	.09	18	2.1	5.6	1.2	59	4.6	8.5	.1	.6	--	93	--	54	6	130	--	49
19	Trent River at Pollocksville, N.C.	D	1-55 to 9-67	[a]370	Max	11	.69	40	5.6	40	3.3	116	23	74	.3	6.4	.40	253	216	106	40	421	8.0	160
					Min	3.5	.00	5.6	.4	2.2	.2	12	3.2	2.5	.0	.1	.00	57	36	20	0	48	6.1	10
					Avg	6.8	.18	21	1.4	4.8	.9	58	9.0	7.4	.2	1.5	.19	100	77	50	11	139	--	80

a/ Approximate. b/ Sampling frequency: D - daily; M - monthly.



EXPLANATION

5 ▼ **Seawater encroachment station and number.**

14 ▽ **Water quality sampling station for which analyses are summarized in table 2.**

Freshwater part of the time and saltwater part of the time.

Saltwater most or all of the time.

Freshwater most or all of the time.

Figure 30.--Generalized salinity of surface water in northeast North Carolina and locations of sampling sites.

Table 3 gives chemical analyses of water from the major lakes in northeast North Carolina. With the exception of Lake Mattamuskeet, all of the lakes sampled in the area contain freshwater. Lake Mattamuskeet is contaminated by salty water that probably enters the lake through drainage canals. These canals are equipped with control gates designed to prevent saltwater entering the canals, but the gates sometimes fail to close properly because of clogging by trash and other debris.

Although all of the lakes other than Mattamuskeet are fresh, water in most of them would require treatment to be suitable for most purposes. There is a surprising variability in the quality of water in different lakes. The differences in water quality among the lakes, like other aspects of their hydrology, seem to be related to the degree to which their surrounding physical environment has been distributed by man. Lakes such as Ellis Lake and Long Lake, which are in near-undisturbed settings are highly acidic and contain little or no dissolved calcium. The beds of these lakes are highly organic peaty soils, and a part of their acidity results from carbonic acid produced by decaying carbonaceous matter. The amount of acid in the water, however, is higher than could be derived from peaty soils alone; and, from the chemical analyses in table 3, it seems likely that the additional acidity is sulfuric acid produced naturally in the lake waters by the oxidation of organic sulfides in the peat beds. The nearly complete absence of calcium in these undisturbed lakes is a phenomenon not previously observed in waters of North Carolina. It likely indicates that the peat in this area is at least as deep as the bottom of the lakes, and the shallow ground water that maintains water levels in the lakes has had residence only in materials that contain none of the shell-material often associated with sediments of the area.

Lakes such as Phelps Lake, Pungo Lake, and, to a lesser extent, New Lake, are in areas that have been drained for agriculture. Because they no longer have free access to shallow ground water, they are maintained primarily by precipitation directly on their surfaces. As a result, water in them is quite similar to rain water that has been concentrated 5 to 10 times by evaporation.

Salinity of Estuaries

Wind and tidal action mix fresh and seawaters in the sounds and estuarine reaches of streams in northeast North Carolina to form a brackish zone within which the salinity of the water is intermediate between freshwater and seawater. Near the upstream end of the zone, water is sufficiently fresh to be useful for most purposes (less than 500 mg/L of dissolved solids), while near the downstream end salinities may approach that of seawater (above 30,000 mg/L of dissolved solids). During periods of low freshwater inflow, if winds are generally in an

Table 3.--Chemical analyses of water from lakes in northeast North Carolina

[Chemical constituents shown in milligrams per liter, except specific conductance, pH, and color]

	Phelps Lake nr Cherry, N.C., 5-16-74	Pungo Lake nr Plymouth, N.C., 5-16-74	New Lake nr Kilkenny, NC 5-16-74	Long Lake nr Havelock, NC 5-17-74	Ellis Lake nr Havelock, N.C., 5-17-74	Lake Mattamuskeet nr Fairfield, N.C., 5-16-74
Silica (SiO_2)	0.3	5.2	1.6	0.4	0.3	0.1
Calcium (Ca)	4.0	6.0	2.0	.0	.0	24
Magnesium (Mg)	1.4	1.9	1.0	.9	1.2	39
Sodium (Na)	5.4	6.3	5.3	4.3	4.9	420
Potassium (K)	.9	1.6	.7	.4	.2	42
Bicarbonate (HCO_3)	2	4	0	0	0	6
Carbonate (CO_3)	0	0	0	1/ 0	0	0
Alkalinity as calcium carbonate ($CaCO_3$)	2	3	0	0	0	5
Sulfate (SO_4)	15	25	13	10	9.5	110
Chloride (Cl)	9.5	8.2	6.4	7.0	8.9	760
Fluoride (F)	.0	.0	.0	.0	.0	.0
Nitrate plus nitrite (N)	.10	.33	.24	.11	.00	.02
Dissolved solids (residue at 180°C)	54	103	46	41	43	1,500
Hardness (Ca, Mg)	16	24	10	4	6	220
Noncarbonate hardness	14	20	10	4	6	220
Specific conductance (micromhos)	75	103	70	78	65	2,650
pH	6.0	5.3	4.6	3.9	4.5	6.7
Color	3	500	70	200	10	20

1/ Acidity as H^+ = 0.2 mg/L.

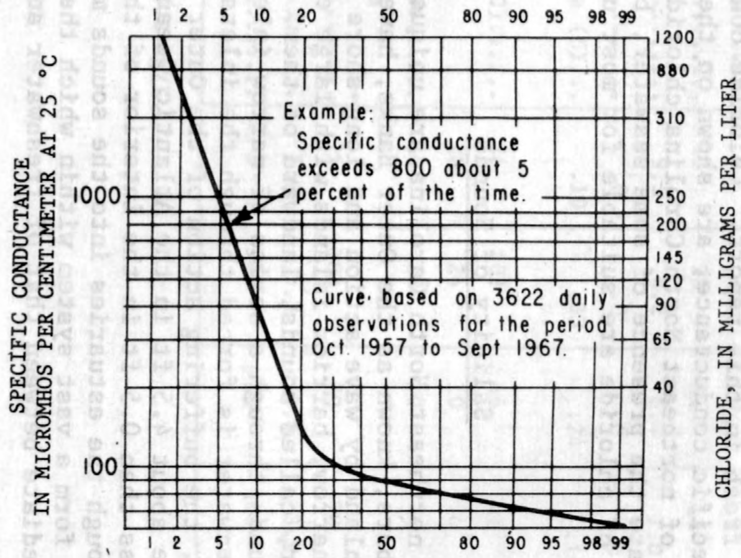
upstream direction, the brackish zone may intrude far up into the estuaries. Conversely, when freshwater inflow is high, and if winds do not oppose downstream movement of water, the brackish zone may be pushed nearly to the major sounds, and the rivers may be fresh throughout most of their length. This creates a rather complicated situation insofar as planning the management of these waters, and information concerning the pattern of seawater encroachment into rivers and streams of the area is of vital importance if these waters are to be managed.

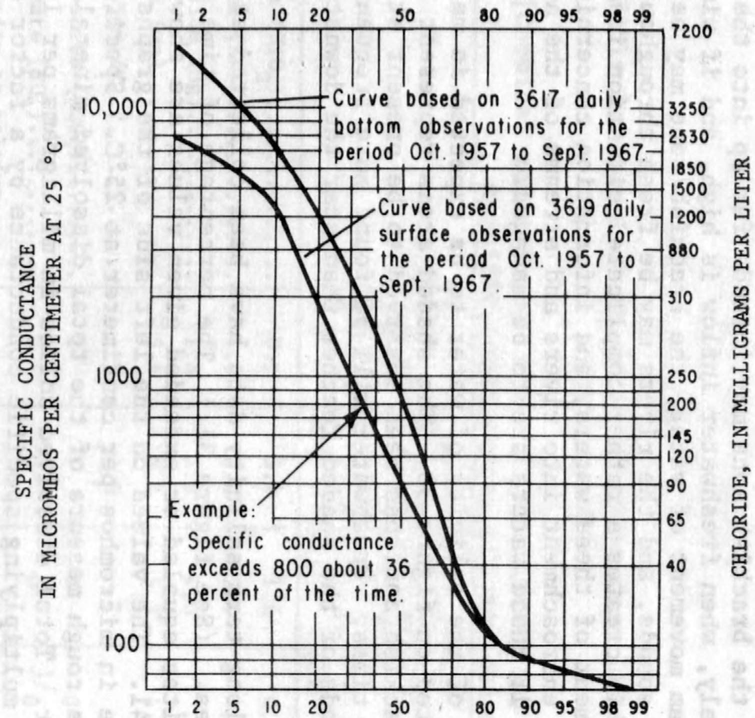
A general view of the salinity of water to be expected in major estuaries is presented on figure 30. The shaded areas represent reaches within which the brackish zone has been observed to be present at times and absent at other times. Freshwater will be found more frequently near the upstream ends of the shaded reaches than near the downstream reaches.

Comprehensive long-term salinity data have been collected at eleven sites within the area. (See figure 31.) The percentage of time that salinity at these sites equaled or exceeded given values are shown in figures 31 through 41. The values on the left side of the graphs are specific conductance in micromhos per centimeter at 25°C. Specific conductance furnishes a rough measure of the total dissolved mineral solids in a sample of water. Total dissolved solids in milligrams per liter may be estimated by multiplying specific conductance by a factor of 0.60 to 0.65. Waters with a specific conductance of 800 or less are arbitrarily considered fresh in this report. Chloride concentrations, calculated from specific conductance, are shown on the right vertical scale. In streams of northeast North Carolina chlorides greater than 50 mg/L usually indicate the presence of some seawater, but waters with less than 200 mg/L of chloride are suitable for most uses, and are considered fresh.

Salinity of Sounds

The sounds of northeast North Carolina are unique in the United States. Offshore bars, known as the Outer Banks, have been built up seaward of the mainland by wave action and long-shore currents, forming a series of long, narrow, barrier islands with large expanses of semi-enclosed open water, called sounds, landward of them. The ocean has access to these sounds through a series of narrow inlets in the Outer Banks. Although seawater is forced through the inlets into the sounds on each flood tide, the buffering action of the Outer Banks is such that tides which average about 4.5 ft in the Atlantic Ocean off Cape Hatteras are dampened to less than 0.5 ft in the interior of the sounds. Freshwater draining through the estuaries into the sounds mixes with tide-driven seawater to form a vast system within which the salinity of water is intermediate between that of freshwater and seawater.

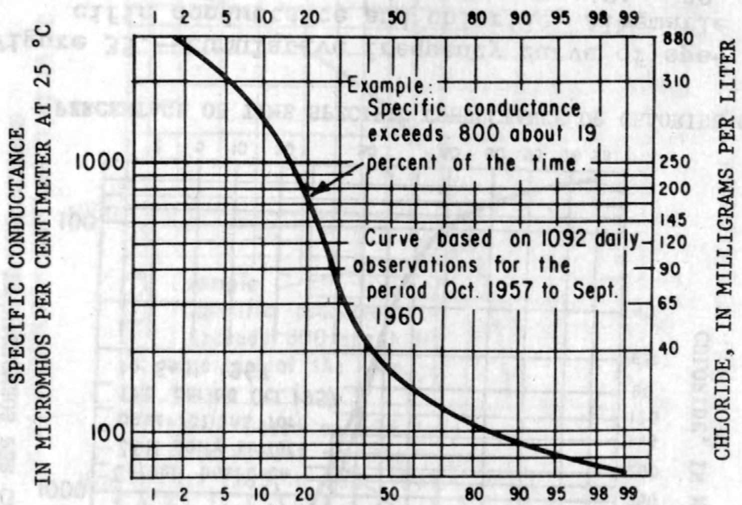


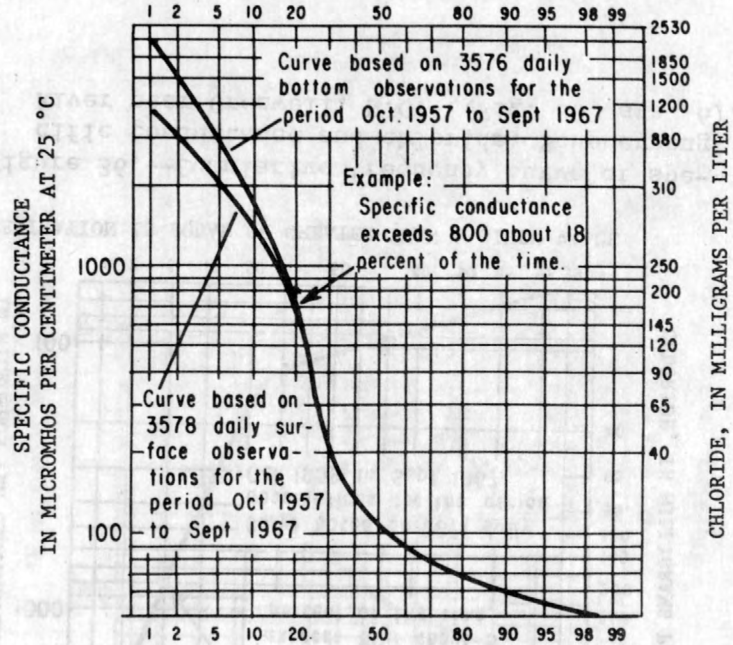


PERCENTAGE OF TIME SPECIFIC CONDUCTANCE OR CHLORIDE CONCENTRATION IS EQUAL OR GREATER THAN A GIVEN VALUE

Figure 31.--Cumulative frequency curve of specific conductance and chloride, Pasquotank River near Elizabeth City, N.C. (Fig. 30, sta. 1).

Figure 32.--Cumulative frequency curve of specific conductance and chloride, Pasquotank River at Elizabeth City, N.C. (Fig. 30, sta. 2).

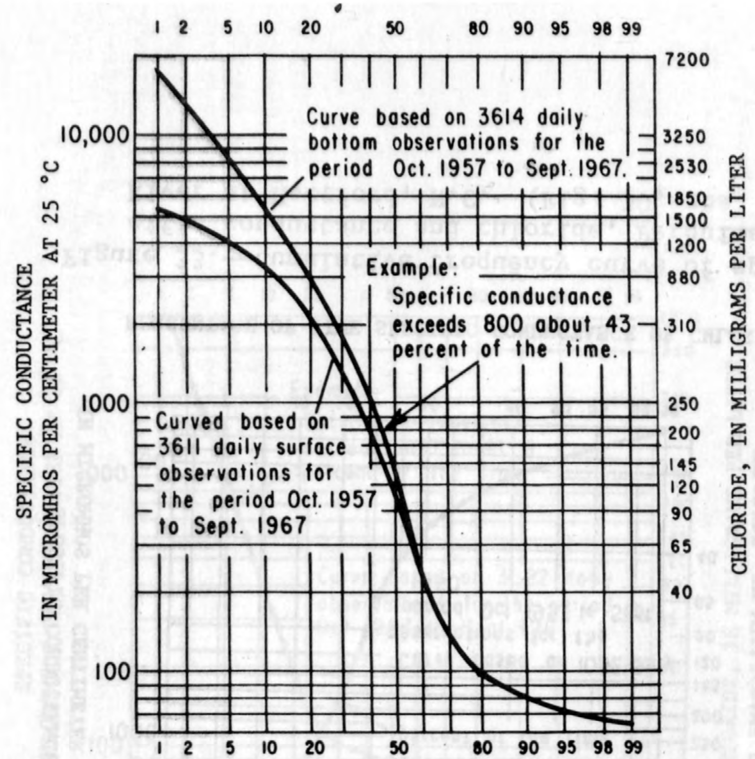


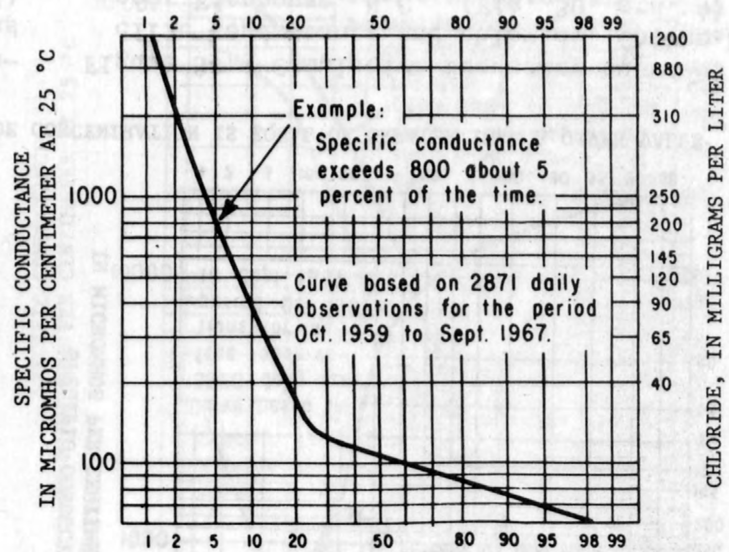


PERCENTAGE OF TIME SPECIFIC CONDUCTANCE OR CHLORIDE CONCENTRATION IS EQUAL OR GREATER THAN A GIVEN VALUE

Figure 33.--Cumulative frequency curve of specific conductance and chloride, Perquimans River at Hertford, N.C. (Fig. 30, sta. 3).

Figure 34.--Cumulative frequency curve of specific conductance and chloride, Chowan River near Edenhouse, N.C. (Fig. 30, sta. 4).

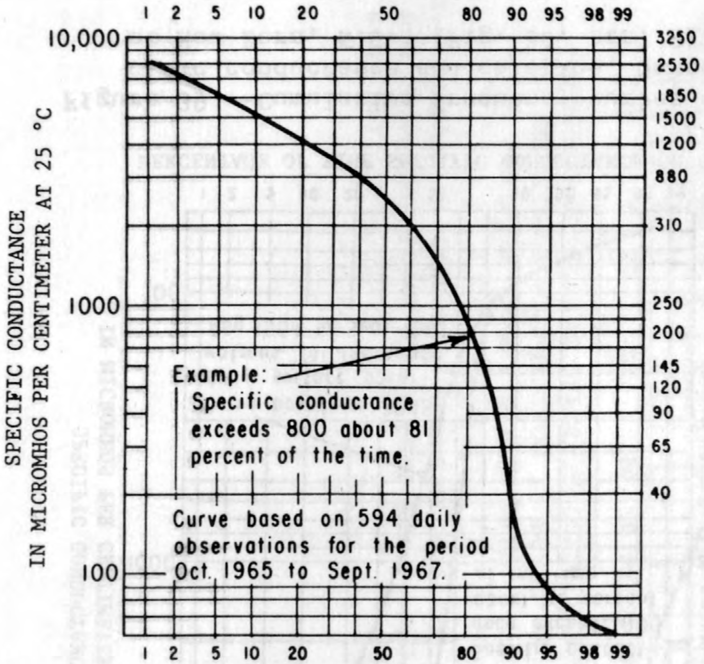


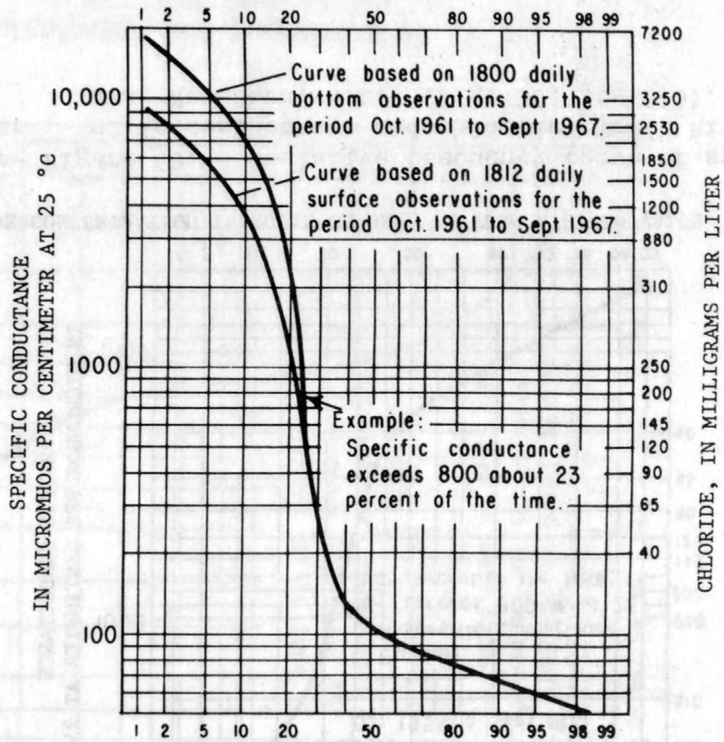


PERCENTAGE OF TIME SPECIFIC CONDUCTANCE OR CHLORIDE CONCENTRATION IS EQUAL OR GREATER THAN A GIVEN VALUE

Figure 35.--Cumulative frequency curve of specific conductance and chloride, Albemarle Sound near Edenhouse, N.C. (Fig. 30, sta. 5).

Figure 36.--Cumulative frequency curve of specific conductance and chloride, Scuppernong River near Creswell, N.C. (Fig. 30, sta. 6).

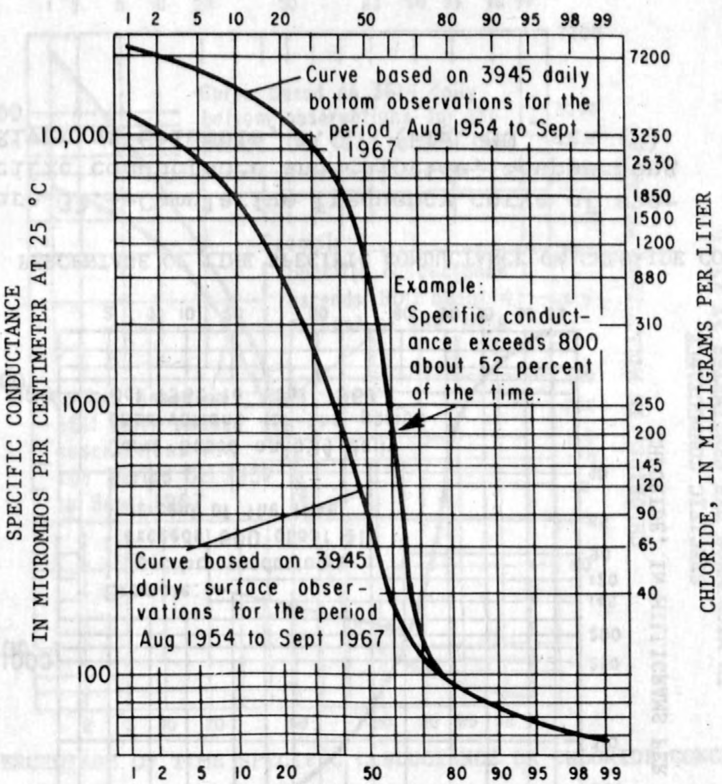


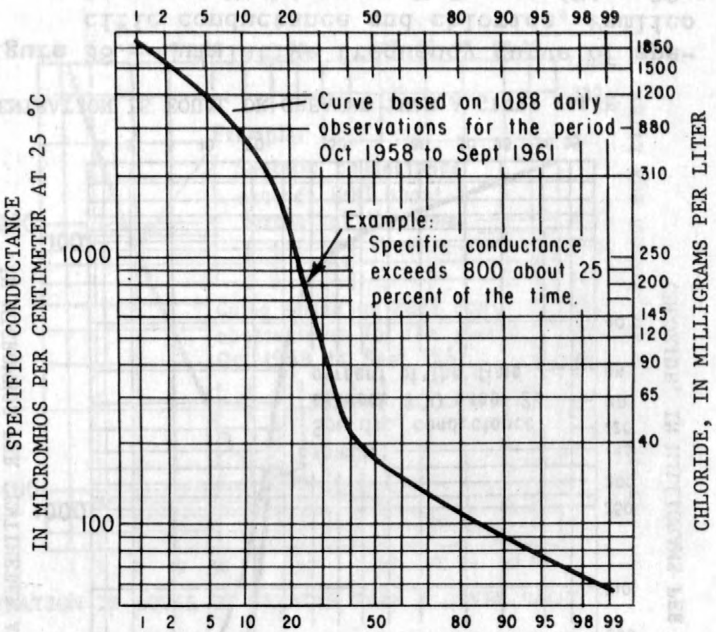


PERCENTAGE OF TIME SPECIFIC CONDUCTANCE OR CHLORIDE CONCENTRATION IS EQUAL OR GREATER THAN A GIVEN VALUE

Figure 37.--Cumulative frequency curve of specific conductance and chloride, Scuppernong River at Columbia, N.C. (Fig. 30, sta. 7).

Figure 38.--Cumulative frequency curve of specific conductance and chloride, Pamlico River at Washington, N.C. (Fig. 30, sta. 8).





PERCENTAGE OF TIME SPECIFIC CONDUCTANCE OR CHLORIDE CONCENTRATION IS EQUAL OR GREATER THAN A GIVEN VALUE

Figure 39.--Cumulative frequency curves of specific conductance and chloride, Neuse River at New Bern, N.C. (Fig. 30, sta. 9).

Figure 40.--Cumulative frequency curve of specific conductance and chloride, Trent River near New Bern, N.C. (Fig. 30, sta. 10).

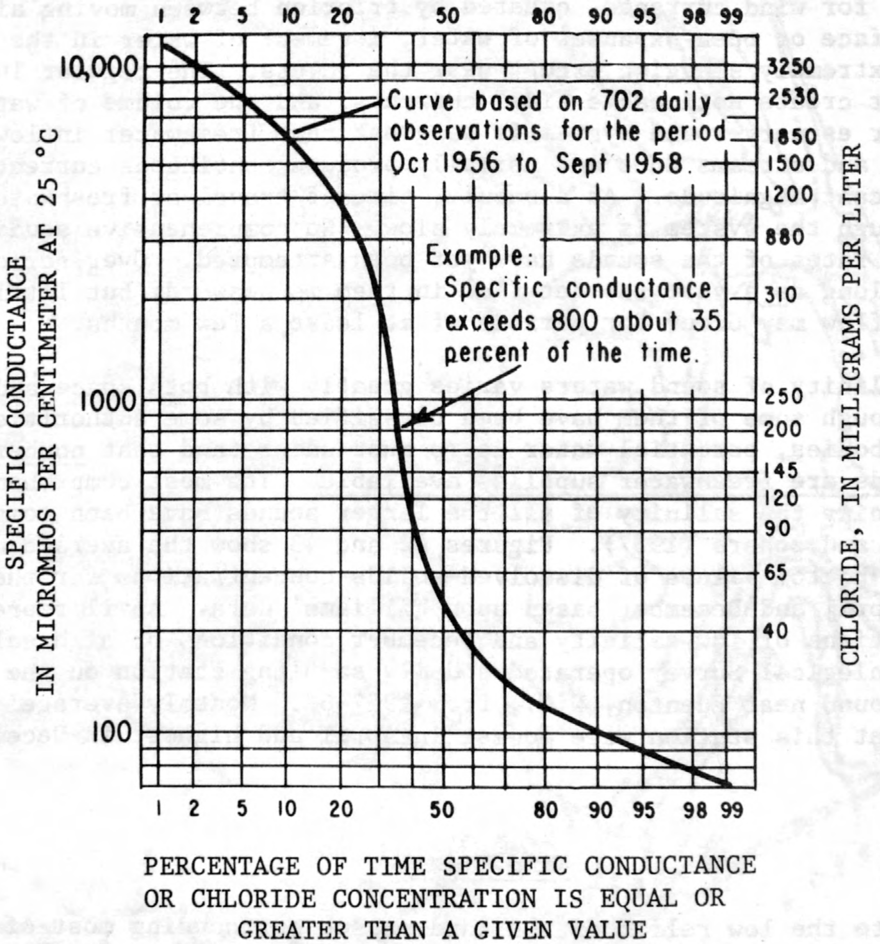


Figure 41.--Cumulative frequency curve of specific conductance and chloride, Trent River near Rheme, N.C. (Fig. 30, sta. 11).

The salinity at any given time and place depends upon the prevailing balance between freshwater and saltwater.

Except for wind currents, created by friction between moving air and the surface of open expanses of water, movement of water in the sounds is extremely sluggish except near the inlets. The regular lunar tides do not create noticeable tidal currents, and the volume of water in the lower estuary-sound system is so great that freshwater inflow from rivers and streams does not normally produce continuous currents of any significant magnitude. As a result, time of travel of freshwater inflow through the system is extremely slow. No comprehensive studies of flushing rates of the sounds have yet been attempted. Over periods of time as long as a year the net flow in them is seaward; but little or no seaward flow may occur for periods of at least a few months.

The salinity of sound waters varies greatly with both space and time. Although some of them have been classified by some authorities as freshwater bodies, potential water users must understand that <u>nowhere in the sounds are freshwater supplies available</u>. The most comprehensive data concerning the salinity of all the larger sounds have been compiled by Williams and others (1967). Figures 42 and 43 show the average of surface and bottom values of dissolved-solids concentrations for the months of April and December based upon Williams' data. April represents conditions of low salinity and December conditions of high salinity. The Geological Survey operated a daily sampling station on the Albemarle Sound near Edenton, N.C., from 1957-67. Monthly average salinities at this station were lowest in April and highest in December (figure 44).

Wind Tides

Owing to the low relief of the land masses surrounding most of the larger bodies of open water, large parts of northeast North Carolina are subject to inundation by high water caused by wind tides. The possibility of such flooding is an important consideration in planning land use of the area. As low-lying areas are cleared and drained for agriculture, the likelihood of major economic losses caused by wind-driven flooding increases. In contrast to flooding caused by excess precipitation, wind tides are likely to transport saltwater that will both destroy growing crops and create an undesirable soil environment for long periods after flood waters have receded. Under natural conditions the deleterious effects of inundation by saline water have been minimized because the high water table impedes the percolation of this water into the soil zone. Once drainage has been accomplished, however, a much larger portion of the flood waters will infiltrate the enlarged unsaturated zone where evaporation and ion-exchange processes can concentrate the salts in the soil zone. This is a reversible process

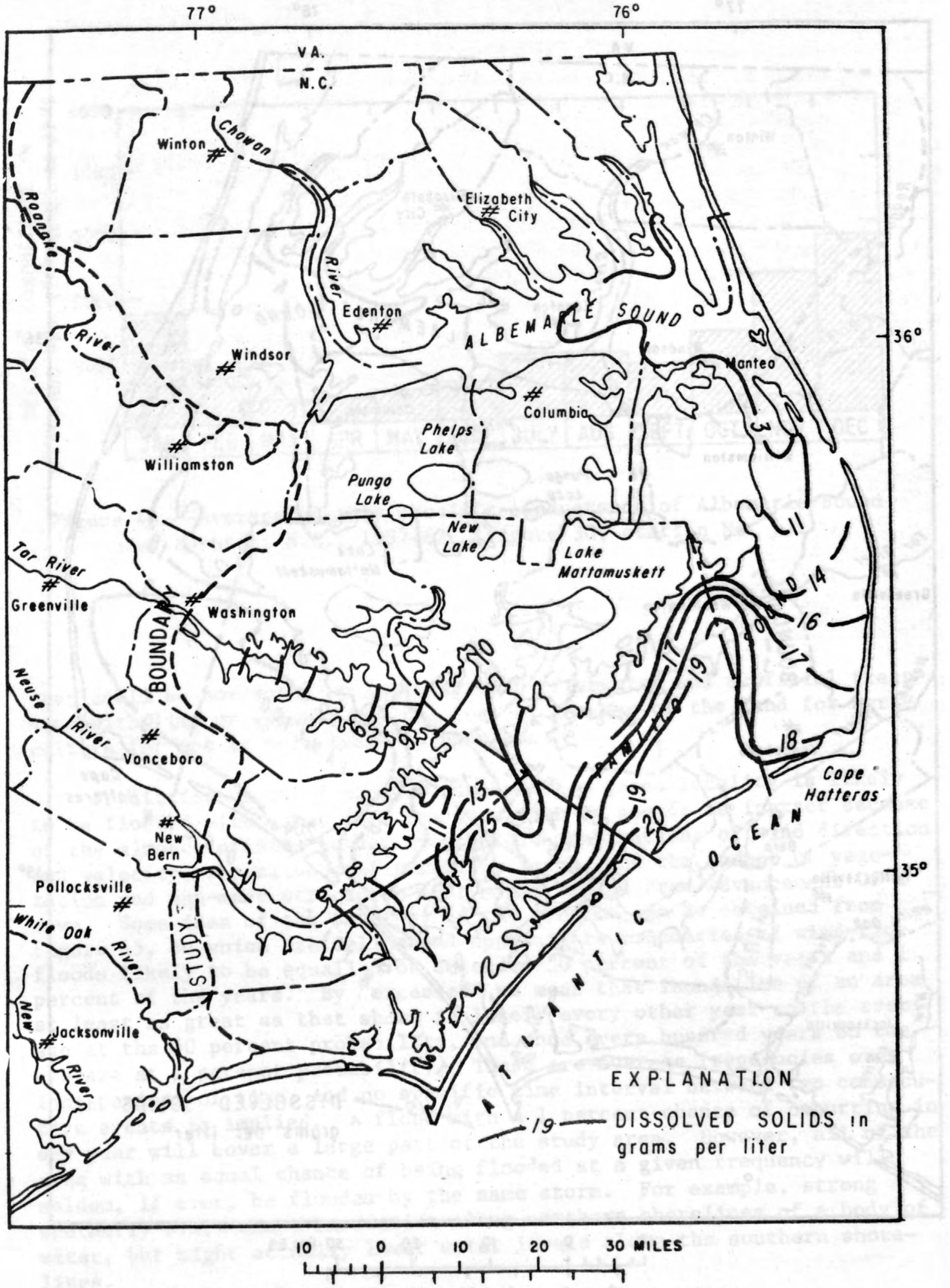


Figure 42.--Average dissolved solids in water in larger sounds of northeast North Carolina for the month of April. (Modified from Williams and others, 1967.)

Figure 43.--Average dissolved solids in water in larger sounds of northeast North Carolina for the month of December. (Modified from Williams and others, 1967.)

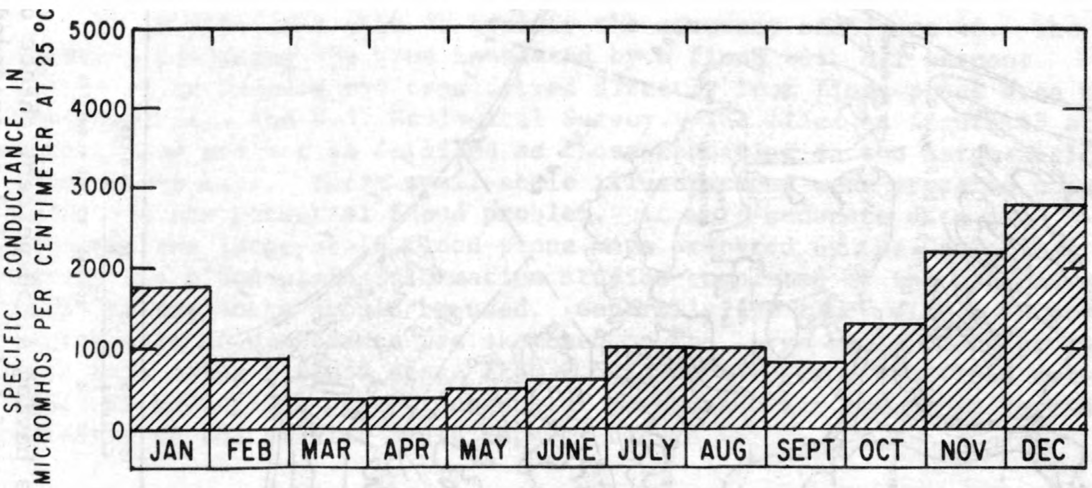


Figure 44.--Average monthly specific conductance of Albemarle Sound near Edenton, N.C., 1957-67 (figure 30, station No. 5).

that could be corrected by leaching with freshwater and surficial treatment with lime or gypsum, but the loss of the use of the land for agriculture for one or more years is possible.

Prediction of the frequency with which a given locality is likely to be flooded with water from the estuaries or sounds is inexact because of the almost infinite number of possible combinations of wind direction and velocity, shoreline configuration, fetch, and the amount of vegetation and man-made structures that might impede free advancement of a wave. Some idea of the severity of the problem can be obtained from figure 45, on which are delineated approximate boundaries of wind-tide floods likely to be equalled or exceeded 50 percent of the years and 1 percent of the years. By "exceeded" we mean that inundation of an area at least as great as that shown is likely every other year on the average at the 50 percent probability, and once every hundred years on the average at 1 percent probability. These are average frequencies over long periods of time, and no specific time interval between two consecutive events is implied. A flood with a 1 percent chance of occurring in any year will cover a large part of the study area. However, all of the area with an equal chance of being flooded at a given frequency will seldom, if ever, be flooded by the same storm. For example, strong southerly winds cause inundation along northern shorelines of a body of water, but might actually lower water levels along the southern shorelines.

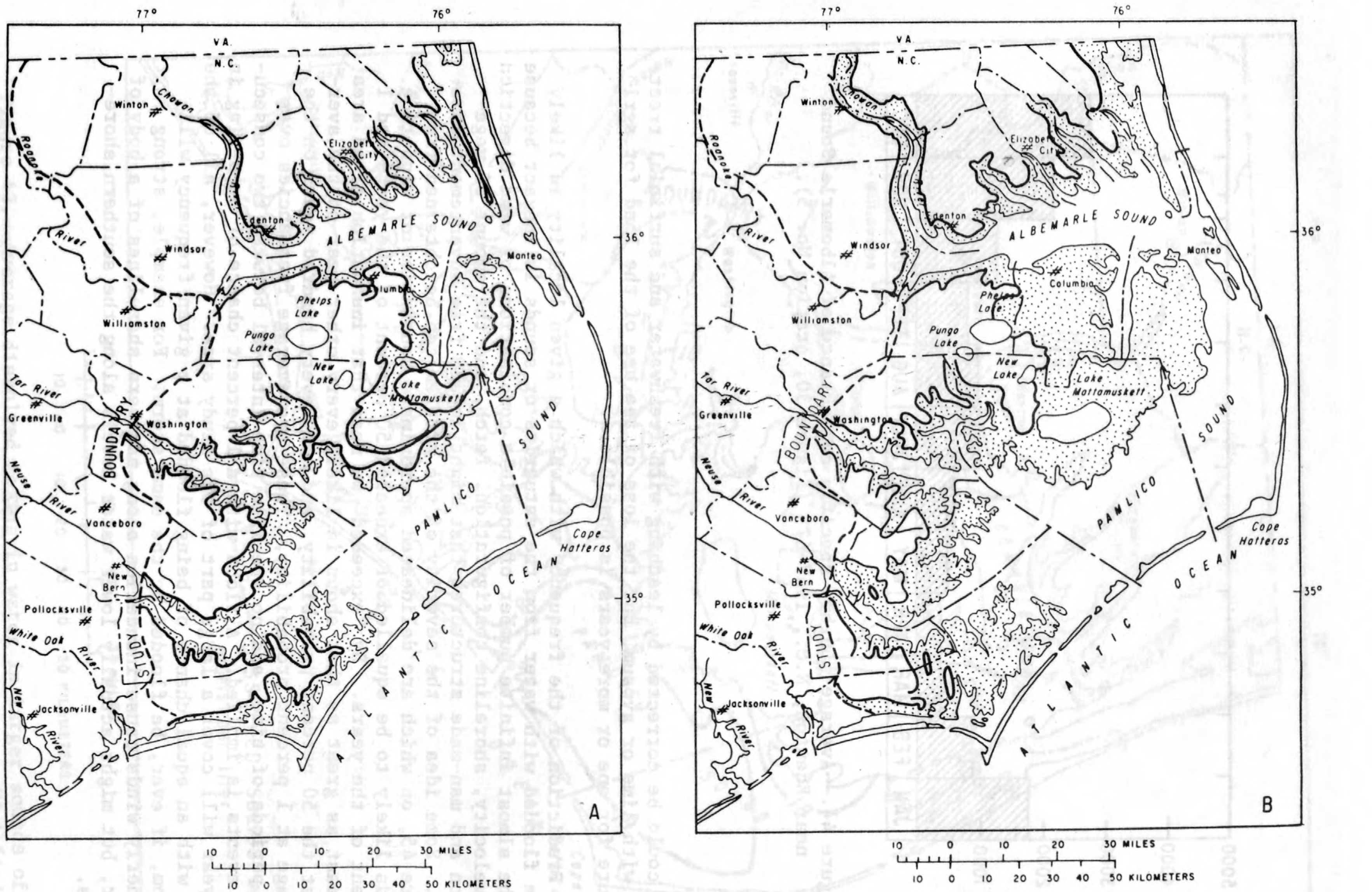


Figure 45.--Area subject to flood inundation caused by wind tides having A, 50 percent chance of being equaled or exceeded in any one year; B, 1 percent chance of being equaled or exceeded in any one year.

It is important also to qualify the accuracy of figure 45. The boundary outlining the area inundated by a flood with a 1 percent chance of exceedance was transferred directly from flood-prone area maps available from the U.S. Geological Survey. The lines on figure 45 are general and are not as detailed as those appearing on the large-scale flood-prone maps. These small-scale illustrations were prepared only to point out the potential flood problem. If more accurate data are desired, the large-scale flood-prone maps prepared by the Geological Survey and flood-plain information studies completed by the U.S. Army Corps of Engineers should be used. Generally the flood with a 50 percent chance of exceedance was sketched on the large scale flood-prone area maps using a flood stage from 2.5 to 3.5 ft below the flood outlined as having a 1 percent chance of exceedance and then transferred directly to the smaller scale maps of figure 45.

Because most of the areas adjacent to the shorelines presently contain dense vegetation or man-made structures, these sources of tidal-flooding information, all of which consider only wave height and land elevation, may tend to overestimate the extent of inundation.

GROUND WATER

Aquifers

Most of the water-bearing rocks of northeast North Carolina were deposited at times when sea level was higher than it is at present. Ancient seas transgressed a number of times upon what is now land area, and, during the various advances and retreats, formed layered sediments that now range in thickness from zero at the western boundary of the Coastal Plain to more than 10,000 ft thick at Cape Hatteras. Depending upon conditions of deposition, sediments were formed in layers or lenses that range in texture from coarse sands and gravels with large pore spaces to fine silts and clays with tiny pore spaces.

The sediments in the area have been classified into units according to their geologic age by Brown and others (1972). In this report, these units have been grouped into three major aquifers; an upper aquifer, an intermediate limestone aquifer, and a lower aquifer. Figure 46 shows block diagrams of the study area depicting the aquifers in the upper 1,000 ft. The upper aquifer consists of the youngest sediments, primarily sands and clays, and contains easily-accessible fresh water throughout most of the area. The limestone aquifer lies directly beneath the upper aquifer. The lower aquifer, which lies beneath the limestone aquifer and on top of crystalline rocks of the basement complex, is the deepest and thickest of the three and consists of the oldest sediments. Details of the geology and physical dimensions of the aquifers will be discussed in later sections.

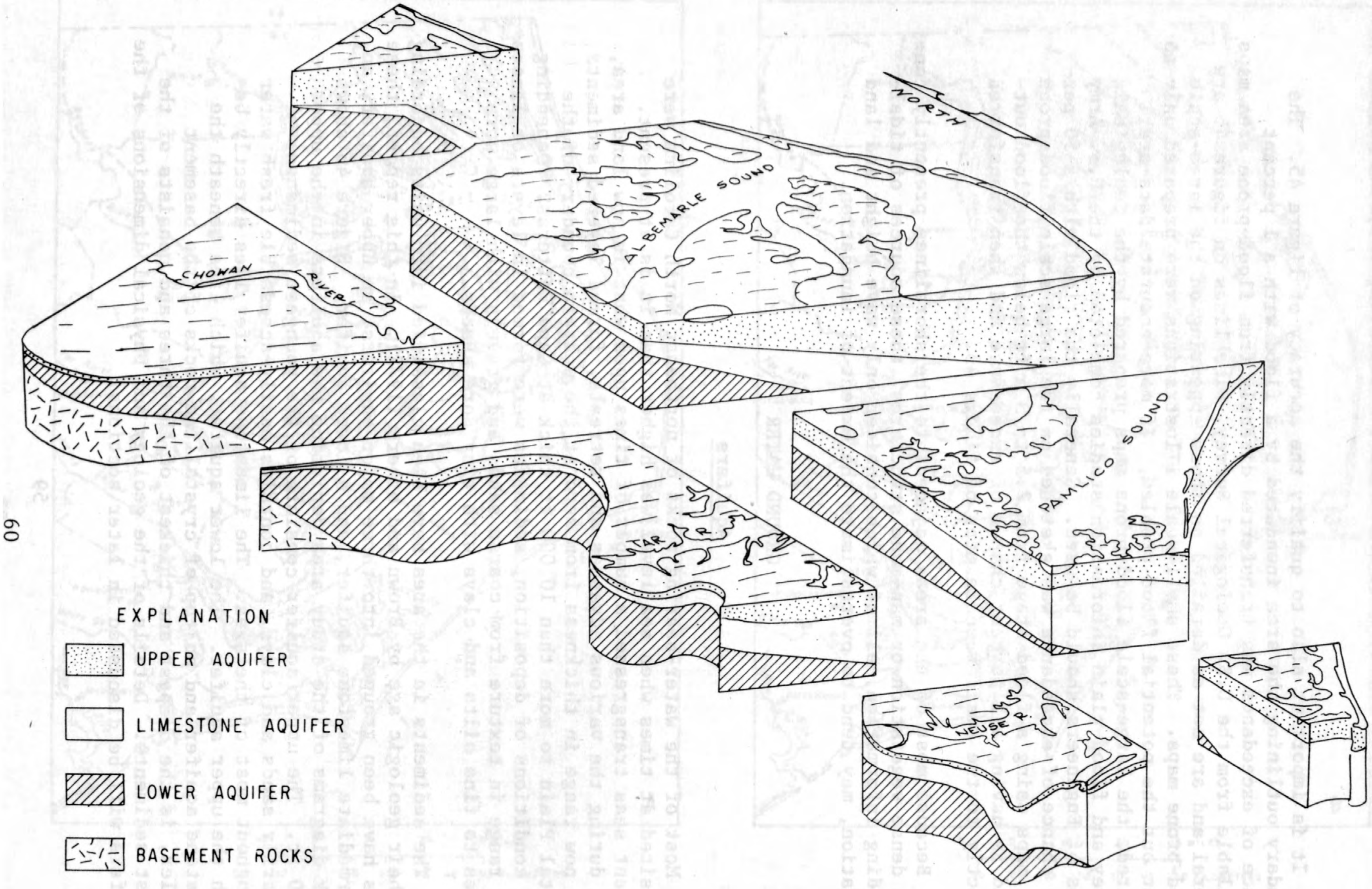


Figure 46.--Generalized block diagrams of northeast North Carolina showing the upper 1,000 feet of the underlying aquifers.

Division of the water-bearing rocks into three major aquifers is useful for depicting a concept of the overall ground-water system, but such a picture is vastly over-simplified. In detail, each aquifer is made up of complexly layered beds of materials of varying texture. Figure 47 shows three well sections on an east-west line near the center of the area. Many of the individual beds that comprise the aquifers are not continuous from one well to the next, but thicken and thin as well as pinch out. The lithology shown in these well sections is also simplified, and the real situation is even more complex.

Under natural conditions, the sands and limestones and dolomites act as conduits or pipelines that store and transmit water readily, while the finer beds of silt and clay and shale act as partial barriers to the movement of water. Where coarser materials are overlain by finer materials, water may become partially confined beneath the finer materials. This confinement causes the water pressure to build up in the coarser materials just as turning off a faucet will cause pressure to build up in a water line. Under such conditions, the finer materials are called <u>confining beds</u> and the underlying coarser materials containing the confined water are called <u>confined aquifers</u>. The limestone aquifer and the lower aquifer are confined aquifers throughout the project area. Under natural conditions, water in the limestone aquifer was under sufficient artesian pressure to cause wells tapping it to flow. Now, however, large withdrawals of water have decreased the pressure within the aquifer to the extent that flowing wells are rare. Water in the upper aquifer is unconfined at shallow depths; but may be confined or semi-confined in the lower sections where clay and silt beds are present. The upper surface of unconfined ground water is the <u>water table</u>.

The confining beds affect the long-term yield of the deeper aquifers because most of the water drawn from these aquifers must first seep downward through the confining beds. Such movement is referred to as <u>leakage</u>. The amount of leakage that can be induced, and thus the maximum sustained regional yield of an aquifer is controlled to a great extent by the thickness and the vertical permeability of the confining beds.

The complex interlayering of aquifers and confining beds explains why some wells are successful while others are failures. The likelihood of obtaining a successful well can be greatly enhanced if care is taken to determine the local geology in detail and to construct wells to draw water from the more productive zones, which are the permeable sand, limestone, and dolomite beds. The position of these beds can be determined by carefully collecting and studying rock samples obtained when a well is drilled and by bore-hole geophysical techniques.

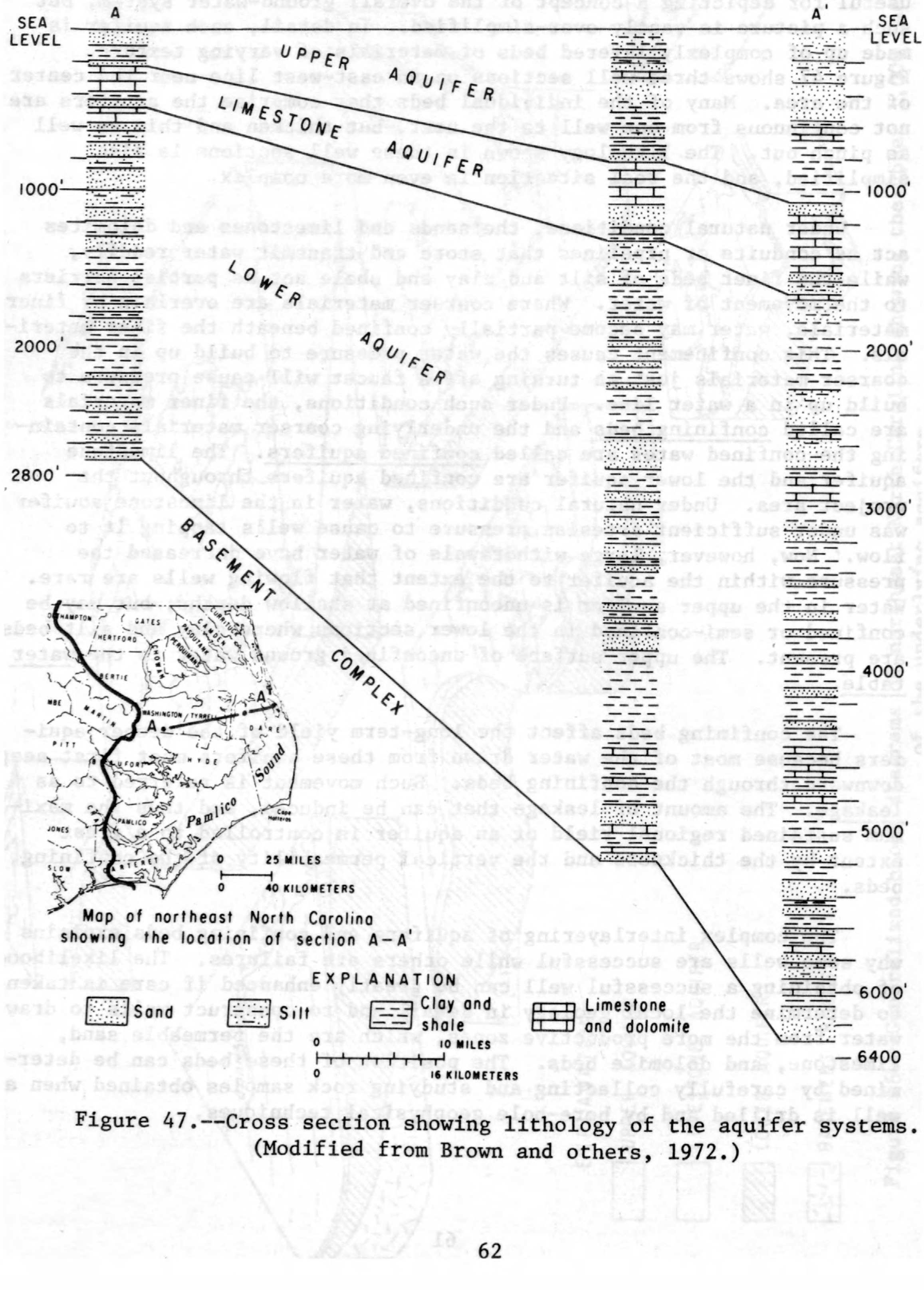


Figure 47.--Cross section showing lithology of the aquifer systems. (Modified from Brown and others, 1972.)

Developing Ground-Water Supplies

Developers and planners sometimes assume that there are no practical limits to the amounts of ground water available in northeast North Carolina, and that the potential supply is adequate for anyone to use whatever amount they need. This, however, is not a valid assumption, and such an attitude is not tenable in long-range planning.

As illustrated in figure 48, an unpumped aquifer is analogous to a barrel having specific volume, say 100 gal, into which water is running at a specific rate, say 5 gal/min. Once the barrel is full, a system exists with a storage of 100 gal, and a recharge rate of 5 gal/min. Outflow from the barrel will also be 5 gal/min. If a decision is to be made to use water from the barrel the following facts must be considered:

1. As long as recharge continues at the original rate up to 5 gal/min of water can be removed from the barrel indefinitely, and the barrel will remain full. The water that is removed will be "captured" from that which was formerly lost as outflow.

2. If more than 5 gal/min are removed, the additional water will be taken from the 100 gal stored in the barrel. Removal of more that 5 gal/min can continue only until the 100 gal in storage have been depleted. Thereafter the barrel will be able to furnish no more than 5 gal/min, which is the rate of recharge.

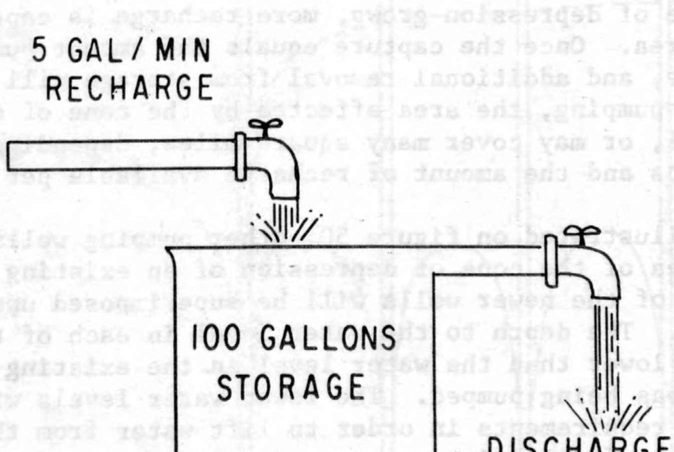


Figure 48.--Aquifers function as both storage vessels and pipelines.

Although this is an oversimplified example, the same principles apply to the utilization of ground water. Aquifers, too, have finite amounts of recharge, storage, and discharge. Removal of water from aquifers should be planned according to the best information available concerning these characteristics. If an aquifer is pumped, not only will part or all of the natural discharge be captured, but water will be removed from storage. In an unconfined aquifer, removal of water from storage involves lowering the water table in the vicinity of the well, thereby dewatering a part of the aquifer. In a confined aquifer, water is usually removed from storage as a result of depressurization of the aquifer, and the aquifer material is not actually dewatered. In both instances, a pressure gradient toward the well from all directions is established. The pressure gradient is referred to as a <u>cone of depression</u>. In the case of an unconfined aquifer, the surface of the cone of depression is the lowered water table. In a confined aquifer, the cone of depression is a lowered pressure surface and not an actual air-water interface. The lowering of the pressure in a confined aquifer may induce leakage to the aquifer from overlying beds. When the cone of depression of an unconfined aquifer intersects a stream or lake, not only is ground-water discharge to the stream diminished, but water from the stream may be induced to move into the aquifer and flow to the well (fig. 49). This capturing of ground-water discharge to the stream and inducement of stream water into the aquifer will diminish the streamflow and may cause the stream to go dry, at least temporarily. Where the water table lies close to land surface, much water may be lost from the water table by evapotranspiration. Lowering the water table by pumping reduces evapotranspiration losses. This reduction is an important potential source of manageable water in northeast North Carolina.

As a cone of depression grows, more recharge is captured from an ever larger area. Once the capture equals the amount pumped, the cone will stabilize, and additional removal from storage will cease. For a given rate of pumping, the area affected by the cone of depression may be quite local, or may cover many square miles, depending upon aquifer characteristics and the amount of recharge available per unit area.

If, as illustrated on figure 50, other pumping wells are installed within the area of the cone of depression of an existing well, the cones of depression of the newer wells will be superimposed upon that of the existing well. The depth to the water level in each of the pumping wells will be lower than the water level in the existing single well when only it was being pumped. The lower water levels will result in higher energy requirements in order to lift water from the wells. Thus, careful spacing of wells is necessary if all are to operate efficiently.

An important consideration in planning the development of ground-water systems is the extent to which the effects of removal of water from a given area will be spread to other areas. Most important among

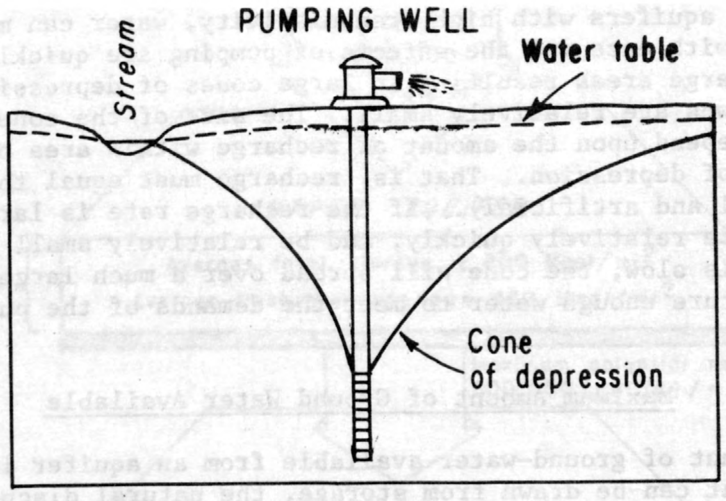


Figure 49.--The cone of depression around a pumping well which is inducing recharge from a nearby stream.

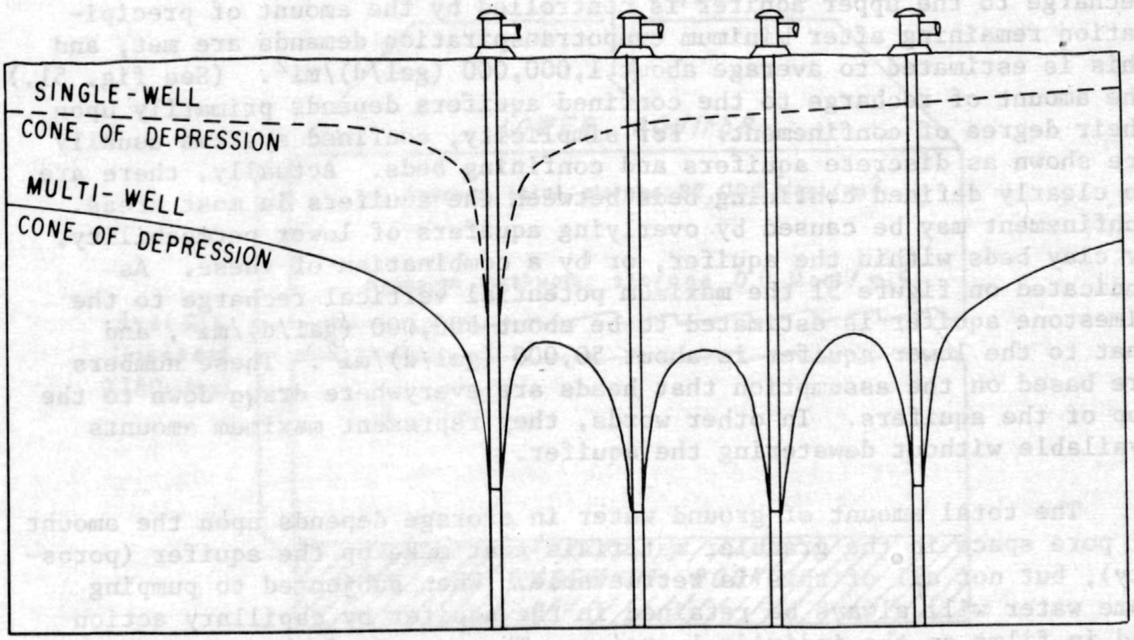


Figure 50.--Wells spaced too closely will interfere with one another.

the factors that control the extent of drawdown caused by pumping wells are the pumping rate, transmissivity, and recharge to the producing aquifer. In aquifers with high transmissivity, water can move through the aquifer with ease and the effects of pumping are quickly spread over relatively large areas resulting in large cones of depression within which drawdowns are relatively small. The size of the cone when stabilized will depend upon the amount of recharge within area of influence of the cone of depression. That is, recharge must equal the discharge (both natural and artificial). If the recharge rate is large, the cone will stabilize relatively quickly, and be relatively small in extent, or if the rate is slow, the cone will spread over a much larger area in order to capture enough water to meet the demands of the pumping well.

Maximum Amount of Ground Water Available

The amount of ground-water available from an aquifer is limited to the water that can be drawn from storage, the natural discharge that can be intercepted and the additional recharge that can be induced into the aquifer. The amount of water available to sustain long-term pumpage is different for each of the aquifers. Under conditions of maximum development we can assume that all natural discharge will cease and additional recharge (that is, recharge in excess of the natural recharge) can be induced into one or all of the aquifers. Under this condition we can equate the long-term sustained yield with maximum potential recharge (that is, with natural plus induced recharge). The maximum potential recharge to the upper aquifer is controlled by the amount of precipitation remaining after minimum evapotranspiration demands are met, and this is estimated to average about 1,000,000 (gal/d)/mi^2. (See fig. 51.) The amount of recharge to the confined aquifers depends primarily upon their degree of confinement. For simplicity, confined systems usually are shown as discrete aquifers and confining beds. Actually, there are no clearly defined confining beds between the aquifers in most areas. Confinement may be caused by overlying aquifers of lower permeability, by clay beds within the aquifer, or by a combination of these. As indicated on figure 51 the maximum potential vertical recharge to the limestone aquifer is estimated to be about 500,000 (gal/d)/mi^2, and that to the lower aquifer is about 50,000 (gal/d)/mi^2. These numbers are based on the assumption that heads are everywhere drawn down to the top of the aquifers. In other words, they represent maximum amounts available without dewatering the aquifer.

The total amount of ground water in storage depends upon the amount of pore space in the granular materials that make up the aquifer (porosity), but not all of this is retrievable. When subjected to pumping some water will always be retained in the aquifer by capillary action and in films on the individual grains. The amount of this <u>retention</u> varies with the type of materials, but ranges from less than 5 percent

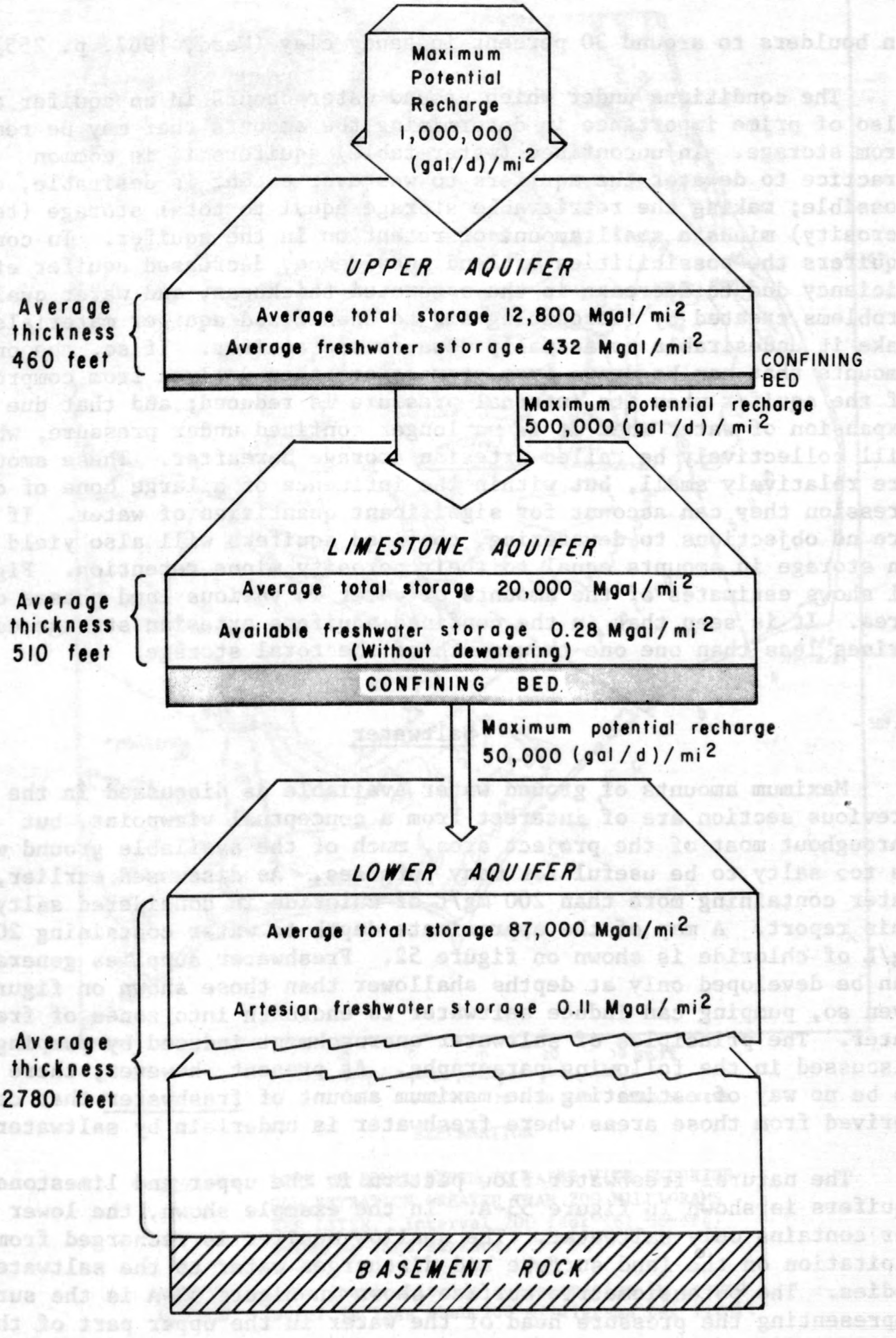


Figure 51.--Estimated average amount of recharge to and storage in the three major aquifers.

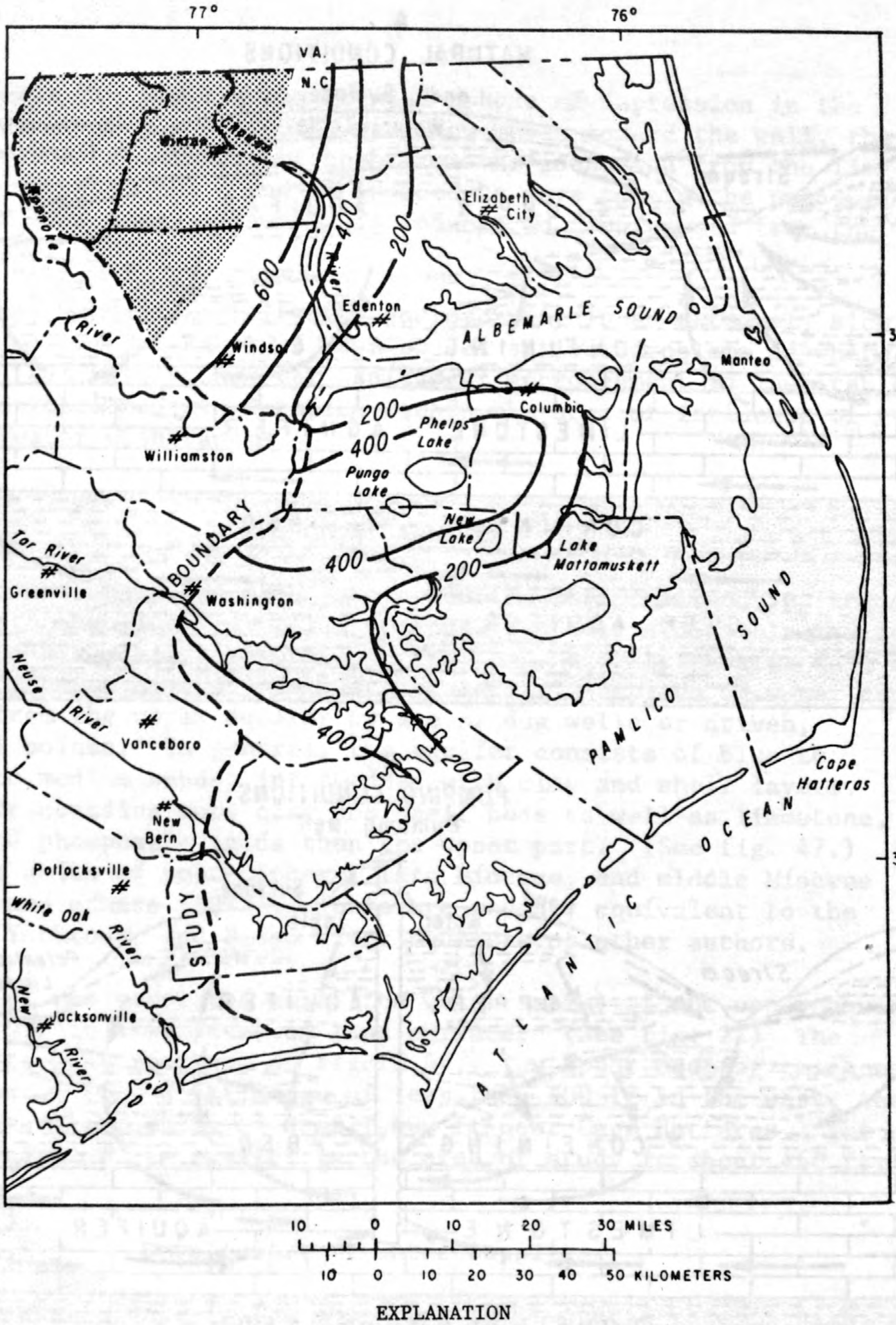
in boulders to around 30 percent in sandy clay (Ward, 1967, p. 255).

The conditions under which ground water occurs in an aquifer are also of prime importance in determining the amounts that may be removed from storage. In unconfined (water-table) aquifers it is common practice to dewater the aquifers to whatever extent is desirable, or possible; making the retrievable storage equal to total storage (total porosity) minus a small amount of retention in the aquifer. In confined aquifers the possibilities of land subsidence, decreased aquifer efficiency due to decrease in the saturated thickness, and water quality problems created by introducing air to unoxidized aquifer materials, may make it undesirable to actually dewater the aquifer. If so, the only amounts that can be drawn from storage are that derived from compression of the aquifer when its internal pressure is reduced; and that due to expansion of water when it is no longer confined under pressure, which will collectively be called artesian storage hereafter. These amounts are relatively small, but within the influence of a large cone of depression they can account for significant quantities of water. If there are no objections to dewatering, confined aquifers will also yield water in storage in amounts equal to their porosity minus retention. Figure 51 shows estimates of the amounts of water in various land phases of the area. It is seen that in the confined aquifers artesian storage comprises less than one one-thousandth of the total storage.

Saltwater

Maximum amounts of ground water available as discussed in the previous section are of interest from a conceptual viewpoint, but throughout most of the project area, much of the available ground water is too salty to be useful for many purposes. As discussed earlier, water containing more than 200 mg/L of chloride is considered salty in this report. A map of the approximate depth to water containing 200 mg/L of chloride is shown on figure 52. Freshwater supplies generally can be developed only at depths shallower than those shown on figure 52. Even so, pumping can induce saltwater to encroach into zones of freshwater. The principles of saltwater encroachment induced by pumping are discussed in the following paragraphs. At present, however, there seems to be no way of estimating the maximum amount of freshwater that can be derived from those areas where freshwater is underlain by saltwater.

The natural freshwater flow pattern in the upper and limestone aquifers is shown in figure 53-A. In the example shown, the lower aquifer contains only saltwater. The shallow aquifer is recharged from precipitation on the land surface and discharges water to the saltwater bodies. The potentiometric surface shown in figure 53-A is the surface representing the pressure head of the water in the upper part of the limestone aquifer. In figure 53-B the limestone aquifer is being



EXPLANATION

—200— LINE OF EQUAL DEPTH TO WATER WITH CHLORIDE CONCENTRATION GREATER THAN 200 MILLIGRAMS PER LITER. Interval 200 feet (61 meters). Datum is land surface.

Area where chloride concentration in ground water is less than 200 milligrams per liter.

Figure 52.--Approximate depth to ground water containing more than 200 milligrams per liter of chloride.

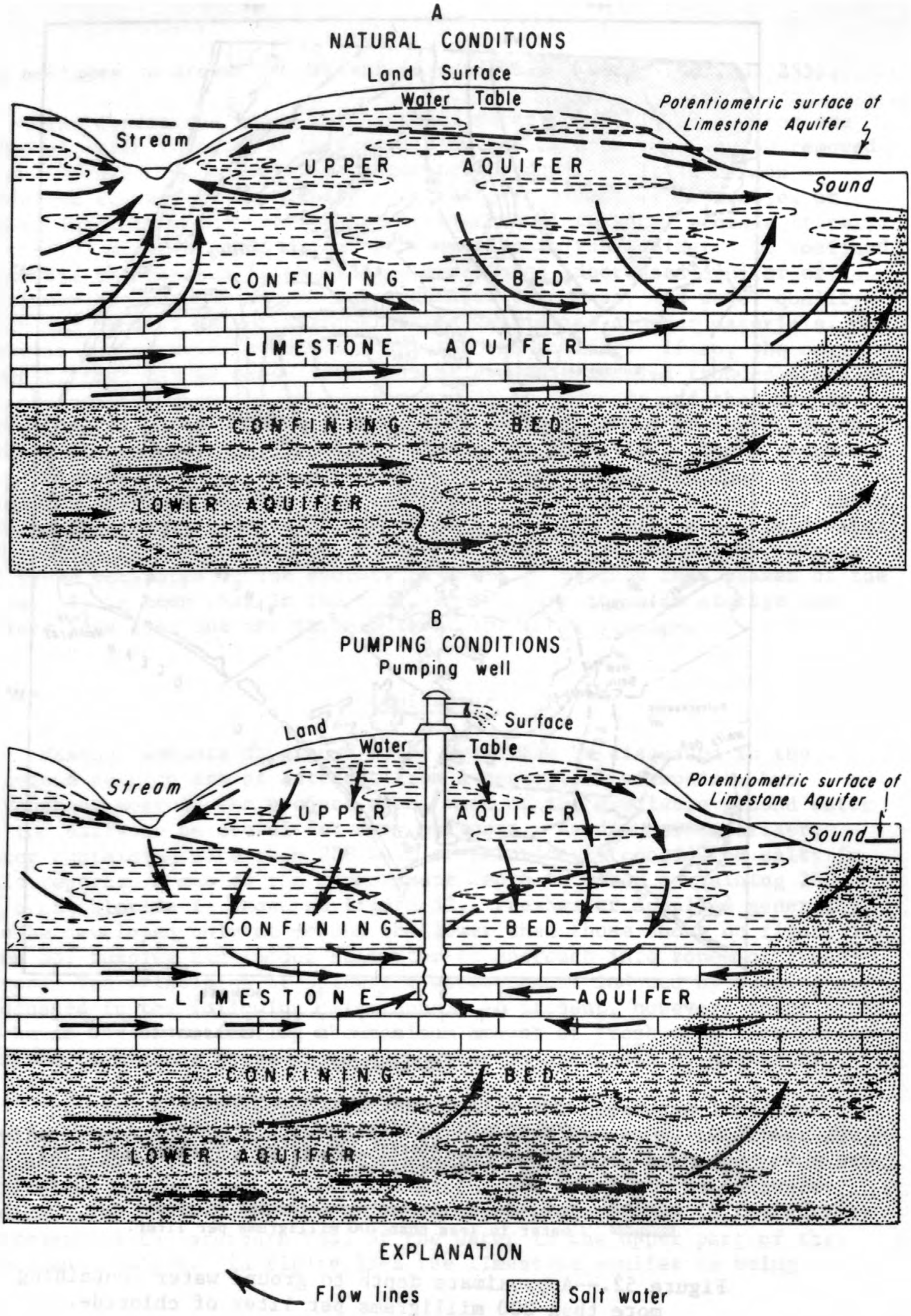


Figure 53.--How saltwater encroachment can occur in freshwater aquifers.

heavily pumped. The pumping has created a cone of depression in the potentiometric surface and ground water now moves toward the well, the point of lowest head. Saltwater both from the sound and from the limestone aquifer beneath the sound is induced to move toward the pumping well. At the same time, saltwater is induced to flow upward from the underlying lower aquifer.

Under most conditions saltwater encroachment is an extremely slow process, and is not yet known to have caused serious problems anywhere in the area. Ultimately, however, saltwater encroachment is inevitable anywhere in northeast North Carolina within the area of influence of large ground-water withdrawals.

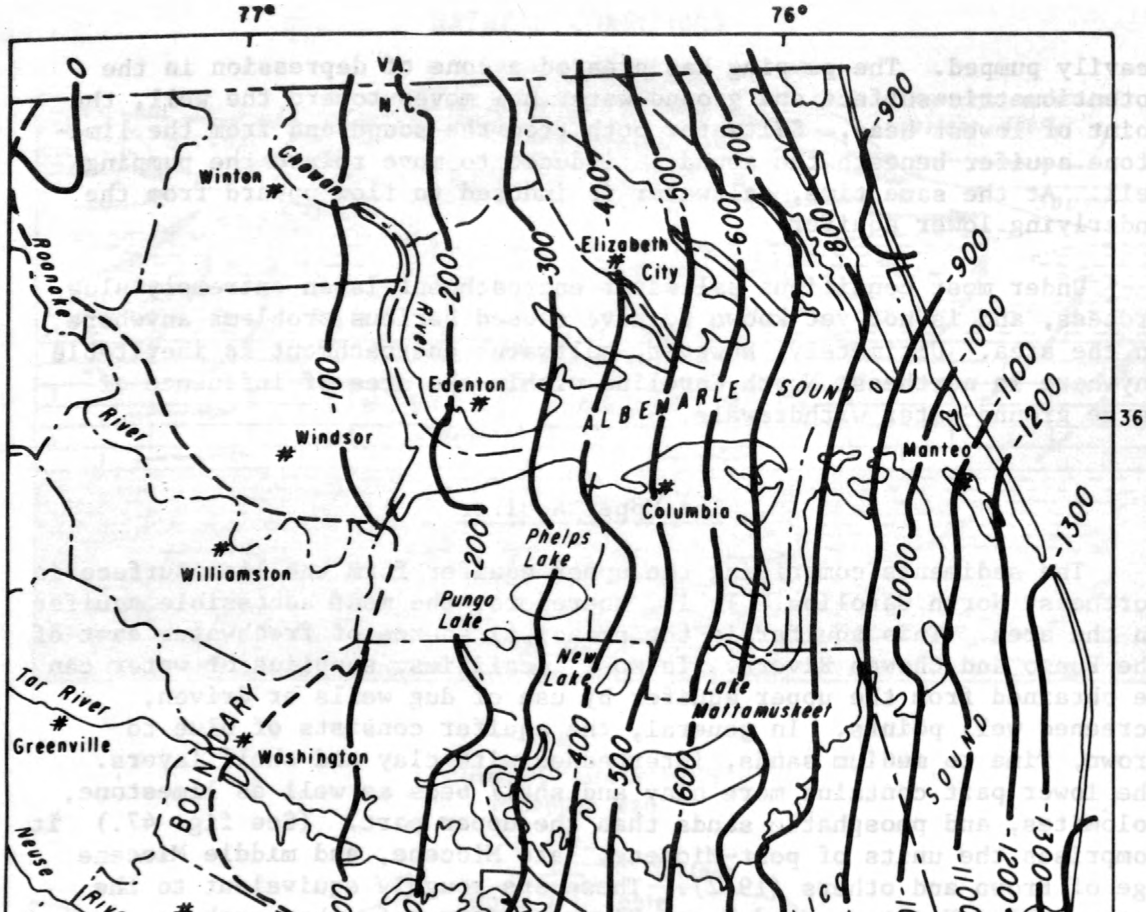
The Upper Aquifer

The sediments comprising the upper aquifer form the land surface in northeast North Carolina. It is, therefore, the most accessible aquifer in the area. This aquifer is the principal source of freshwater east of the Pungo and Chowan Rivers. In most localities, supplies of water can be obtained from the upper aquifer by use of dug wells or driven, screened well points. In general, the aquifer consists of blue to brown, fine to medium sands, interbedded with clay and shell layers. The lower part contains more clay and shell beds as well as limestone, dolomites, and phosphatic sands than the upper part. (See fig. 47.) It comprises the units of post-Miocene, late Miocene, and middle Miocene age of Brown and others (1972). These are roughly equivalent to the water-table, Yorktown, and Pungo River aquifers of other authors.

The top of the saturated zone (the water table) of the upper aquifer is at or within a few feet of land surface. (See fig. 2.) The altitude of its base is shown on figure 54. The upper aquifer thickens toward the east. From a thickness of less than 100 ft in the west, the aquifer reaches a thickness of over 1,400 ft near Cape Hatteras. The average thickness of the aquifer in the area of study is about 460 ft.

Development of Water Supplies

Where transmissivity is low and potential recharge rate is high, as is typical of the upper aquifer in northeast North Carolina, the size of the cone of depression will tend to remain small and drawdowns near pumping wells will be large. The net result is that yields of individual wells tend to be low, and wells can be placed much closer together than in the other aquifers without appreciably interfering with one another. This is illustrated on figure 55 which shows estimated distance-drawdown curves along the 500 gal/min maximum-yield line of



EXPLANATION

—*100*— STRUCTURE CONTOUR--shows altitude of base of the upper aquifer. Contour interval 100 feet (15 meters). Datum is mean sea level.

Figure 54.--Altitude of the base of the upper aquifer.

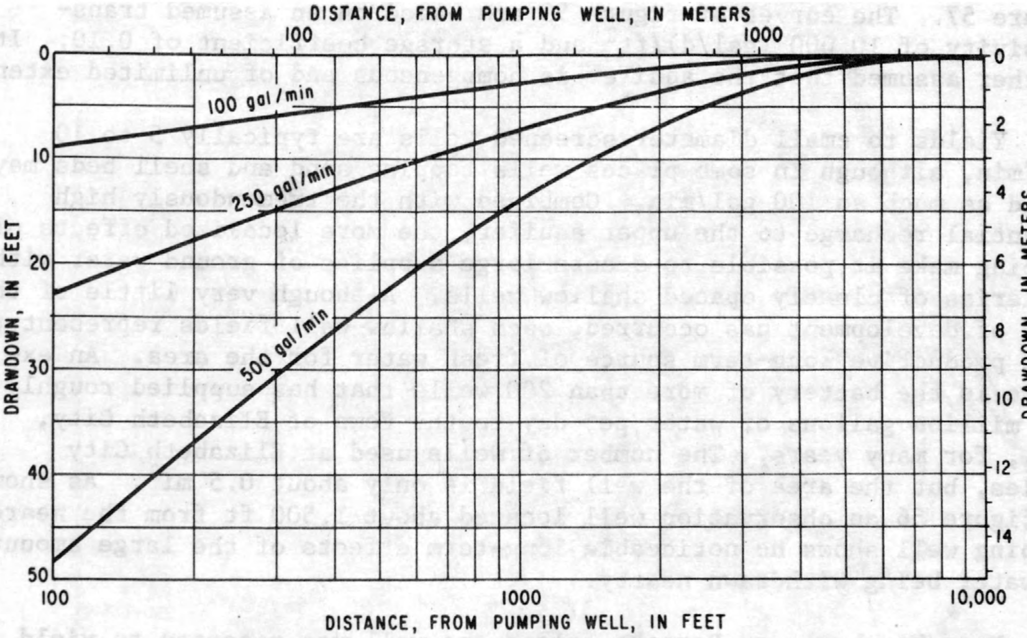


Figure 55.--Distance-drawdown curves for various pumping rates along the 500 gal/min maximum-yield line for the upper aquifer. (Pumping time assumed to be at least 1 year.)

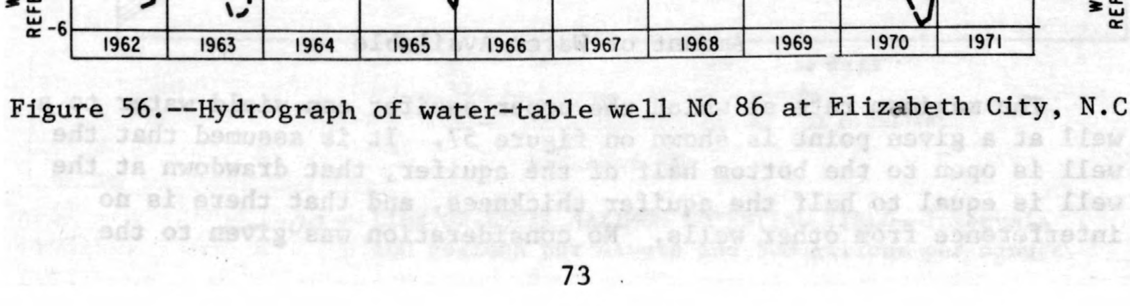


Figure 56.--Hydrograph of water-table well NC 86 at Elizabeth City, N.C.

figure 57. The curves of figure 55 are based on an assumed transmissivity of 10,000 $(gal/d)/ft^2$ and a storage coefficient of 0.10. It is further assumed that the aquifer is homogeneous and of unlimited extent.

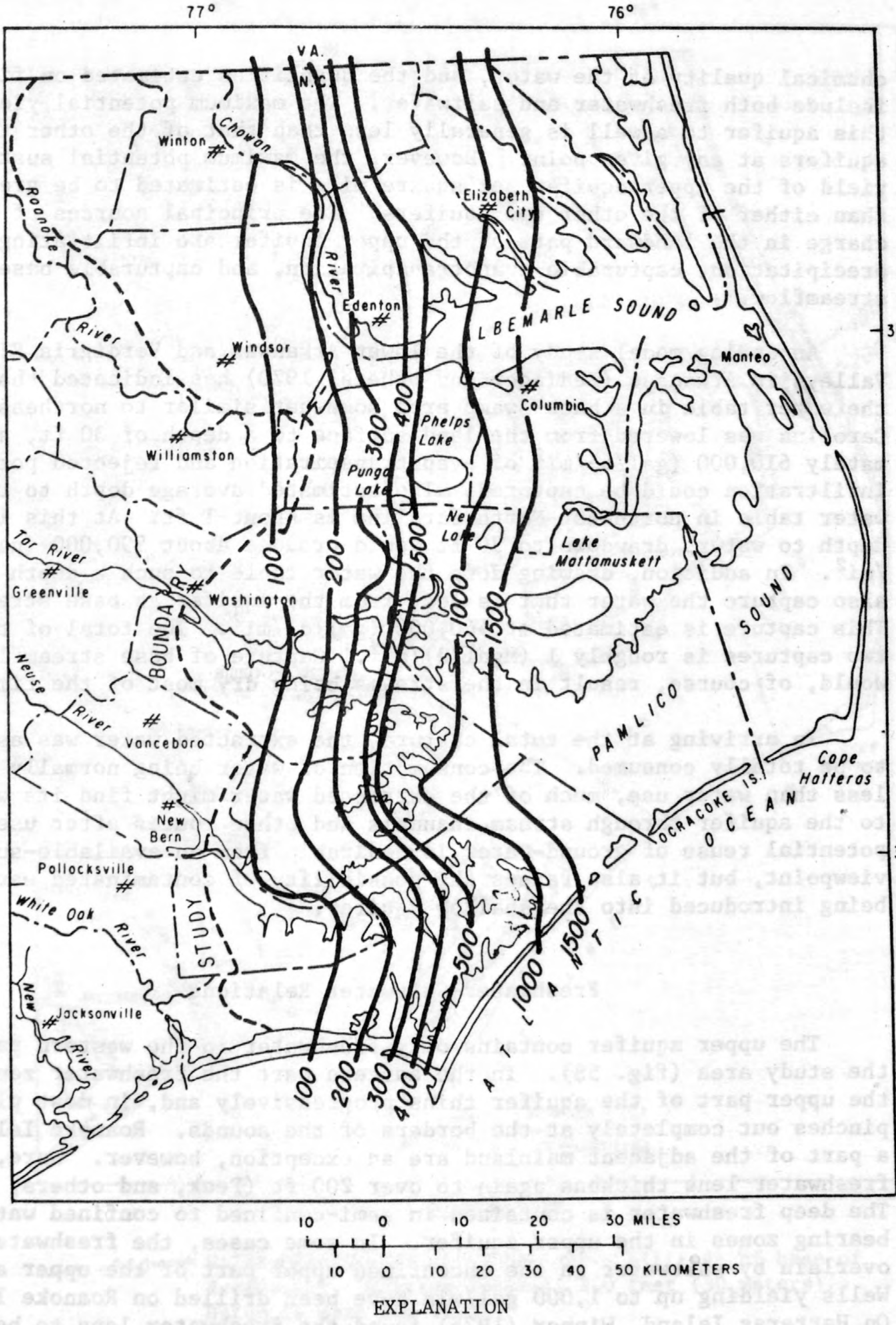
Yields to small diameter screened wells are typically 5 to 10 gal/min, although in some places wells tapping sand and shell beds may yield as much as 100 gal/min. Combined with the tremendously high potential recharge to the upper aquifer, the more localized effects of pumping make it possible to secure large supplies of ground water with batteries of closely spaced shallow wells. Although very little of this type of development has occurred, such shallow-well fields represent the most productive long-term source of fresh water for the area. An example is the battery of more than 200 wells that has supplied roughly one million gallons of water per day to the town of Elizabeth City, N.C., for many years. The number of wells used at Elizabeth City varies, but the area of the well field is only about 0.5 mi^2. As shown on figure 56 an observation well located about 1,500 ft from the nearest pumping well shows no noticeable long-term effects of the large amounts of water being withdrawn nearby.

Near Wanchese, on Roanoke Island one well was reported to yield nearly 1,000 gal/min of freshwater (driller's report, on file at North Carolina Department of Natural Resources and Community Development). This yield is exceptionally large for the area. The upper aquifer is the only local source of freshwater on the Outer Banks. Winner (1975) in a study of the Cape Hatteras National Seashore, which extends from near Manteo southward to Ocracoke Island, found that only small yields from individual wells would afford dependable supplies of freshwater. Only on the large Hatteras Island (where Cape Hatteras is located) can wells be pumped at rates up to 70 gal/min. At a few other places on the Seashore wells could be pumped as much as 30 gal/min. Elsewhere yields would have to be much less than this. Along the rest of the Outer Banks, the ground-water situation is expected to be similar to that within the Seashore.

One reason why the potential of the upper aquifer for providing large ground-water supplies has not been fully explored is because the quality of water is frequently such that it requires treatment to make it suitable for some uses. This problem will be discussed later.

Amount of Water Available

The maximum rate at which the upper aquifer can yield water to a well at a given point is shown on figure 57. It is assumed that the well is open to the bottom half of the aquifer, that drawdown at the well is equal to half the aquifer thickness, and that there is no interference from other wells. No consideration was given to the



EXPLANATION

—*100*— LINE OF EQUAL MAXIMUM POTENTIAL YIELD--Intervals 100 gallons per minute and 500 gallons per minute.

Figure 57.--Maximum potential yield of the upper aquifer to individual wells without regard to water quality or well interference.

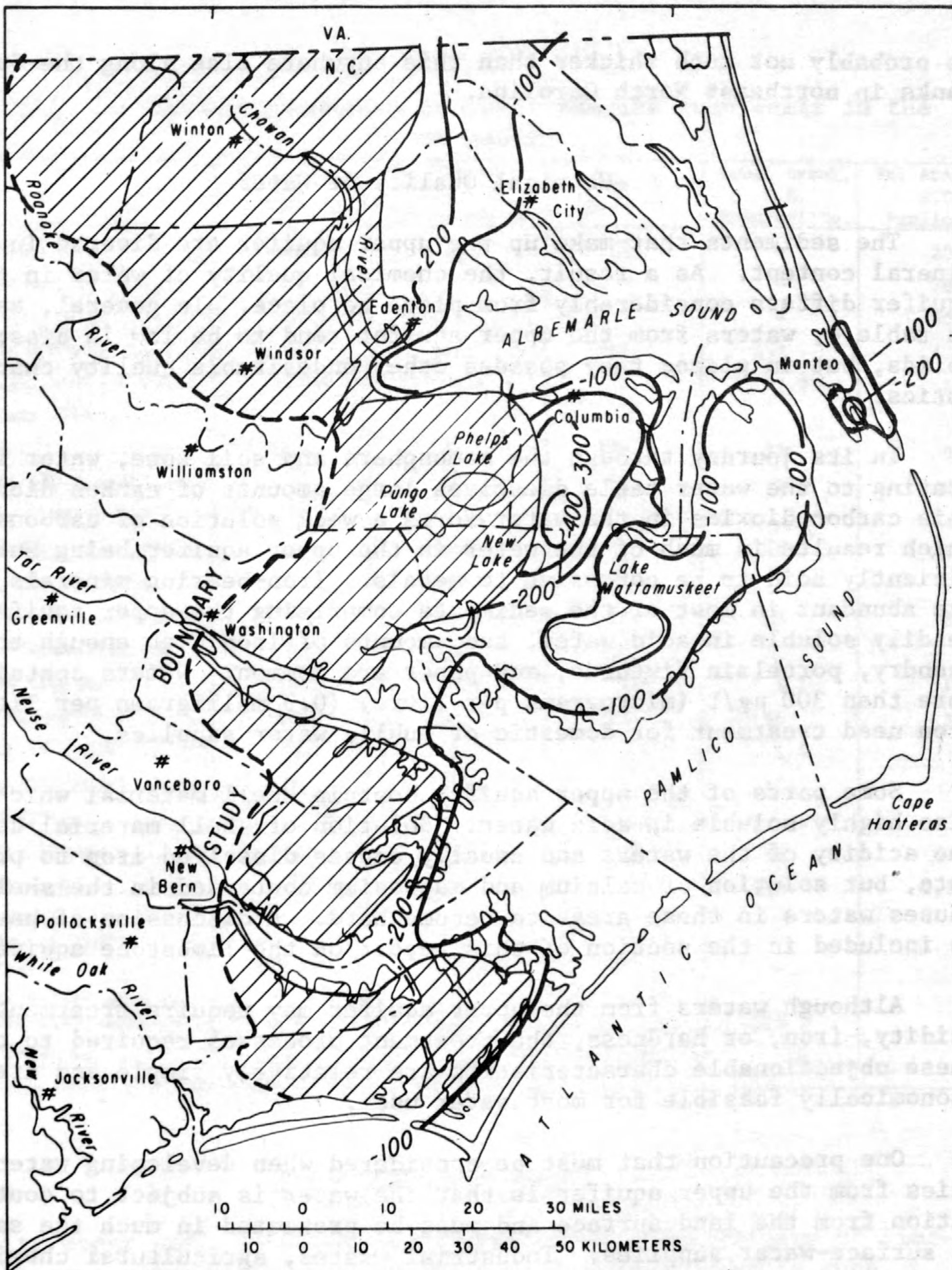
chemical quality of the water, and the quantities estimated on figure 57 include both freshwater and saltwater. The maximum potential yield of this aquifer to a well is generally less than that of the other two aquifers at any given point. However, the maximum potential sustained yield of the upper aquifer per square mile is estimated to be greater than either of the other two aquifers. The principal sources of recharge in the landward part of the upper aquifer are infiltrating precipitation, capturable evapotranspiration, and capturable base streamflow.

An analog model study of the lower Arkansas and Verdigris River Valleys in Arkansas (Bedinger and others, 1970) has indicated that if the water table in a back-swamp area somewhat similar to northeast North Carolina was lowered from the land surface to a depth of 30 ft, approximately 610,000 $(gal/d)/mi^2$ of evapotranspiration and rejected potential infiltration could be captured. The estimated average depth to the water table in northeast North Carolina is about 1 ft. At this initial depth to water, drawdown to 30 ft would produce about 590,000 $(gal/d)/mi^2$. In addition, drawing down the water table to such a depth would also capture the water that is lost from the aquifer as base streamflow. This capture is estimated at 460,000 $(gal/d)/mi^2$. The total of these two captures is roughly 1 $(Mgal/d)/mi^2$. Capture of base streamflow would, of course, result in the streams being dry most of the time.

In arriving at the total capture, the extracted water was assumed to be totally consumed. The consumption of water being normally much less than water use, much of the extracted water might find its way back to the aquifer through stream channels and other routes after use. Such potential reuse of ground-water is desirable from an available-supply viewpoint, but it also raises the possibility of contaminated water being introduced into the shallow aquifer.

Freshwater-Saltwater Relations

The upper aquifer contains only freshwater in the western part of the study area (fig. 58). In the eastern part the freshwater zone in the upper part of the aquifer thins progressively and, in most places, pinches out completely at the borders of the sounds. Roanoke Island and a part of the adjacent mainland are an exception, however. Here, the freshwater lens thickens again to over 200 ft (Peek, and others, 1972). The deep freshwater is contained in semi-confined to confined water-bearing zones in the upper aquifer. In some cases, the freshwater is overlain by saltwater in the unconfined upper part of the upper aquifer. Wells yielding up to 1,000 gal/min have been drilled on Roanoke Island. On Hatteras Island, Winner (1975) found the freshwater lens to be as much as 100 ft thick. Elsewhere along the Cape Hatteras National Seashore, the freshwater lens is rarely as much as 40 ft thick. The lens



EXPLANATION

—200— WATER-QUALITY-ZONE CONTOUR--shows altitude of base of freshwater. Contour interval 100 feet (30 meters). Datum is mean sea level.

Aquifer contains only freshwater.

Aquifer contains both freshwater and saltwater.

Figure 58.--Freshwater-saltwater relations in the upper aquifer.

is probably not much thicker than this anywhere else along the Outer Banks in northeast North Carolina.

Chemical Quality of Water

The sediments that make up the upper aquifer are diverse in their mineral content. As a result, the chemical quality of water in the aquifer differs considerably from place to place. In general, as shown in table 4, waters from the upper aquifer tend to be low in dissolved solids, but in places they possess other undesirable quality characteristics.

In its journey through the atmosphere and soil zone, water infiltrating to the water table dissolves large amounts of carbon dioxide. This carbon dioxide in the water forms a weak solution of carbonic acid which results in much of the water in the upper aquifer being sufficiently acid to be corrosive to metals. Iron-bearing minerals, which are abundant in most of the sediments comprising the upper aquifer, are readily soluble in acid water, and amounts of iron high enough to stain laundry, porcelain fixtures, and paper are common. Waters containing more than 300 μg/L (micrograms per litre) (0.3 milligrams per litre) of iron need treatment for domestic or public water supplies.

Some parts of the upper aquifer contain shell material which is also highly soluble in acid water. Solution of shell material decreases the acidity of the waters and usually causes dissolved iron to precipitate, but solution of calcium and magnesium contained in the shells causes waters in these areas to become hard. A discussion of hardness is included in the section of this report on the limestone aquifer.

Although waters from the upper aquifer may require treatment for acidity, iron, or hardness, the treatment processes required to correct these objectionable characteristics are relatively simple and are economically feasible for most water uses.

One precaution that must be considered when developing water supplies from the upper aquifer is that the water is subject to contamination from the land surface and must be protected in much the same way as surface-water supplies. Industrial wastes, agricultural chemicals and fertilizers, accidental spills of petroleum products, or other noxious materials including leachate from landfills may move downward to the water table and contaminate shallow water supplies. Such contamination has been rare thus far and no significant examples are known to exist in the study area at present.

Table 4.--Chemical Analyses of water samples from wells in the upper aquifer

	Camden, N.C. Camden Co.	Nr. Elizabeth City, N.C. Pasquotank Co.	Manteo, N.C. Dare Co.	South Creek, N.C. Beaufort Co.	Nr. Arapahoe, N.C. Pamlico Co.
Depth (ft)...............	105	32	35	-	20
Temperature (°C)..........	-	-	-	-	70°
Color....................	21	-	-	-	50
Sp. Cond. (µmho)..........	1,200	300	267	452	41
pH.......................	7.4	6.6	7.4	7.2	4.2
Bicarbonate (HCO3) (mg/L)............	379	131	108	37	0
Carbonate (CO3)(mg/L).....	0	0	0	0	0
Phosphate (PO4)(mg/L).....	2.0	.6	.0	.0	-
Hardness (Ca, Mg)(mg/L)...	234	116	106	48	6
Noncarbonate Hardness (mg/L)................	0	9	17	18	6
Calcium (Ca)(mg/L)........	42	33	37	11	.7
Magnesium (Mg)(mg/L)......	31	8.4	3.5	5.1	1.1
Sodium (Na)(mg/L).........	149	16	17	60	3.1
Potassium (K)(mg/L).......	20	1.4	.7	1.4	.7
Chloride (Cl)(mg/L).......	192	9.6	25	95	6.3
Fluoride (F)(mg/L)........	.1	.2	.0	.0	.0
Silica (SiO2)(mg/L).......	50	34	7.1	15	6.9
Iron (Fe)(µg/L)...........	79	300	-	810	2,460
Dissolved Solids (Residue at 180°C) (mg/L)...............	-	-	-	-	38
Dissolved Solids (Sum of constituents)(mg/L).....	674	210	-	218	32
Nitrate (NO3)(mg/L).......	-	.6	.6	.0	.00

The Limestone Aquifer

In its upper part, the limestone aquifer consists largely of limestone with some calcareous sand and shale. The lower part is much sandier with abundant calcareous sand and sandy limestones and dolomitic limestones. (See fig. 47.) The upper part tends to be more permeable than the lower part. This aquifer, as defined in this report, comprises the units of Oligocene, Claiborne, and Sabine age of Brown, and others (1972). These units are generally equivalent to the Castle Hayne aquifer of other authors.

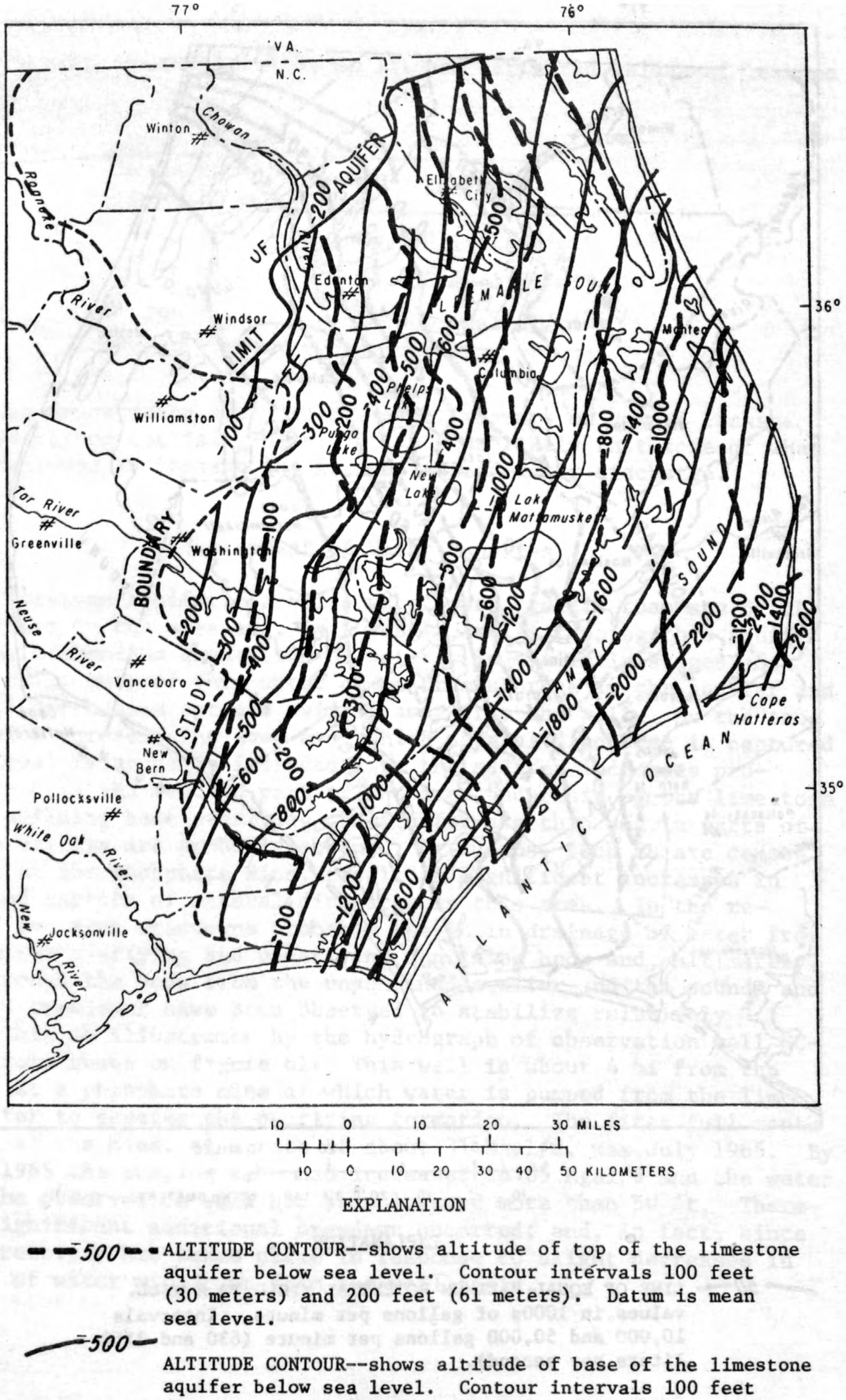
The limestone aquifer dips to the east at an average rate of about 20 ft/mi (fig. 59). The aquifer thickens to the east and southeast and reaches a thickness of about 1,200 ft near Cape Hatteras. The average thickness of the aquifer is 510 ft.

Amount of Water Available

Estimates of the maximum rate at which the limestone aquifer can be pumped at any given point is shown in figure 60. These estimates are based on assumption of a fully penetrating well with drawdown to the top of the aquifer and no interference from other wells. No consideration is given to the chemical quality of the water that would be produced nor to the physical limitations of flow in a single well bore. The yields increase to the east and southeast as both the thickness of the aquifer and its depth below land surface increase. The thicker the aquifer, the greater its ability to transmit water per unit of drawdown. The greater its depth below land surface, the greater the available drawdown. The yields shown on figure 60 are based upon the estimated water-transmitting characteristics of the aquifer itself. Little is known about the amounts of capturable recharge available once artesian storage has been depleted, except near the phosphate mines near Aurora. It is probable, particularly where the overlying confining beds are thick and tight, that sustained yields are considerably less than those shown.

The drawdown conditions assumed in computations used to construct figure 60 actually exist at a phosphate mine near Aurora, N.C., which is near the south bank of the Pamlico River about 18 mi southeast of Washington. Withdrawal of water from the limestone aquifer started in July 1965 and has continued without interruption since at rates ranging from about 50 to about 65 Mgal/d. The number of wells in use at any time varies but is usually 12 or 13 so arranged that water levels in the limestone aquifer are lowered to a depth of 120 ft below sea level in an area of about 400 acres in order to permit dry-pit mining of the phosphate ore. Drawdown is at or below the top of the limestone aquifer in about a 1 mi^2 area, and drawdown effects resulting from these large withdrawals have been detected more than 25 mi from the center of pumping (Peek and Nelson, 1975). The availability of water from the limestone aquifer has been lessened within this large cone of depression, expecially near the center of pumpage.

The sustained yield of the aquifer is assumed to be the amount that can be captured from recharge that enters the aquifer where it either outcrops or subcrops beneath thin beds of fairly permeable materials, plus the amount that can be induced to leak into a cone of depression through overlying confining beds. In the vicinity of the phosphate

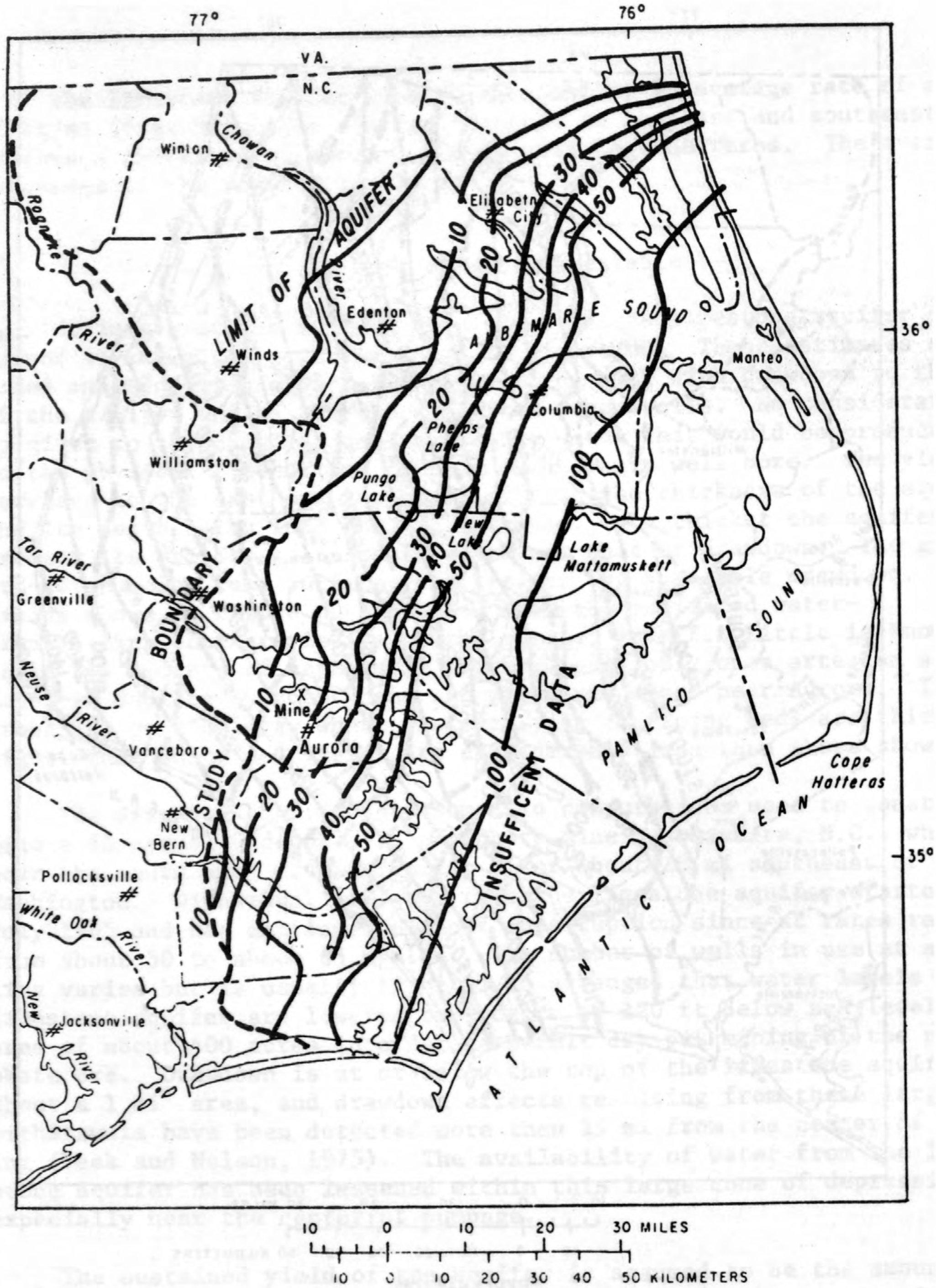


EXPLANATION

500 ALTITUDE CONTOUR--shows altitude of top of the limestone aquifer below sea level. Contour intervals 100 feet (30 meters) and 200 feet (61 meters). Datum is mean sea level.

500 ALTITUDE CONTOUR--shows altitude of base of the limestone aquifer below sea level. Contour intervals 100 feet (30 meters) and 200 feet (61 meters). Datum is mean sea level.

Figure 59.--Altitudes of the top and base of the limestone aquifer.



EXPLANATION

—50— LINE OF EQUAL MAXIMUM POTENTIAL YIELD TO A WELL. values in 1000s of gallons per minute. Intervals 10,000 and 50,000 gallons per minute (630 and 3150 liters per second).

Figure 60.--Maximum potential yield of the limestone aquifer to individual wells without regard to water quality.

mine near Aurora, Sherwani (1973, p. 38) has estimated values of leakage to be:

Thickness of Confining Bed	Leakage
0 ft	500,000 (gal/d)/mi^2
30 ft	28,000 (gal/d)/mi^2
250 ft	14,000 (gal/d)/mi^2

These values undoubtedly also include small amounts of upward leakage through underlying confining beds. It is also likely that some of what Sherwani included as leakage is captured ground-water discharge.

Development of Water Supplies

The limestone aquifer transmits water more readily than any of the other aquifers in the area and, as a result, wells tapping this aquifer can produce tremendous quantities of water. In the early stages of pumping a well, much of this water comes from storage in the aquifer and the cone of depression spreads swiftly away from the well. As the cone of depression spreads, the area over which natural discharge is captured and additional recharge is included into the aquifer increases proportionally. In the western part of the area underlain by the limestone aquifer, confining beds overlying the aquifer are thin and in parts of the stream valleys are probably absent. Drawdowns, such as are caused by pumpage at the phosphate mine, result in significant increases in recharge and capture of natural discharge in this area. In the remainder of the area drawdowns probably result in drainage of water from storage in the overlying and underlying confining beds and, ultimately, leakage through the beds from the unconfined aquifer and the sounds and estuaries. Drawdowns have been observed to stabilize relatively quickly. This is illustrated by the hydrograph of observation well NC-13 near Aurora shown on figure 61. This well is about 4 mi from the well field at a phosphate mine at which water is pumped from the limestone aquifer to dewater the overlying formation. The first full month of pumping at the mine, at a rate of about 31 Mgal/d, was July 1965. By September 1965 the pumping rate had increased to 65 Mgal/d and the water level in the observation well had been lowered more than 50 ft. Thereafter no significant additional drawdown occurred; and, in fact, since 1969 some recovery has taken place in response to slight decreases in the amount of water withdrawn from the well field.

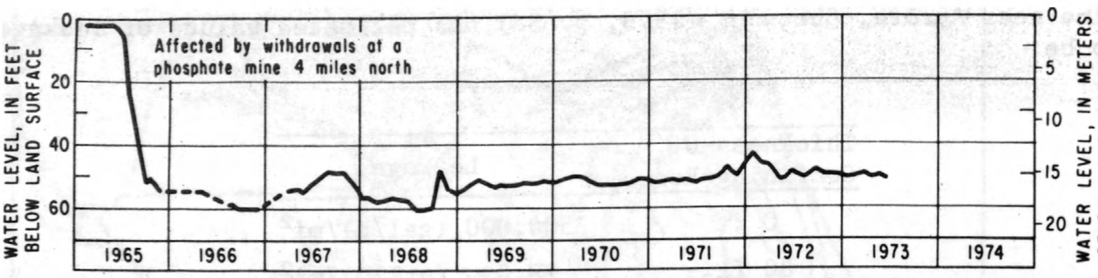


Figure 61.--Hydrograph of well NC 13 near Aurora, N.C., showing the response of the limestone aquifer to the withdrawal of large amounts of water.

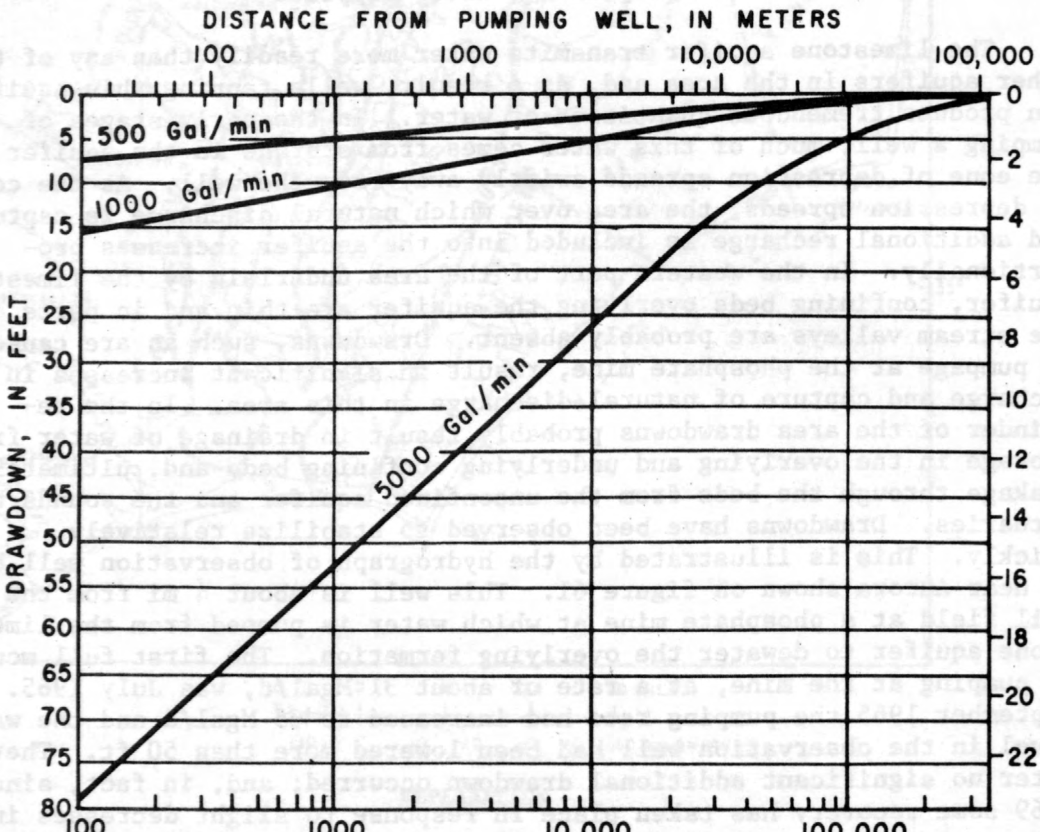


Figure 62.--Distance-drawdown curves for various pumping rates for the limestone aquifer near Aurora, N.C. (Pumping time assumed to be at least 1 year.)

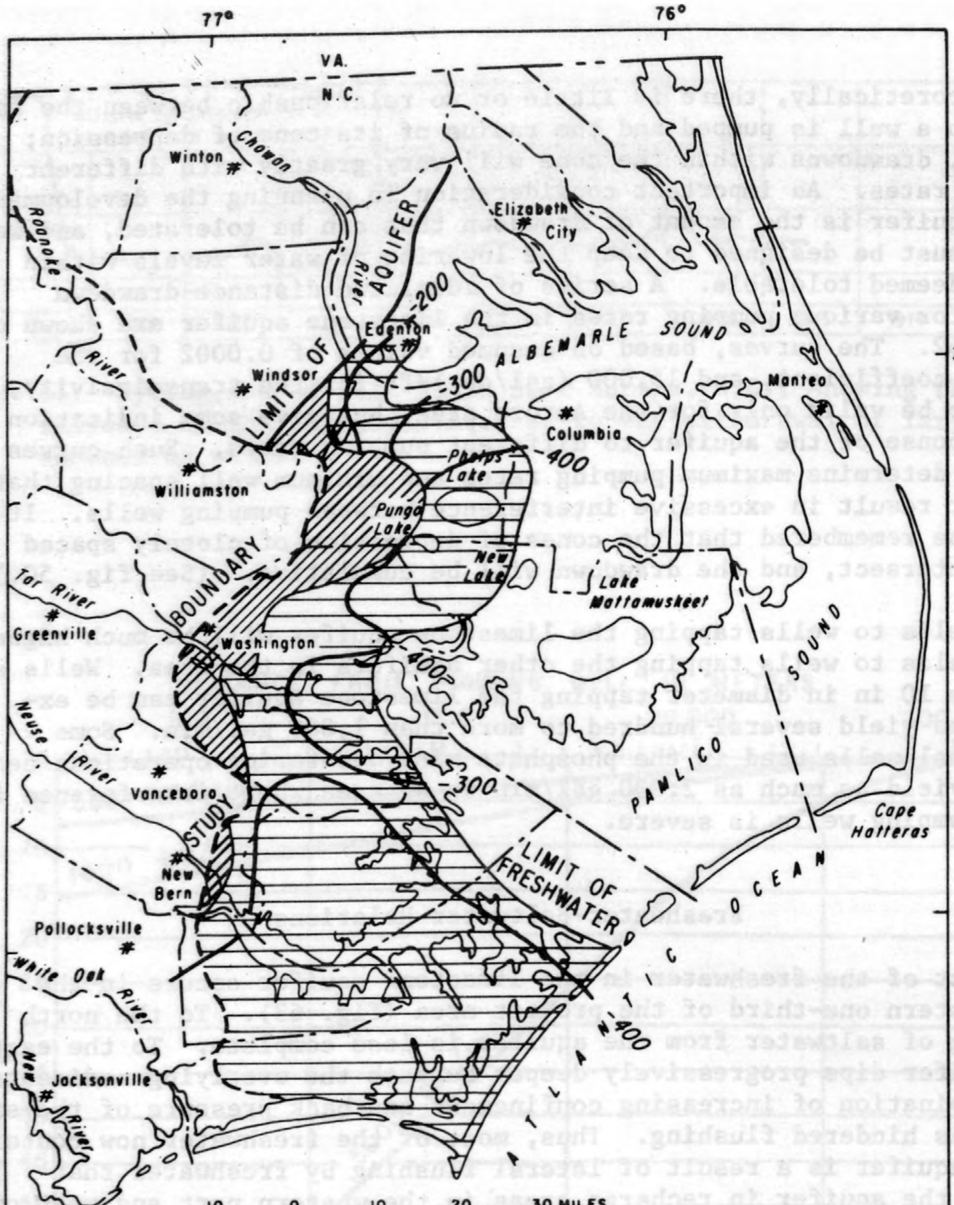
Theoretically, there is little or no relationship between the rate at which a well is pumped and the radius of its cone of depression; however, drawdowns within the cone will vary greatly with different pumping rates. An important consideration in planning the development of an aquifer is the amount of drawdown that can be tolerated, and well fields must be designed to keep the lowering of water levels within limits deemed tolerable. A series of idealized distance-drawdown curves for various pumping rates in the limestone aquifer are shown on figure 62. The curves, based on assumed values of 0.0002 for the storage coefficient, and 15,000 (gal/day)/ft for the transmissivity, are known to be valid only for the Aurora area, but give some indication of the response of the aquifer to different pumping rates. Such curves are used to determine maximum pumping rates and minimum well spacing that will not result in excessive interference between pumping wells. It should be remembered that the cones of depression of closely spaced wells intersect, and the drawdown will be cumulative. (See fig. 50.)

Yields to wells tapping the limestone aquifer will be much higher than yields to wells tapping the other aquifers in the area. Wells as small as 10 in in diameter tapping the limestone aquifer can be expected to yield several hundred to more than 1,000 gal/min. Some individual wells used in the phosphate mine dewatering operations near Aurora yield as much as 2,000 gal/min in an area where interference from other pumping wells is severe.

Freshwater-Saltwater Relations

Most of the freshwater in the limestone aquifer occurs in the southwestern one-third of the project area (fig. 63). To the north flushing of saltwater from the aquifer is less complete. To the east, the aquifer dips progressively deeper beneath the overlying sediments; the combination of increasing confinement and back pressure of the saltwater has hindered flushing. Thus, most of the freshwater now contained in the aquifer is a result of lateral flushing by freshwater that entered the aquifer in recharge areas in the western part and west of the project area where the limestone units cropout--or subcrop--beneath the upper aquifer.

Near the western border of the area, flushing of saltwater is complete, and the limestone aquifer contains only freshwater. Freshwater has been found all the way to the Outer Banks in the southern part of the area. Throughout most of the area where freshwater is found, however, the freshwater is underlain by saltwater.



EXPLANATION

—400— WATER-QUALITY-ZONE CONTOUR--shows altitude of base of freshwater. Contour interval 100 feet (30 meters). Datum is mean sea level.

Aquifer contains only freshwater.

Aquifer contains both freshwater and saltwater.

Aquifer contains only saltwater.

Figure 63.--The freshwater-saltwater relations in the limestone aquifer.

Chemical Quality of Water

The quality of freshwater in the limestone aquifer in northeast North Carolina is typical of waters from most limestone formations. It is hard, high in alkalinity, and tends to form scale. It may also contain silica in amounts objectionable for some uses and, in some localities iron exceeds 300 μg/l, the maximum amount recommended for public water supplies. Analyses of freshwater from four wells tapping the limestone aquifer in northeast North Carolina are listed in table 5.

Table 5.--Chemical analyses of water samples from wells in the limestone aquifer

	Plymouth, N.C. Washington Co.	Belhaven, N.C. Beaufort Co.	Bayboro, N.C. Pamlico Co.	Beaufort, N.C. Carteret Co.
Depth (ft).............	171	313	195	382
Color..................	7	-	9	20
Sp. Cond. (μmho)........	893	1,200	633	578
pH.....................	7.4	6.5	7.6	7.4
Bicarbonate (HCO_3) (mg/L)............	363	237	415	380
Carbonate (CO_3)(mg/L).....	0	0	0	0
Phosphate (PO_4)(mg/L).....	.02	.0	.0	.0
Hardness (Ca, Mg)(mg/L)...	260	287	343	276
Noncarbonate Hardness (mg/L)..............	0	0	3	0
Calcium (Ca)(mg/L).......	50	42	49	83
Magnesium (Mg)(mg/L).....	33	44	54	16
Sodium (Na)(mg/L)........	74	133	8.4	13
Potassium (K)(mg/L)......	21	30	9.1	6.5
Chloride (Cl)(mg/L)......	94	117	11	7.0
Fluoride (F)(mg/L).......	.6	.8	.6	.3
Silica (SiO_2)(mg/L).......	38	44	56	41
Iron (Fe)(μg/L)..........	500	60	120	400
Manganese (Mn)(μg/L)......	10	-	.000	.000
Aluminum (Al)(μg/L)......	100	100	200	100
Lithium (Li)(μg/L).......	-	-	300	400
Dissolved Solids (Residue at 180°C) (mg/L)..............	491	-	-	360
Dissolved Solids (Sum of constituents)(mg/L)......	495	666	394	357
Nitrate (NO_3)(mg/L).......	.2	.3	.6	2.2

Hard waters are usually recognized because they do not lather readily and form curds when mixed with soap. The hardness of these waters is caused by calcium and magnesium dissolved from limestone and dolomite which are abundant throughout the aquifer. Because hardness is a property not caused by a single constituent, it is reported as the amount of calcium carbonate ($CaCO_3$) that would be chemically equivalent to all of the hardness-causing constituents present in solution. To some degree, the amount of hardness that is objectionable to an individual depends upon what type of water the individual is accustomed to. The following arbitrary scale has been used to classify the hardness of water:

Hardness as $CaCO_3$ (mg/l)	Classification
0-60	soft
61-120	moderately hard
121-180	hard
180 +	very hard

Based upon this system most of the water from the limestone aquifer is hard or very hard.

Silica (SiO_2) is usually present in limestone-aquifer waters in amounts ranging from 20 to 40 mg/l, but occasionally approaches 80 mg/l. Silica can form bothersome scale in high-pressure steam boilers and on the blades of steam turbines. Silica can also be removed, but not so readily as calcium and magnesium.

Once water percolates from the upper aquifer into the limestone aquifer any dissolved iron present will usually start to precipitate, and most limestone waters do not contain high iron concentrations. Near recharge areas, however, where water has had short residence time in the aquifer, the iron concentration may be 300 µg/l or more and can stain clothing, bathroom fixtures, utensils, and papers.

The Lower Aquifer

The lower aquifer comprises all rocks of Paleocene, Cretaceous, and Jurassic age in the area as they have been defined by Brown and others (1972). In some reports, rocks roughly equivalent to the rocks of Paleocene age are treated separately as the Beaufort aquifer. The lower aquifer underlies virtually all of the Coastal Plain of North Carolina. The base of the lower aquifer lies directly upon the crystalline basement rocks. The lower aquifer consists mostly of thin beds of shale interbedded with fine to medium sands. Here and there, thin beds of dolomite, limestone (mostly sandy), or shells occur.

The aquifer both dips and thickens to the east and southeast (fig. 64). The thickness at Cape Hatteras is over 7,000 ft. The average thickness of the aquifer in the area of study is 2,800 ft. The aquifer dips at an average rate of 25 ft/mi.

Amount of Water Available

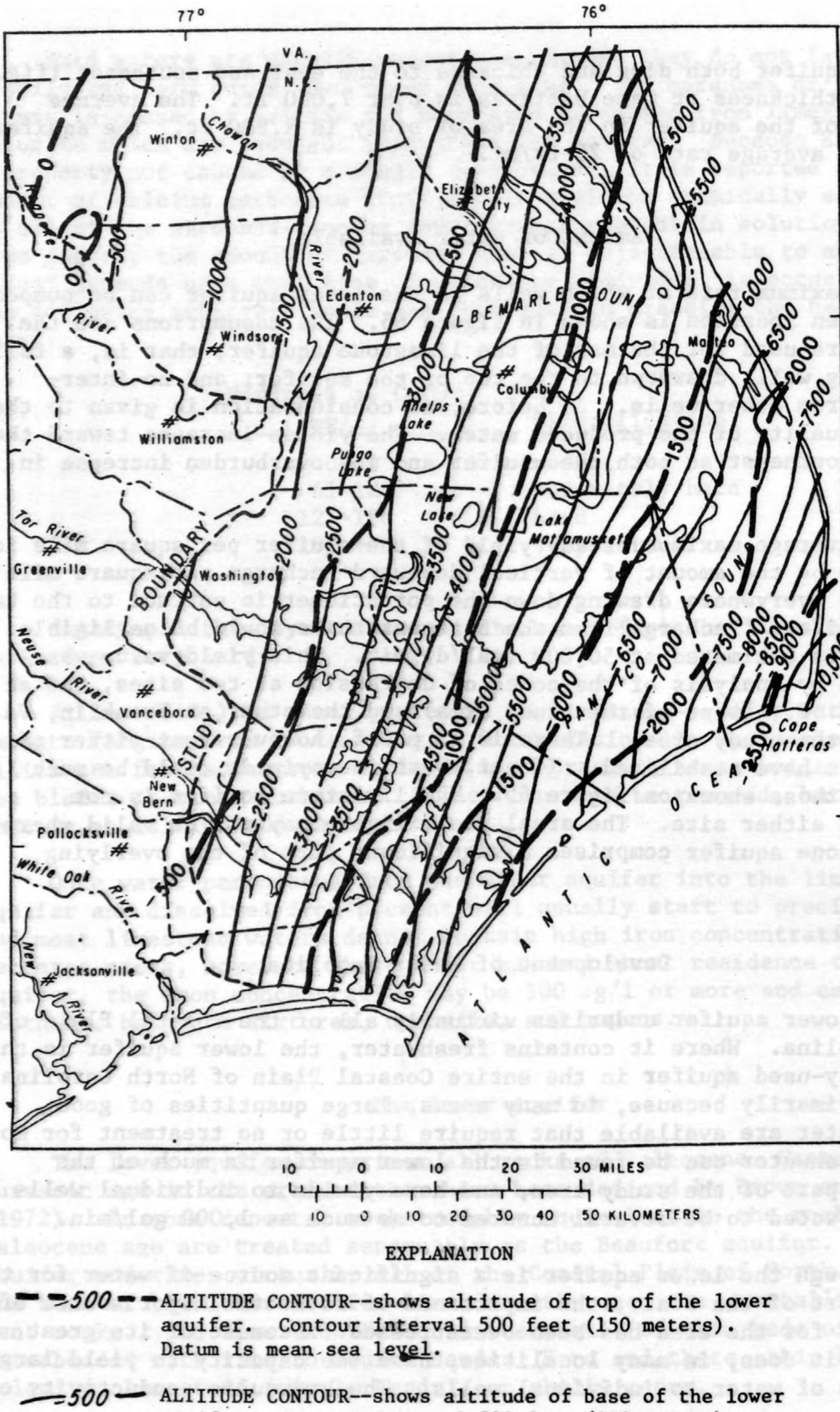
The maximum rate at which wells in the lower aquifer can be pumped at any given location is shown in figure 65. The assumptions are the same as were used for the map of the limestone aquifer, that is, a fully penetrating well; drawdown to the top of the aquifer; and no interferrence from other wells. As before, no consideration is given to the chemical quality of the produced water. The yields increase toward the east and southeast as both the aquifer and its overburden increase in thickness.

The average maximum steady yield of the aquifer per square mile is assumed to be the amount of vertical downward recharge per square mile induced by everywhere drawing down the potentiometric surface to the top of the aquifer. Recharge from the basement rocks would be negligible. The yield is estimated at 50,000 (gal/d)/mi^2. This yield value was determined by analysis of the cones of depression at two sites, one at Kinston; N. C., (west of the study area) and the other at Franklin, Va., (north of the study area). There is no proof, however that either of these cones have stabilized. If not, sustained yields could be much less than those shown on figure 65. The limestone aquifer is not present at either site. The areal yield figure may not be valid where the limestone aquifer comprises a significant part of the overlying section.

Development of Water Supplies

The lower aquifer underlies virtually all of the Coastal Plain of North Carolina. Where it contains freshwater, the lower aquifer is the most widely-used aquifer in the entire Coastal Plain of North Carolina. This is primarily because, in many areas, large quantities of good quality water are available that require little or no treatment for most uses. Freshwater can be found in the lower aquifer in much of the northwest part of the study area, and here yields to individual wells can be expected to be several hundred to as much as 1,000 gal/min.

Although the lower aquifer is a significant source of water for the eastern part of the State, the importance of it as the major source of freshwater for the area has been overstressed. Because of its great thickness it does, in many localities, have the capacity to yield large quantities of water to individual wells. The hydraulic conductivity of

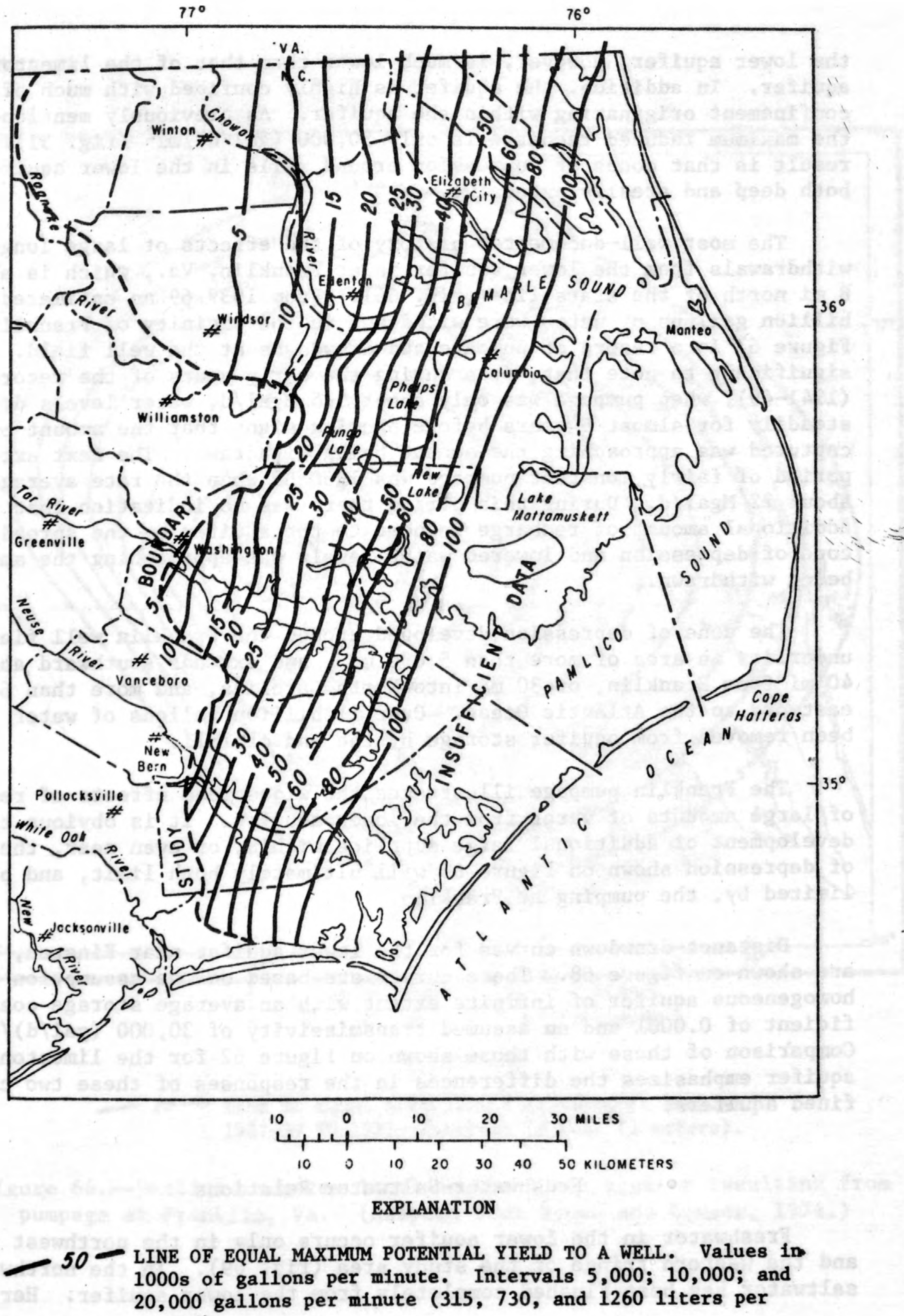


EXPLANATION

—500— ALTITUDE CONTOUR--shows altitude of top of the lower aquifer. Contour interval 500 feet (150 meters). Datum is mean sea level.

—500— ALTITUDE CONTOUR--shows altitude of base of the lower aquifer. Contour interval 500 feet (150 meters). Datum is mean sea level.

Figure 64.--Altitudes of the top and base of the lower aquifer.



EXPLANATION

— 50 — LINE OF EQUAL MAXIMUM POTENTIAL YIELD TO A WELL. Values in 1000s of gallons per minute. Intervals 5,000; 10,000; and 20,000 gallons per minute (315, 730, and 1260 liters per second).

Figure 65.--Maximum potential yield of the lower aquifer to individual wells without regard to water quality.

the lower aquifer, however, is much lower than that of the limestone aquifer. In addition, the aquifer is highly confined with much of the confinement originating within the aquifer. As previously mentioned, the maximum induced recharge is only 50,000 (gal/d)/mi^2 (fig. 51). The result is that cones of depression around wells in the lower aquifer are both deep and areally extensive.

The most well-documented history of the effects of large long-term withdrawals from the lower aquifer is at Franklin, Va., which is about 8 mi north of the state line (fig. 66). From 1939-69 an estimated 158 billion gallons of water were withdrawn in the vicinity of Franklin. Figure 67 is a record of pumpage and drawdowns at the well field. It is significant to note that, even during the early years of the record (1941-49), when pumpage was only about 5.5 Mgal/d, water levels declined steadily for almost 5 years before showing signs that the amount being captured was approaching the amount being withdrawn. The next extended period of fairly constant pumpage was 1960-65 when the rate averaged about 22 Mgal/d. During this period there was no indication that the additional amount of recharge induced to the aquifer by the spreading cone of depression and lowered water levels was approaching the amount being withdrawn.

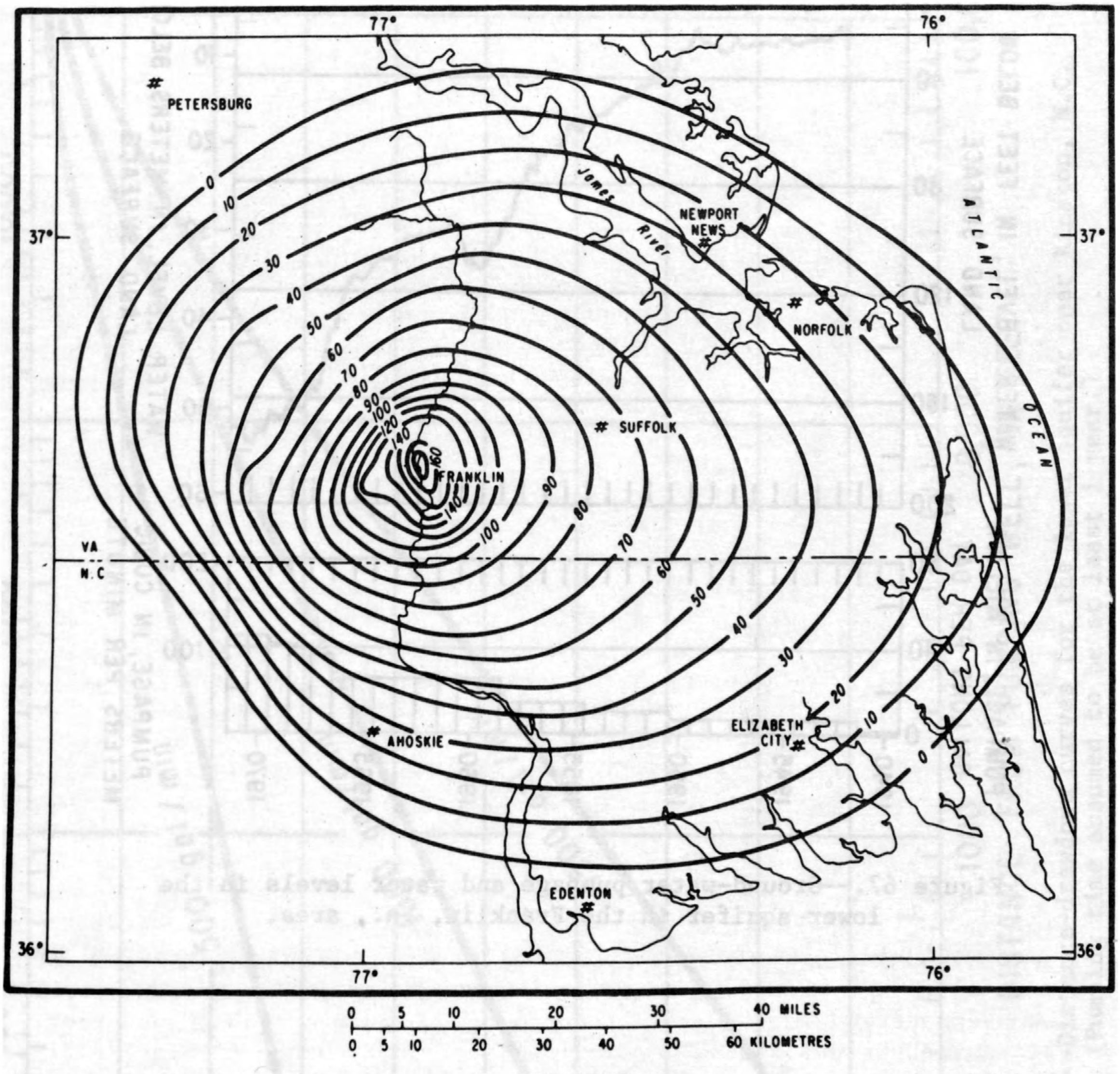
The cone of depression developed around the Franklin well field now underlies an area of more than 5,000 mi^2, and extends southward about 40 mi from Franklin, or 30 mi into North Carolina, and more than 60 mi eastward to the Atlantic Ocean. Over 11 billion gallons of water had been removed from aquifer storage by the end of 1971.

The Franklin pumpage illustrates the widespread effects of removal of large amounts of water from the lower aquifer. It is obvious that development of additional large supplies within, or even near, the cone of depression shown on figure 66 will ultimately both limit, and be limited by, the pumping at Franklin.

Distance-drawdown curves for the lower aquifer near Kinston, N.C., are shown on figure 68. These curves are based on the assumption of a homogeneous aquifer of infinite extent with an average storage coefficient of 0.0001 and an assumed transmissivity of 30,000 (gal/d)/ft. Comparison of these with those shown on figure 62 for the limestone aquifer emphasizes the differences in the responses of these two confined aquifers.

Freshwater-Saltwater Relations

Freshwater in the lower aquifer occurs only in the northwest part and the western fringe of the study area (fig. 69). In the northwest saltwater has been flushed completely from the lower aquifer. Here



EXPLANATION

— 20 — LINE OF EQUAL APPROXIMATE WATER-LEVEL DECLINE. 1937-39 TO 1971--interval 10 feet (3 meters).

Figure 66.--Decline in water level in the lower aquifer resulting from pumpage at Franklin, Va. (Adapted from Brown and Cosner, 1974.)

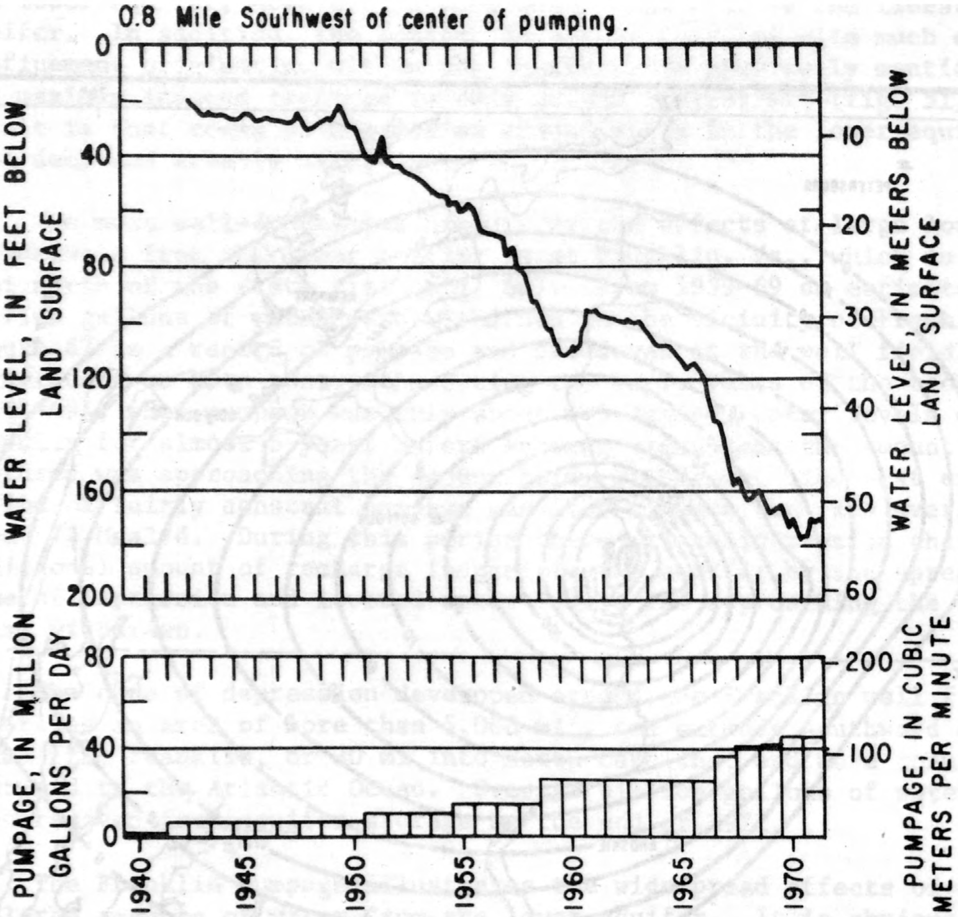


Figure 67.--Ground-water pumpage and water levels in the lower aquifer in the Franklin, Va., area.

the limestone is absent and the lower aquifer lies immediately below upper aquifer and not far below the land surface.

Within a 20-mi wide strip east of the completely freshwater area and along the western fringe of much of the remainder of the area, freshwater overlies saltwater in this aquifer. Farther east, the aquifer yields only saltwater.

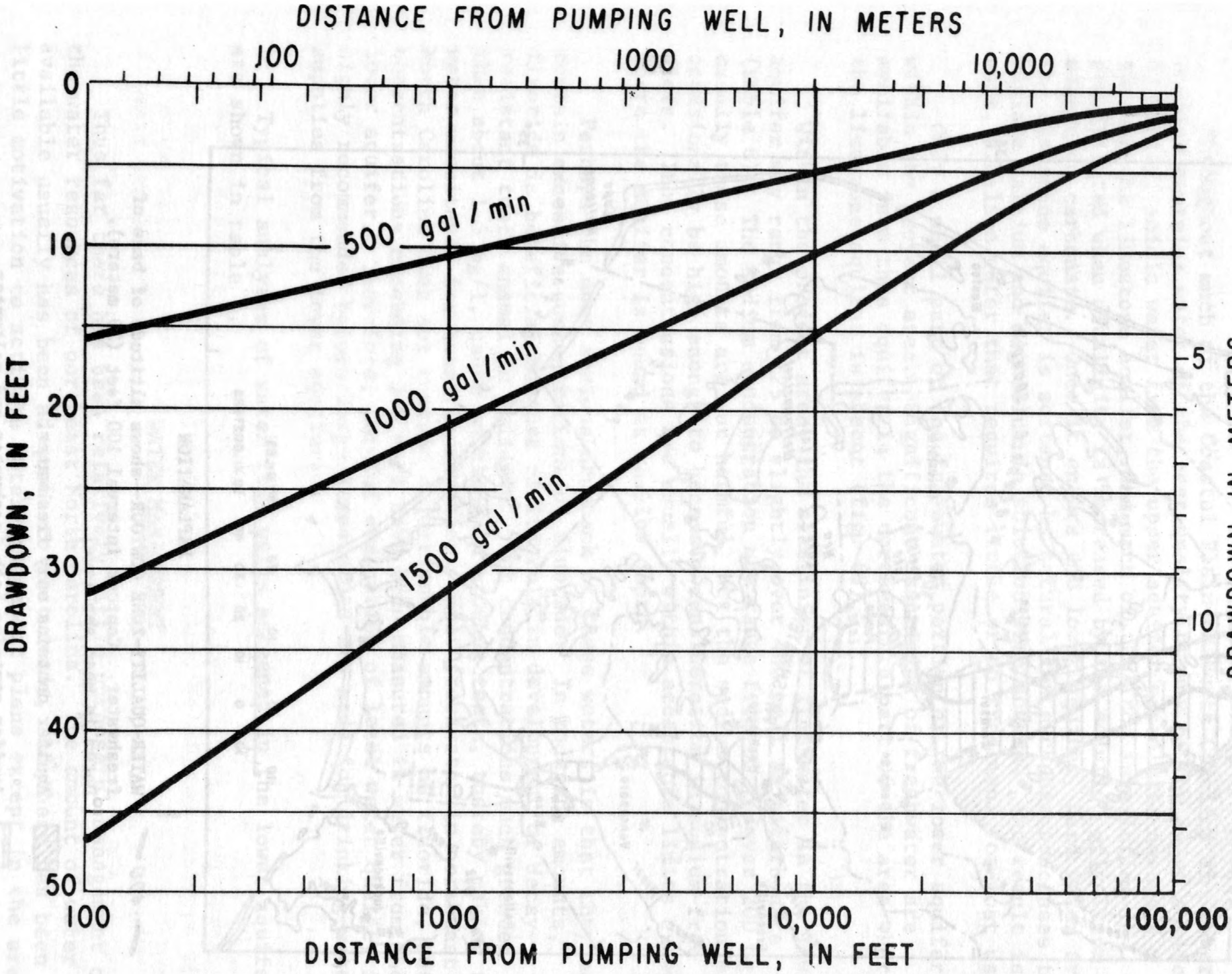
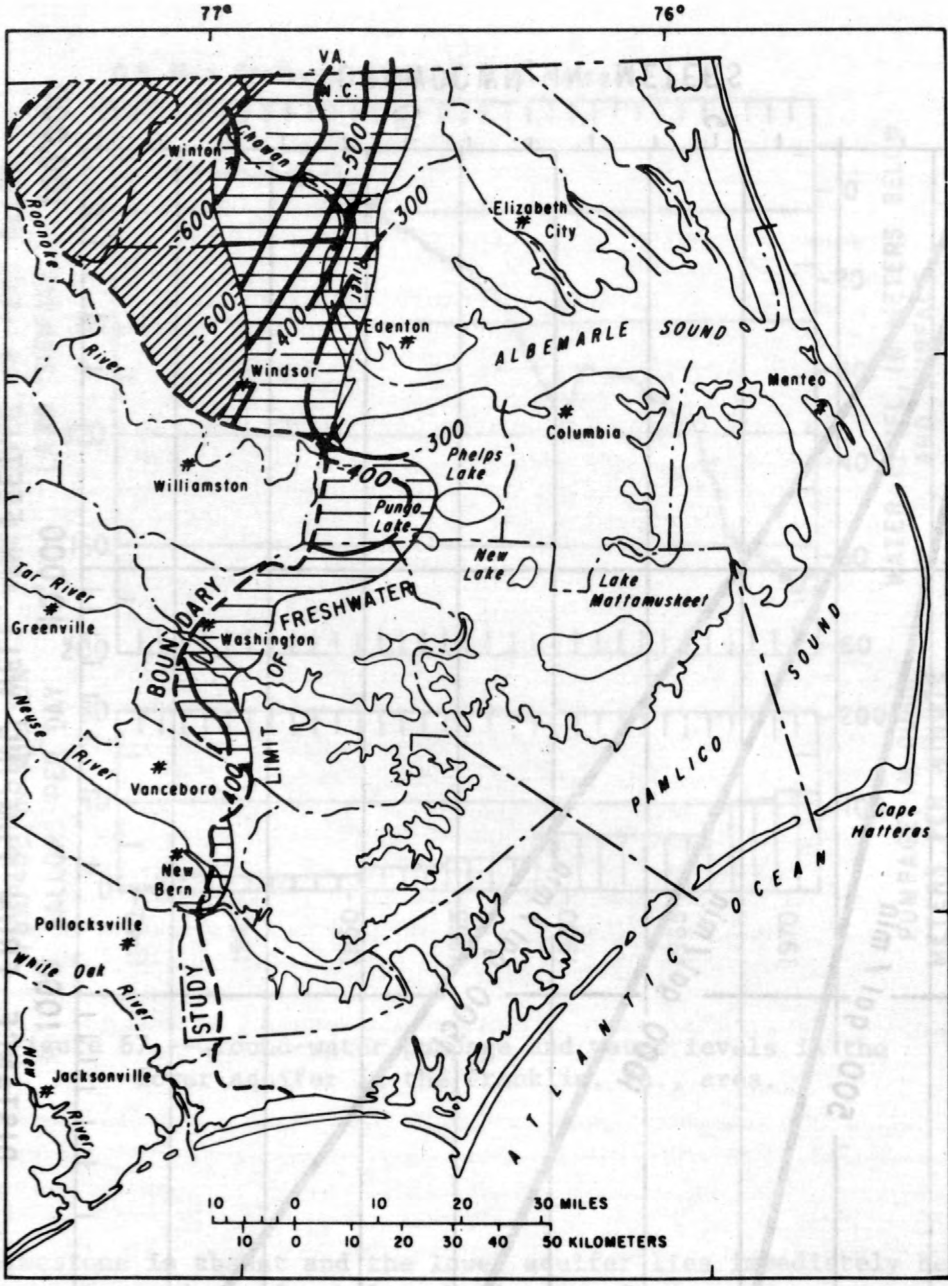


Figure 68.--Distance-drawdown curves for the lower aquifer near Kinston, N.C.
(Pumping time assumed to be at least 1 year.)



EXPLANATION

—-400— WATER-QUALITY-ZONE CONTOUR--shows altitude of base of freshwater. Contour interval 100 feet (30 meters). Datum is mean sea level.

Aquifer contains only freshwater.

Aquifer contains both freshwater and saltwater.

Aquifer contains only saltwater.

Figure 69.--Freshwater-saltwater relations in the lower aquifer.

Chemical Quality of Water

Throughout much of the Coastal Plain of North Carolina the lower aquifer contains water of the best quality of any of the major aquifers. Typically, acidic water from the upper aquifer percolates downward through the limestone aquifer, and much of the iron in solution is precipitated when alkalinity is increased by the solution of calcium and magnesium carbonate. Once it enters the lower aquifer, hard water from the limestone aquifer is softened by natural ion exchange processes that replace calcium and magnesium in solution with sodium. The result is a soft, alkaline water that requires little or no treatment for most uses.

Only a small part of the freshwater portion of the lower aquifer is within the project area. Significant quantities of freshwater are available from this aquifer in the northwestern part of the area where the limestone aquifer is absent (fig. 69).

Within the project area, the alkalinity of freshwater in the lower aquifer may range from 125 to slightly over 400 mg/l as bicarbonate (table 6). The sodium concentration may range from 60 to over 200 mg/l; usually these amounts are not harmful, but the sodium concentration may occasionally be high enough to become a consideration in sodium-free diets. Iron concentrations are usually within acceptable limits except where the aquifer is found at shallow depth.

Perhaps the most serious drawback of these waters is that they may contain excessive concentrations of fluoride. In moderate amounts, fluoride is beneficial because of its role in development of decay-resistant tooth enamel in children. But concentrations much greater than about 1.5 mg/l, cause mottling in growing teeth, thereby making the water unsuitable for human consumption. Most freshwater in northeast North Carolina does not contain objectionable amounts of fluoride, but concentrations exceeding 5.0 mg/l have been measured in water from the lower aquifer. Therefore, careful evaluation of local water quality is highly recommended before large investments are made for drinking-water supplies from the lower aquifer.

Typical analyses of water from wells screened in the lower aquifer are shown in table 6.

WATER MANAGEMENT

Thus far there has been relatively little purposeful management of the water resources of northeast North Carolina. The amount of water available usually has been adequate to meet needs, and there has been little motivation to activate water-management plans except in the area

Table 6.--Chemical analyses of water samples from wells in the lower aquifer

	Murfreesboro, N.C. Hertford Co.	Powellsville, N.C. Bertie Co.	Woodland, N.C. Northampton Co.	Washington, N.C. Beaufort Co.
Depth (ft)............	432	310	259	480
Temperature (°C).........	17.5	19.5	17.8	-
Color....................	7	11	50	-
Sp. Cond. (µmho).........	281	632	358	1,230
pH.......................	7.8	7.8	7.6	8.7
Alkalinity as CaCO3 (mg/L)................	138	317	179	-
Bicarbonate (HCO3) (mg/L)................	168	387	218	336
Carbonate (CO3)(mg/L)....	0	0	0	26
Nitrate (N)(mg/L)........	.07	.36	-	-
Phosphate (PO4)(mg/L)....	1.9	-	1.1	2.9
Hardness (Ca, Mg)(mg/L)..	4	16	5	12
Noncarbonate Hardness (mg/L)................	0	0	0	0
Calcium (Ca)(mg/L).......	1.2	2.8	1.0	2.8
Magnesium (Mg)(mg/L).....	.2	2.2	.7	1.2
Sodium (Na)(mg/L)........	64	140	82	250
Potassium (K)(mg/L)......	4.8	15	7.4	9.0
Chloride (Cl)(mg/L)......	4.0	14	4.1	149
Sulfate (SO4)(mg/L)......	5.2	5.8	4.5	-
Fluoride (F)(mg/L).......	.3	1.2	.4	5.6
Silica (SiO2)(mg/L)......	27	20	3.7	9.3
Iron (Fe)(µg/L)..........	120	580	2,700	270
Manganese (Mn)(µg/L).....	10	0	40	-
Aluminum (Al)(µg/L)......	0	0	0	-
Suspended Lithium (Li) (µg/L)................	0	0	500	-
Dissolved Solids (Residue at 180°C) (mg/L)................	196	396	222	-
Dissolved Solids (Sum of constituents)(mg/L)....	192	395	214	679
Nitrate (NO3)(mg/L)......	.3	1.6	1.6	-
Date.....................	5-14-64	9-27-55	7-9-5	2-8-63

affected by withdrawals at the phosphate mine in Beaufort County. Water management has, of course, taken place on a large scale during the processes of improvement of stream channels to hasten flood drainage and in the construction of canals to drain swamps for agriculture, but the main concern in these practices is land management. Scant attention has been given to their overall effects on the hydrologic system. It is shown in figures 27 and 28 that artificial channel improvement significantly changes the flow patterns of streams, and the effects of drainage to make swamplands farmable is likely to be even more disruptive of the natural hydrologic cycle. However, land drainage and channel improvement are established facts throughout much of the area, and future water-management schemes must be based upon existing conditions of land management rather than the assumption of an undisturbed hydrologic system.

Schemes for water management should consider all aspects of the hydrologic system. Perhaps the most important step in managing the water resources of the area is the development of a conceptual framework within which individual decisions can be made. This has been done to some extent in the preceding sections of this report.

Two major considerations must be kept in mind in planning areal development of water supplies. First, the results of any major alteration of the hydrologic regime on the operation of the entire hydrologic system must be considered. The interdependency of the various land-phases of the hydrologic cycle clearly implies that it is not possible to develop large supplies of water from any one source without affecting other parts of the areal water budget. For example, the shallow aquifer represents the most productive long-term source of fresh water in the area. However, if a significant portion of the potential supply available from this aquifer is developed in an area, surface drainage from the area will be diminished and small streams will probably be dry much of the time. Similarly, pumpage from the upper aquifer will decrease the recharge to the lower aquifers. Since most water users actually consume only a small percentage of their total withdrawal, it is often possible with careful planning to dispose of used water in such a way as to conteract many of the detrimental effects of large-scale withdrawals.

It is not within the scope of this report to consider the results of water management upon parts of the environment other than the hydrologic systems, but the ecological implications of lowered water tables and dried-up streams and swamps should be evaluated in planning total areal development.

The second hydrologic consideration is the effects of water withdrawal and use on water quality. The possibilities of saltwater encroachment, and the introduction of polluted water to streams and aquifers must occupy a position of importance equal to that of concern about the amounts of water available.

The fundamental aspects of water management philosophy must be based upon the gross water budget as discussed in the first section of this report. The amount of water in the area is virtually fixed by nature. Any practical management philosophy must recognize that, although water is a renewable resource, it is nevertheless a finite resource.

Much remains to be learned about the hydrology of northeast North Carolina before specific recommendations can be made concerning how best to manage the system. Reexamination of the water budget as defined in the first section of this report will be worthwhile in order to establish some general guidelines as to where water-management feasibility studies should be directed. The water budget can be summarized by the following equation:

$$\underset{\text{(precipitation)}}{P} = \underset{\text{(evapotranspiration)}}{ET} + \underset{\text{(runoff)}}{RO} + \underset{\text{(change in ground-water storage)}}{\Delta GW} \qquad (2)$$

which provides a framework for discussing possible ways of managing the water resources of the area.

Precipitation

Precipitation provides the only source of input to the system, and is perhaps the only part over which we have no real control. Since earliest history man has tried to manage the amount of atmospheric moisture falling upon his habitat. Methods have ranged from filling the air with a variety of pollutants to ceremonial dances around a totem pole. As yet there is no valid reason to believe that man has ever been able to intentionally change his weather to any noticeable degree. Therefore, we conclude that precipitation is fixed at an average of 50 in per year, and that water management must start after rainfall reaches the surface of the earth.

Evapotranspiration

Under the present conditions evapotranspiration may be said to have first call on water that enters the area as precipitation. It returns a lion's share, 34 in or 68 percent of total precipitation back to the atmosphere as vapor, and even during dry years evapotranspiration demands tend to be met at the expense of other parts of the hydrologic cycle. Evapotranspiration has been the subject of a considerable amount of study in arid areas, but has received scant attention in wetter climates. One possible means for controlling ET in areas such as northeast North Carolina is to lower the water table far enough that it will be below both the root zone and the depth to which capillary action can readily bring water near enough to land surface to be evaporated. Throughout much of the project area large-scale drainage for agriculture may result in lowering the water table 1 or 4 ft within the next few years (Heath, 1975). Because no studies have been done relating evapotranspiration to depth to water table in this area it is not possible to predict what effect this will have on ET losses relative to the overall water budget.

Investigations in somewhat similar areas in Arkansas (Bedinger, and others, 1971) indicate that decreases in ET may not be significant to depths of around 5 ft, and that some ET losses are apparent to depths of about 25 ft. These data were used earlier in this report to estimate that water levels uniformly drawn down to 30 ft below land surface would allow salvage of about 590,000 (gal/d)/mi^2 of ET losses in northeast North Carolina. It is recognized that the transfer of data and techniques from other areas, as was done here, introduces the possibility of large errors, and these estimates are intended primarily to point out that large amounts of water can be potentially salvaged from the upper aquifer by reducing ET losses. It is, of course, not practical to lower the water table uniformly over large portions of the area by as much as 30 ft; but pumping large numbers of closely spaced wells possibly could locally effect the capture of a significant amount of the water that is naturally lost to the atmosphere.

Some undesirable results can be associated with a drastically lowered water table. Streamflow, for example, would be greatly reduced, particularly during base flow; and small streams would go dry for long periods during most years. In areas of thick peat soils, the near-surface drying effect of a lowered water table can cause soil compaction and oxidation with the end result being land-surface subsidence (Heath, 1975, p. 85). Also, in drained soils, certain land-management practices require that the water table be kept as high as is consistent with good crop production.

Runoff

The most common method of managing water supplies on a large scale is surface storage of excess runoff. In inland areas, surface storage is accomplished by means of reservoirs created by dams across stream channels. In northeast North Carolina, however, the terrain is so flat that suitable dam sites are not available. The only significant amount of fresh surface-water storage in the area at present is in natural lakes. Although these lakes store large quantities of water, they average only 4 ft in depth; and the amount of water stored in them in proportion to their surface areas is much less than in inland artificial reservoirs. Figure 70 shows the relation of storage to surface area in mountain and Piedmont reservoirs compared to natural lakes in the project area.

Surface storage either in excavated artificial lakes or in diked areas above land surface has been suggested. The scope of this report does not permit an evaluation of either the engineering or the economic feasibility of such storage, but there are obviously problems with either approach. The high water table, which is at or near the surface in most undrained parts of the area, would make sizable excavations difficult. Even in areas that have been drained for agriculture, the water table is seldom more than 4 ft below land surface.

The most frequently mentioned possibility for storing surface water in coastal areas is in above-ground reservoirs created by surrounding the reservoir area with earthen dikes. During periods of high overland runoff the dikes would be filled (presumably by pumping), and the water held for use when needed. Whether water can be successfully stored in diked enclosures depends upon whether the sides and bottoms of the reservoirs can be made sufficiently watertight to suspend water above the natural water table. At most locations, reservoirs would have to be lined with clay or some other impervious material, which would add greatly to construction costs. Another problem with above-ground reservoirs in many areas would be keeping them adequately filled. Reservoirs created by on-channel dams are able to catch and store flood flows in their entirety if needed, while off-channel reservoirs, especially if above ground, must be filled by pumping. Even if all streamflow could be captured, storage requirements in the Coastal Plain are much higher for a given available draft than in the interior of the State (Arteaga and Hubbard, 1975). Figure 71 shows storage versus available draft for two small drainage areas, one of which is near the edge of the project area and the other in the mid-Piedmont. In order to be assured of a given draft at the 20-yr recurrence interval, the Coastal Plain setting would require more than double the storage volume of the Piedmont setting. While these two examples do not constitute a definitive statistical sample, they are probably typical.

In special cases where large amounts of water are available from dewatering operations, or perhaps near estuaries that are fresh at least part of the time, surface storage may be practical in the project area. Surface storage does not, however, seem to represent a generally applicable management tool in northeast North Carolina.

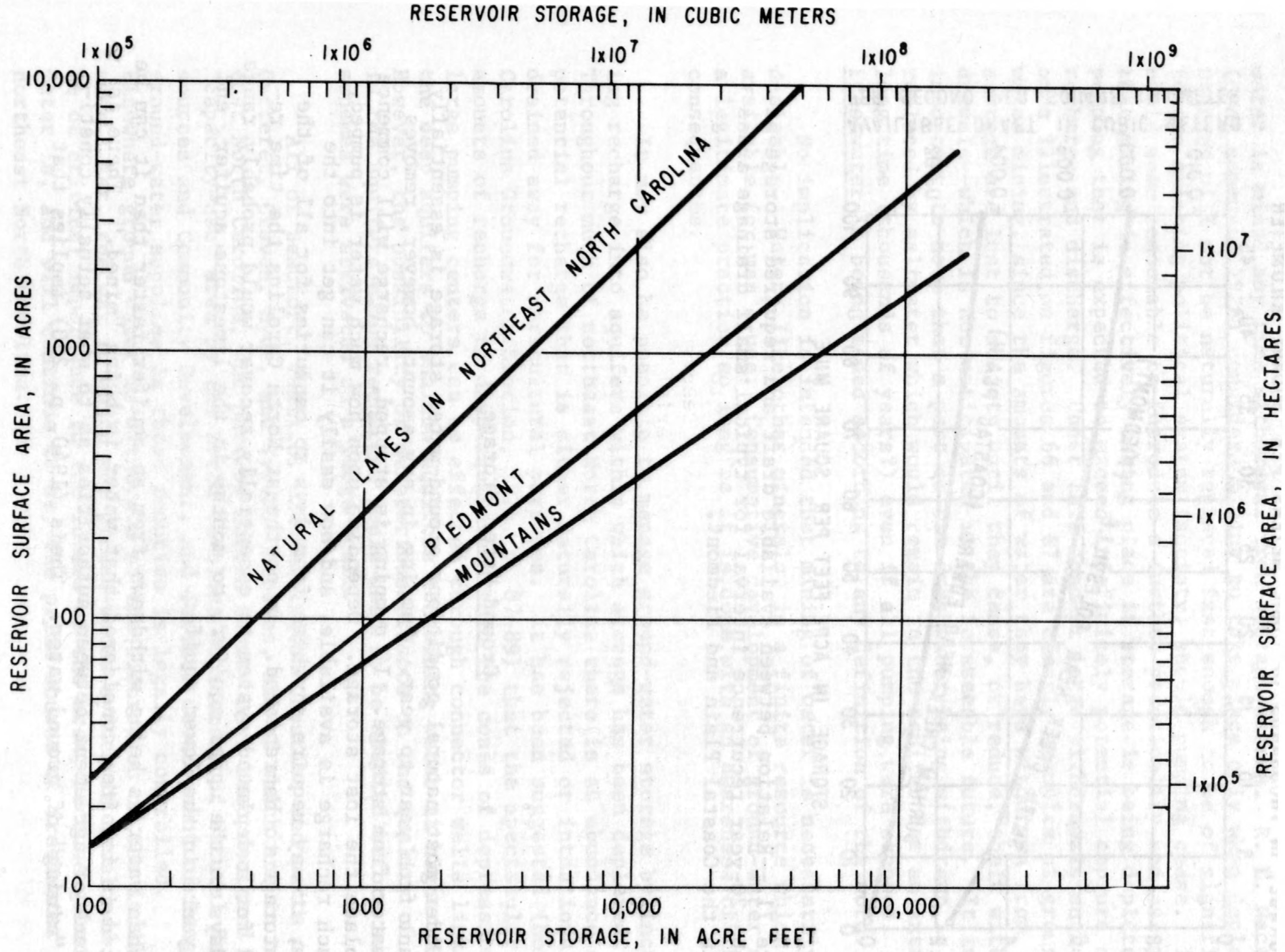


Figure 70.--Relation between lake-surface area and water storage in natural lakes in northeast North Carolina and reservoirs in the Piedmont and mountains. (Adapted from Arteaga and Hubbard, 1975.)

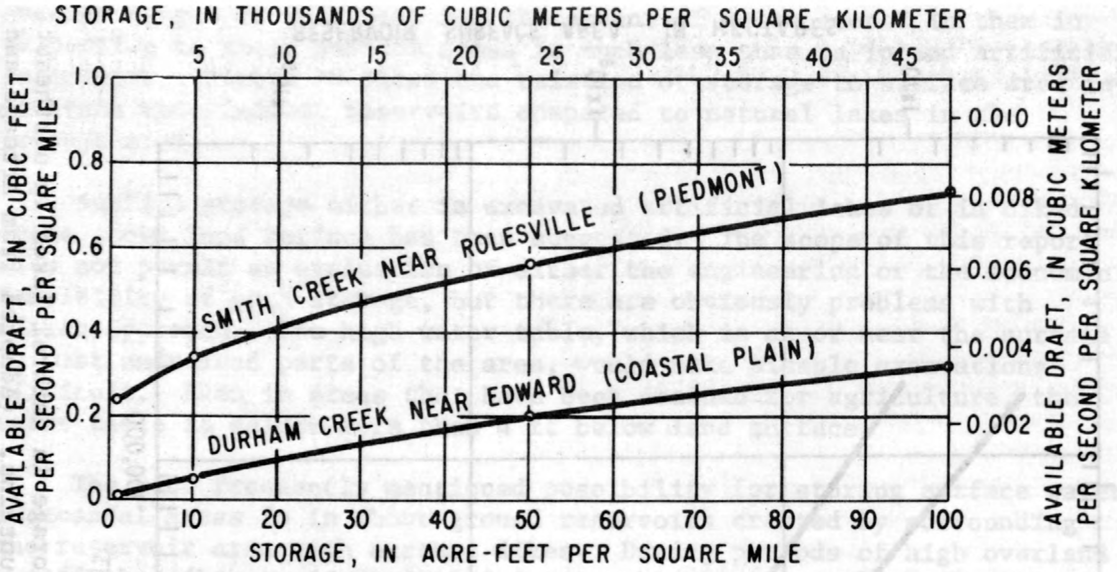


Figure 71.--Relation between available draft and required storage at the 20-year recurrence interval for typical small drainage areas in the Coastal Plain and Piedmont.

Ground-Water Storage

Under most natural conditions ground-water storage is essentially constant from year to year. Pumping in any amount, however, removes some water from storage. If pumping is stopped, recharge will commence to replace the lost storage. Depending upon how much water is pumped, how much recharge is available, and how easily it can get into the system, it may require anywhere from days to centuries for all of the lost storage to be replaced. In northeast North Carolina the time required for a depleted system to essentially recover would probably range from days in the upper aquifer, to months in the limestone aquifer, and a few years in the lower aquifer.

When water is being withdrawn from an aquifer faster than it can be replaced it is often considered that water is being "mined." There is some lack of agreement between authorities as to what actually constitutes "mining" of ground water. Theis (1940, p. 280) implies that water is mined any time withdrawal from storage occurs. R. L. Nace (oral commun., 1976) considers mining to take place only when depleted storage will not be naturally replaced fast enough to be of significance to the existing political system (society) should pumping cease. It would seem reasonable to introduce a further practicality and assume that mining is effectively taking place if storage is being depleted by pumping that is expected to exceed indefinitely potential capture of recharge and discharge. Under this concept large withdrawals such as the ones illustrated on figures 66 and 67 are clearly examples of ground-water mining, since the amounts of water they have withdrawn from storage are lost to society until they cease, or reduce, their withdrawals--which is not anticipated in the foreseeable future. It is also important to note that a part of the freshwater being withdrawn is being replaced by saltwater which would remain in the aquifer for an extremely long time (thousands of years?) even if all pumping were stopped. Thus, freshwater is being mined according to any definition of the word.

No implication is intended that mining of water is necessarily undesirable. Water, like other minerals, is a finite resource which is available for man's use. Consumptive development of ground-water may be a legitimate practice so long as it is done with an awareness of the consequences.

It may also be possible to manage ground-water storage by increasing recharge into aquifers within which storage has been depleted. Throughout much of northeast North Carolina there is an abundance of potential recharge that is either naturally rejected or intentionally drained away for agricultural purposes. It has been suggested (North Carolina Groundwater Section, 1974, p. 87-89) that the spectacular amounts of recharge to deep aquifers within the cones of depression of large pumping centers can be effected through connector wells linking the deep aquifers to shallow aquifers containing water at higher heads. However, the possibility of deleterious effects on the quality of water in the aquifers being recharged would need to be studied before such schemes were activated on a large scale.

All of Beaufort, Pamlico, and Washington Counties and parts of Carteret, Craven, Hyde, and Tyrell Counties, all of which are in northeast North Carolina, and part of Martin County have been declared a "capacity-use" area by the North Carolina Department of Natural Resources and Community Development, and further development of large ground-water supplies in these counties is legally controlled. Elsewhere ground water is withdrawn at the discretion of the individual user. Yet, the way in which the ground-water system is developed will be of critical importance to the future of the area, because ground water is, and will continue to be, the prime source of freshwater in northeast North Carolina.

Recommendations

There are a number of deficiencies in our knowledge of the hydrology of northeast North Carolina. Considering the increased demands that are already beginning to be imposed on the system, steps should be taken to gain a better understanding of the following aspects of the areal hydrology.

1. Evapotranspiration should be studied in various terrains within the area. ET is, without doubt, the largest areal consumer of water. However, estimates of the amount of ET must now be based upon techniques developed for other, quite different, areas. These and new techniques must be tested and verified in humid, swampy areas.

   Equally important, studies of the effect of lowering the water table on the rate and amount of ET are needed.

2. Methods for "harvesting" water from the upper aquifer should be developed. This aquifer is potentially the most prolific source of freshwater in the area. Many users already depend on it for water supplies; and, as most demand is made upon water from the deeper aquifers, the upper aquifer will become more important.

3. The ability of the limestone and lower aquifers to yield water on a long-term basis needs further study. The estimates given in this report are thought to be as good as can be made from presently available data. They are, however, based upon widely scattered data from only a few locations, and are subject to considerable error.

4. Surface-water storage does not appear to be an attractive water management tool in most of the project area. Where large amounts of fresh surface water are seasonally or periodically available however, supplementary storage may be feasible. The engineering and economic aspects of how such storage could best be accomplished are worth investigating.

5. Ground-water storage has been affected more by man's activities than any other phase of the areal hydrologic cycle. Huge additional withdrawals are already being planned, and the depletion of stored ground water is becoming a major concern in some areas. Studies should be initiated immediately on methods of increasing recharge where cones of depression have developed.

6. Deterioration of the chemical quality of ground water by encroachment of saltwater into naturally fresh zones caused by heavy pumping is a threat throughout the area. At present no way is known to predict either the probability or rate of seawater encroachment under anything but the most simple hydrologic conditions. Research is needed that will lead to a better understanding of the mechanics of encroachment in nonhomogeneous porous media such as the three major aquifers in northeast North Carolina.

SUMMARY

1. Northeast North Carolina has an abundance of water; but problems such as contamination of freshwater by saltwater, the absence of large freshwater streams, seasonal variations in streamflow and the lack of a proven means for large-scale storage of freshwater, make it difficult to develop large supplies of potable water throughout much of the area.

2. An average of about 17,500 ft^3/s of freshwater flows into the area through the Chowan, Roanoke, Tar, and Neuse Rivers. This water is extremely important in maintaining the ecology of the estuaries and sounds; but it mixes with seawater in the lower parts of the rivers; and little of it is suitable for most uses. Few natural streams originate within the area, and most of these are subject to seawater encroachment, or go dry for parts of most years. Artificial channels created by channelization and ditching for agricultural drainage often contain perennial flow, but watersheds for these channels are usually small and seasonal flows may be very low.

3. Three aquifers supply water to wells in the area. The upper aquifer contains the water table, and has the greatest potential for supplying large amounts of water on a long-term basis. Individual well yields are usually quite low (less than 100 gal/min), and few large supplies have been developed in the upper aquifer.

   The limestone aquifer underlies the upper aquifer and contains confined ground water. Wells in the limestone aquifer typically yield several hundred to as much as 2,000 gal/min. Except near its western border, the limestone aquifer contains saltwater at depth, and the possibility of saltwater encroachment must be considered when developing water supplies from it.

   The lower aquifer underlies the limestone aquifer, and contains saltwater except in the northwestern part of the study area. Wells in the lower aquifer may yield several hundred to as much as

1,000 gal/min, but it is well confined and the potential for long-term yields of water from it are not as good as in the overlying aquifers.

4. The chemical quality of the fresh surface waters of northeast North Carolina is generally good where not mixed with seawater. The freshwaters do not contain objectionable amounts of any dissolved mineral constituents, except that some streams draining the area in which the Castle Hayne Limestone is near land surface contain moderately hard water during periods of low flow. The only undesirable characteristic of the freshwaters of northeast North Carolina is that water drained from swampy areas may be colored. This is not a problem for drinking purposes, but above 20-40 units on the platinum-cobalt scale, it may stain laundry, paper and like items.

   The chemical quality of ground waters is highly variable. Water from the upper aquifer is generally low in dissolved solids, but in some places may require treatment for acidity, iron, or hardness. Water from the limestone aquifer generally is hard, high in alkalinity, and tends to form scale in water lines, boilers, water heaters, etc. Finally, water from the lower aquifer, where fresh, generally is soft and non-corrosive, but may contain objectionable amounts of iron, sodium, and fluoride.

5. Additional work needs to be done on developing methods for harvesting water from the upper aquifer, for utilizing water lost in agricultural drainage, for large-scale storage of water in the area, for estimating the amount of salvageable freshwater in aquifers containing both freshwater and saltwater, and for predicting the rate of saltwater movement toward pumping wells.

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