GROUND-WATER RECHARGE

IN

NORTH CAROLINA

By

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CONTENTS

ILLUSTRATIONS

Page

TABLES

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INTRODUCTION

The 1980's were marked by increased awareness of the need to prevent ground-water pollution. There were several reasons for this, including expanded use of ground water for human consumption and increased recognition of the complexity of ground-water systems and of the technical difficulties and huge cost of eliminating ground-water pollution.

Because nearly all ground-water pollution originates at or near the land surface in areas where ground-water systems are replenished, the delineation of ground-water recharge areas and studies of the factors affecting recharge have, in recent years, received considerable attention. The present emphasis on these aspects of ground-water recharge contrasts rather sharply with the emphasis that recharge previously received. Throughout most of the history of ground-water hydrology, the emphasis was on the yield of aquifers and recharge was of interest primarily as one of the components of water budgets. Ground-water recharge is, of course, still an important element in water budgets but of equal, if not greater, importance now it is a key element in the delineation of the areas that are the source of water obtained from supply wells. These are the areas now commonly referred to as **wellhead-protection areas.**

The Groundwater Section of the North Carolina Division of Environmental Management initiated a series of studies in 1991 related to the development of a wellhead-protection program. The results of these studies are contained in a *Wellhead-Protection-Program Applications Manual* (Heath, 199 1) and in *An Evaluation of the Feasibility of Implementing the Draft North Carolina Wellhead Protection Ordinance* (Smutko and Danielson, 1992).

The fundamental premise of the wellhead-protection program is that the water withdrawn from a supply well is derived from ground-water recharge on an identifiable area surrounding the well. This area is referred to as the **contributing area. The** size of the contributing area for any well depends on the pumping rate of the well and on the rate of recharge to the aquifer supplying the water. Successful application of the wellhead-protection program requires, therefore, both the identification of ground-water recharge areas and estimates of recharge rates.

The N.C. Groundwater Section initiated a project in 1992 devoted to the statewide delineation of ground-water recharge areas at a map scale of 1:250,000 (about 1 inch = 4 miles). The boundaries of the areas were converted to digital form by the North Carolina Center for Geographical Information and Analysis, which permits maps to be printed at any desired scale. A 1:500,000 scale version of the map has been reproduced and distributed by the Groundwater Section (Heath, 1993). The purpose of this report is to describe the approach used in that project and to discuss some of the other aspects of ground-water recharge in North Carolina. Relative to recharge rates, the Groundwater Section began a study in 1993 of several areas in different parts of the State, with the objective of developing improved estimates of ground-water-recharge rates.

BASIC ASPECTS OF GROUND-WATER RECHARGE AND DISCHARGE

The conditions that control recharge to and discharge from ground-water systems are exceedingly complex because they involve not only climatic conditions but also land use and the composition and structure of the soils and rocks that comprise the ground-water system. Before discussing these conditions, it is desirable to first discuss the components of the ground-water system.

The Ground-Water System

The term **ground-water system,** as used in this report, applies to the zone that extends from the land surface to the greatest depths reached by continuous water-bearing openings - that is, by openings large enough to permit the movement of water. (See Figure 1, page 3) According to this usage, the ground-water system includes, in most areas, an **unsaturated zone** immediately below the land surface which contains both air and discontinuous threads and films of water. Below the unsaturated zone is a **saturated zone in** which openings contain only water.

The soils and rocks that comprise the ground-water system can, on the basis of hydrologic considerations, be divided into aquifers and confining beds. An **aquifer** is a rock layer or group of layers which function as a hydraulic unit and through which water moves freely enough to supply water to a well or spring at a useful rate. A **confining bed** is a rock layer in which the openings are so small that water can move across it, from one aquifer to another, only at an exceedingly slow rate. Confining beds do not serve as sources of water; rather, they function as barriers that impede the movement of water.

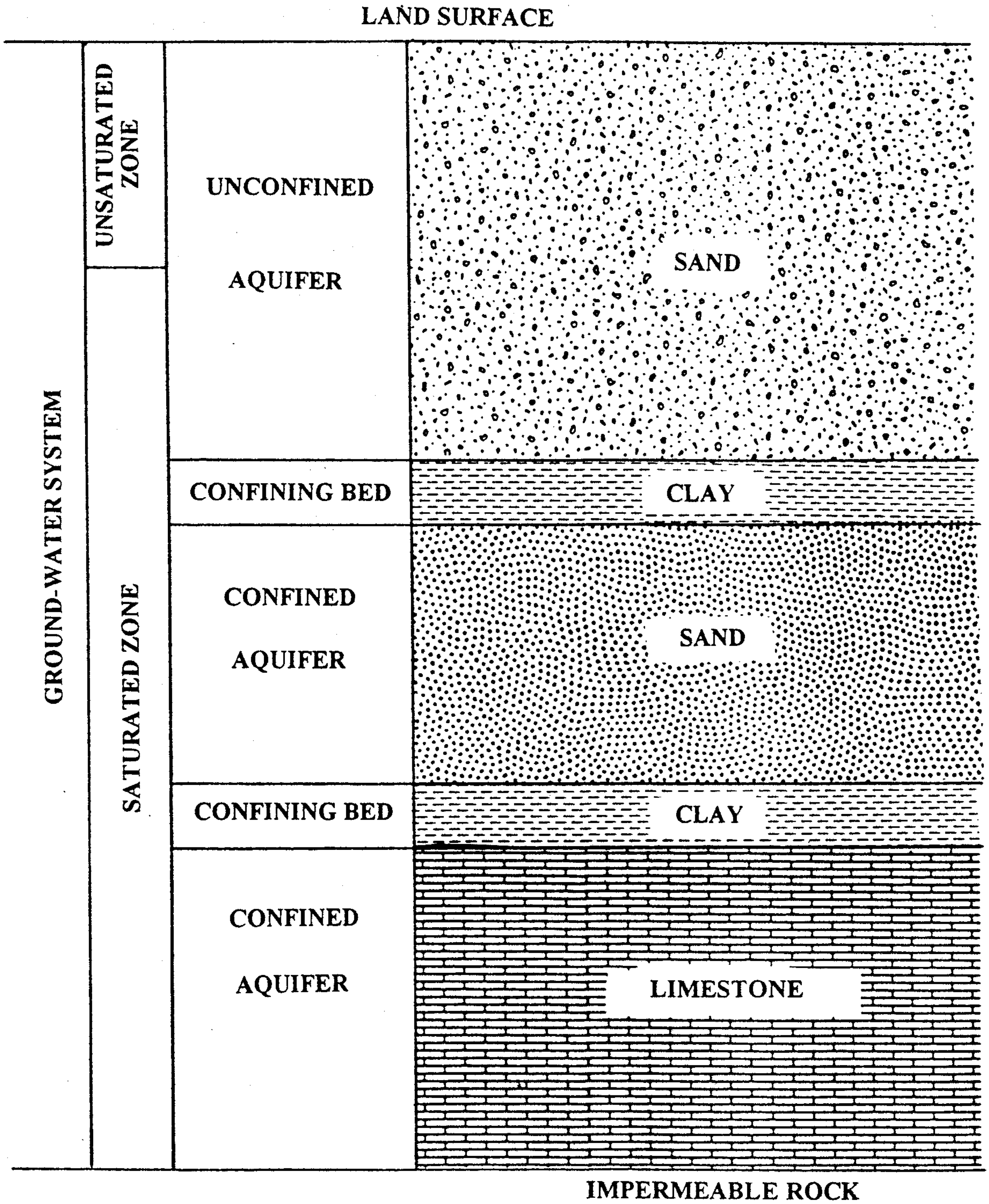


Figure 1.--Sketch showing the subdivisions of the ground-water system.

Confining beds also cause the aquifers in the ground-water system to be divided into two distinct types. Where confining beds occur in the saturated zone, the aquifers that exist below these beds are full of water and are referred to as **confined aquifers; thus the** significance of the term confining *bed. The* uppermost confining bed, in most areas, is overlain by an aquifer that is only partly full of water. Such aquifers are referred to as **unconfined aquifers,** and they occupy (include) both the upper part of the saturated zone and all of the unsaturated zone.

Unconfined Aquifers and Ground-Water Recharge

Because the unconfined aquifers that underlie North Carolina begin at the land surface, they are the gateway through which most recharge to, and discharge from the ground-water system occurs. Ground-water recharge occurs when and as water moving into the ground-water system arrives at the top of the saturated zone. The requirement that water reach the top of the saturated zone in order to be considered ground-water recharge is an important one because only water in the saturated zone will flow from the water-bearing openings in an aquifer into a well or spring. Only water that will so move is, by definition, ground water. (See Figure 2, page 5) In order to move into a well or spring, water must be under a hydrostatic pressure equal to or greater than the atmospheric pressure. The level in the saturated zone at which the water is under a pressure equal to atmospheric is referred to as the water table.

All of the water in the unsaturated zone is under a pressure less than the atmospheric pressure and, for this reason, it will not move into a well or spring. In unconfined aquifers composed of sand and rock particles smaller than very fine gravel-that is, composed of particles with diameters less than about 1/4 inch or 6 millimeters-there is a thin zone above the water table in which the openings are saturated with water under a pressure less than atmospheric. Because the openings in this zone are saturated, it is considered, in this report, to be a part of the saturated zone. However, the water in this zone is not ground water because, being under a pressure less than atmospheric, it will not move into a well or spring.

The thin zone above the water table, mentioned in the preceding paragraph, is referred to as the capillary fringe (Figure 2). The capillary fringe ranges in thickness from about 5 inches in coarse sand (grain diameters less than about 0.04 inch or 1 mm) to about 40 inches in silt (grain diameters less than about 0.0025 inch or 0.06 mm).

Although relatively thin, the capillary fringe is important in relation to ground-water recharge. This importance stems partly from the fact that the thickness of the capillary fringe is

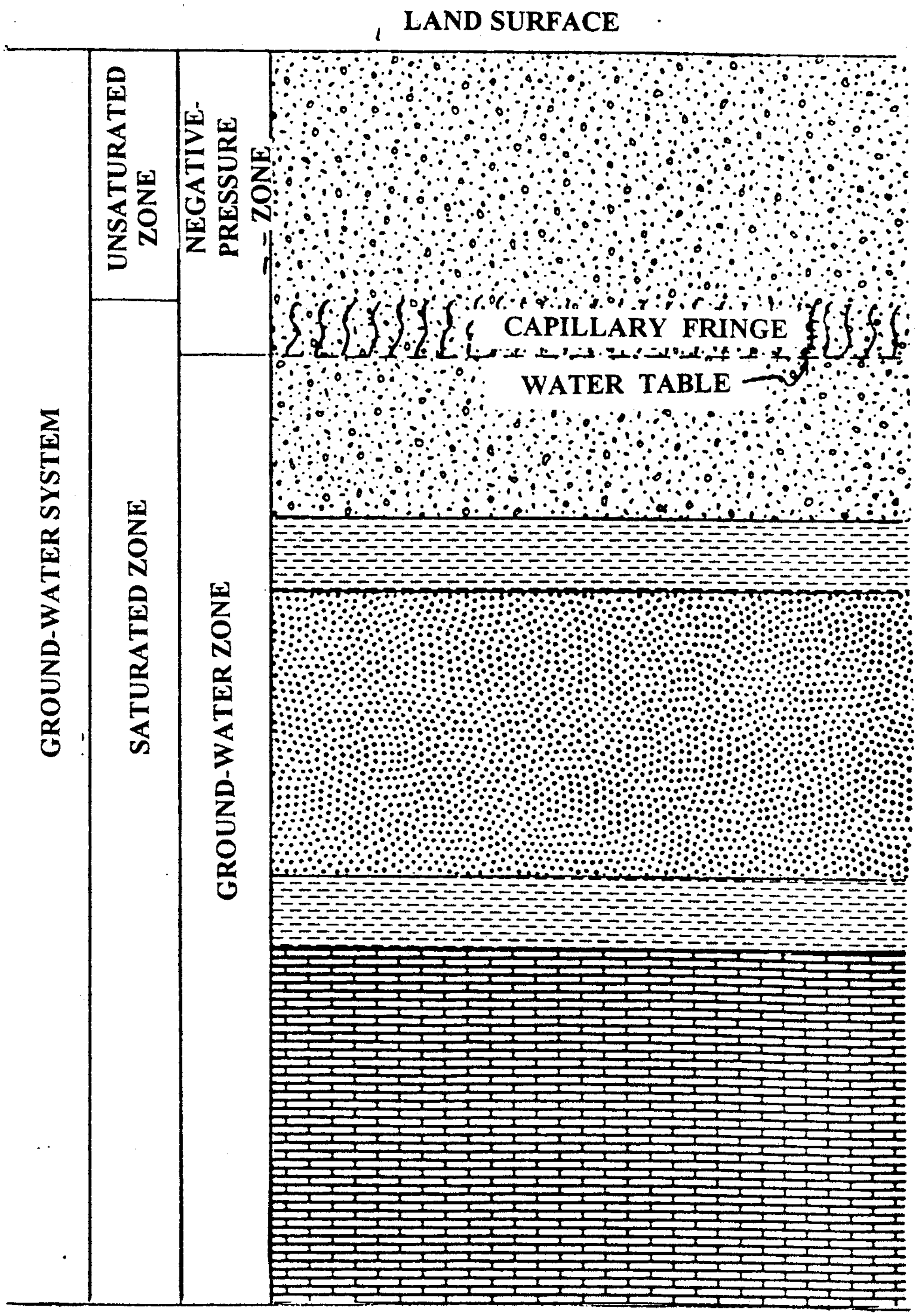


Figure 2.--Sketch showing the relation between the unsaturated and the saturated zones and the negative pressure and ground-water zones.

controlled primarily by the surface tension' of water and by the diameter of the openings between the rock particles. Thus, at any place and time, the thickness of the capillary fringe does not change significantly. If this were not the case, water moving downward across the unsaturated zone would, upon reaching the top of the capillary fringe, cause the thickness of the fringe to increase. Instead, the thickness of the capillary fringe remains essentially unchanged, and both the top of the capillary fringe and the water table rise. Thus, as noted earlier, ground-water recharge occurs when water moving downward across the unsaturated zone of the surficial unconfined aquifer reaches the top of the saturated zone, which coincides approximately with the top of the capillary fringe.

Recharge also occurs whenever water is present on the land surface in any area in which ground-water flowlines have a downward component, even if the top of the saturated zone is at land surface. In such areas, the rate of recharge is limited to the rate at which ground water moves downward away from the land surface. If more water is available at the land surface in these areas than can enter the ground-water system, the excess may either move out of the area as sheet flow or through ephemeral channels, or collect in depressions on the surface until it enters the ground or evaporates. Water on the land surface in recharge areas which is unable to enter the ground-water system has been referred to as **rejected recharge** by C. V. Theis.

Because recharge is derived from precipitation, which is an intermittent process, the arrival of water at the top of the saturated zone is also an intermittent process, as shown by the periodic rises in the water table in observation wells such as that shown in Figure 16, page 30. However, it is important to note that recharge areas can usefully be divided into two types. The first of these are areas in which the top of the saturated zone is either always below land surface and which can therefore accept recharge any time water is available on the land surface, or are areas in which ground-water flowlines always have a downward component. Adapting the terminology applicable to surface streams, these might appropriately be referred to as **perennial recharge areas,**

The second type of recharge area is one in which the top of the capillary fringe is periodically at land surface, so that underground space is not available to receive recharge, and in which ground-water flowlines are either horizontal or have an upward component. Recharge can occur in these areas only when evapotranspiration losses or lateral ground-water flow cause the top of the capillary fringe to decline below land surface and, of course, when water is available on the land surface. These areas might appropriately be referred to as **intermittent recharge areas.**

Intermittent recharge areas include floodplains and the higher parts of some wetlands. In these areas the top of the saturated zone is at or above land surface during periods in the winter and early spring. During the warmer seasons, the loss of water through the transpiration of plants and evaporation of water from the capillary fringe cause the water table to decline. This results in space being available for recharge at times during late spring, summer, and early fall.

The seasonal differences in recharge and discharge areas discussed in the preceding paragraphs are illustrated in the sketches in Figures 3 through 6. Figures 3 and 4, page 9, show a typical area in the Coastal Plain and Figures 5 and 6, page 10, show an area in the Piedmont. The principal landscape settings, and whether a recharge or a discharge area, are labeled on each sketch. As discussed earlier, the key to whether an area is a recharge area or a discharge area depends on the position of the water table and the top of the capillary fringe relative to the land surface and on the direction of the vertical component of ground-water flowlines.

Ground-Water Discharge Areas

Water that recharges the ground-water system moves through the aquifers and across the confining beds from recharge areas to places where ground-water discharge occurs. (See Figure 7, page 11) Ground-water discharge is the return of water from the saturated zone either to the land surface or to the atmosphere. Therefore, the identification of ground-water discharge areas and their hydraulic effect on ground-water systems are topics of considerable importance in ground-water hydrology.

Water discharges from ground-water systems whenever and wherever the water table intersects the land surface. In North Carolina (and most of the eastern United States), this condition exists at springs, along the channels of streams and through the sides and bottoms of lakes and reservoirs, and along the shoreline of estuaries, sounds, and the ocean. Water also leaves the ground-water system in vapor form where the roots of growing plants extend into the saturated zone and by evaporation from the top of the capillary fringe where it is within several feet of the land surface during warm dry periods.

Identification of ground-water discharge areas does not pose a problem at springs, lakes, along perennial streams, and along estuary, sound, and ocean shorelines. All of these, in fact, are what appropriately can be referred to as perennial discharge **areas** because they are places of continuous, though not constant, discharge.

In contrast, when the water table is near its seasonal high position, ground water may discharge into the channels of intermittent streams and through seeps and intermittent springs on hillsides. Also, relative to ground-water discharge in vapor form, most of this discharge is also seasonal, occurring mostly during the growing season and when air temperatures are high. All of these areas of intermittent discharge can usefully be referred to as **intermittent discharge areas.**

I pointed out in the preceding section that recharge areas can be divided into perennial and intermittent recharge areas. Now, we see in the preceding paragraphs that discharge areas may similarly be sub-divided into two types. An interesting aspect of this, and certainly one that was not unexpected, is that the intermittent recharge and intermittent discharge areas occupy the same areas and, parts of these areas may, in fact, change from a recharging to a discharging condition and vice versa in a period of several hours or, at most, a few days.

For example, consider floodplain wetlands with a shallow depth to the water table and in which plant roots reach the saturated zone and evaporation occurs from the top of the capillary fringe. During warm, rainless periods, these are ground-water discharge areas. However, this discharge provides underground storage space so that, during the next rain, ground-water recharge can occur. Complications like this make it difficult to deal quantitatively with ground-water recharge over short time periods and in small areas.

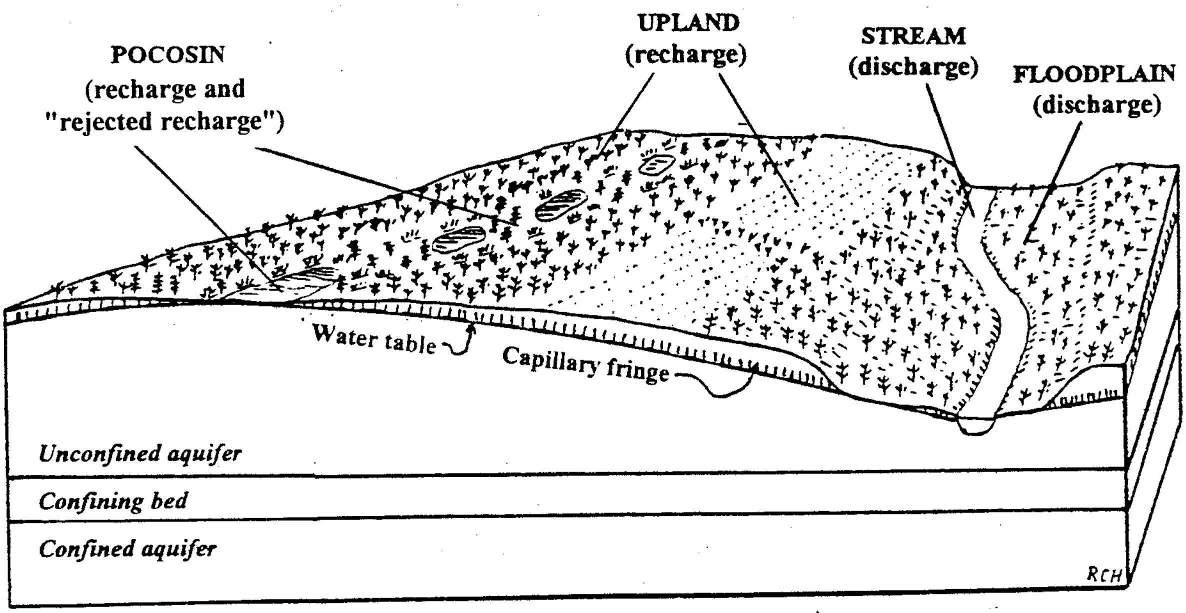


Figure 3.--Recharge and discharge areas during the winter in a typical Coastal Plain setting.

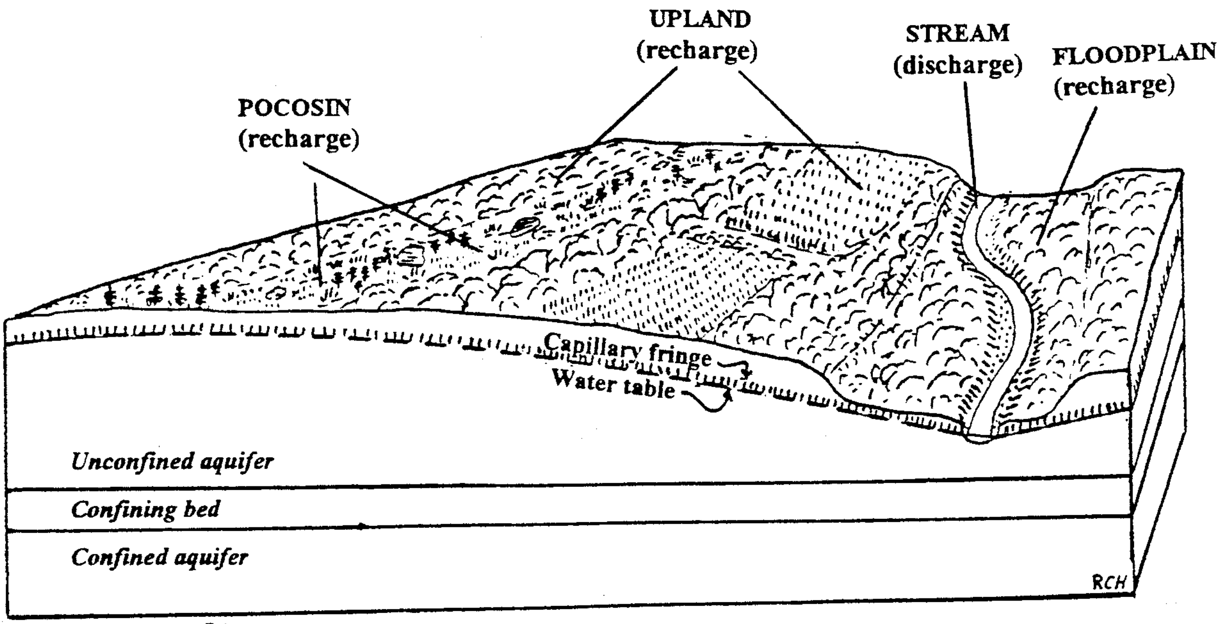


Figure 4.--Recharge and discharge areas during the growing season in a typical Coastal Plain setting.

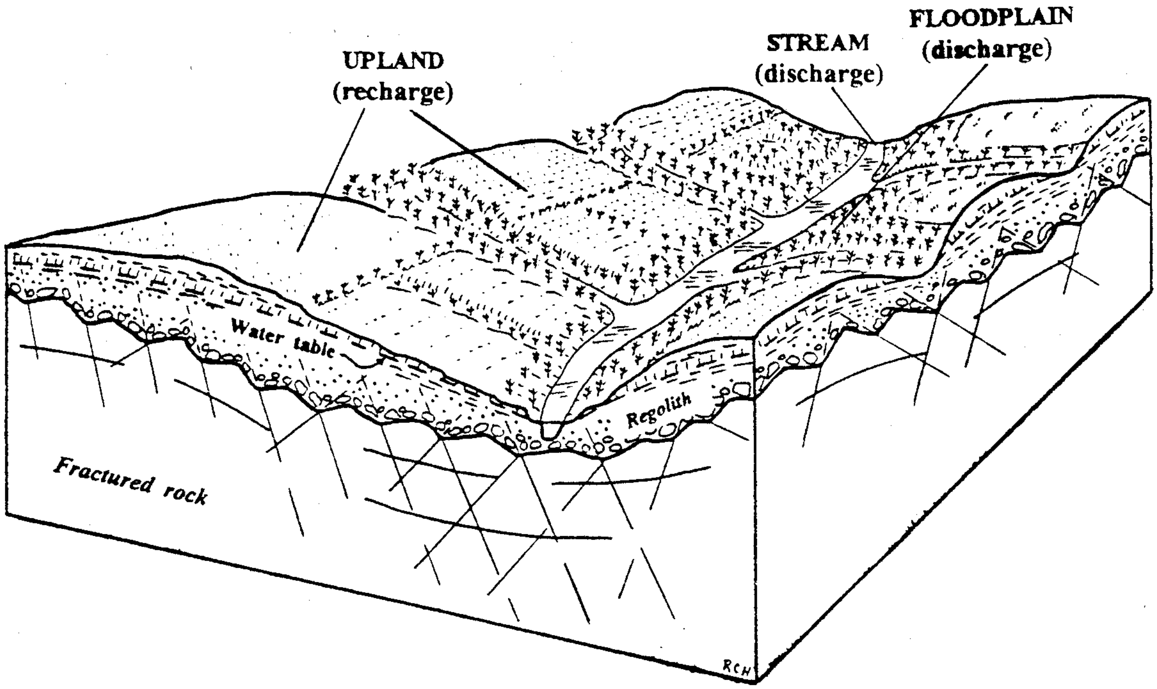


Figure 5.--Recharge and discharge areas during the winter in a typical Piedmont setting.

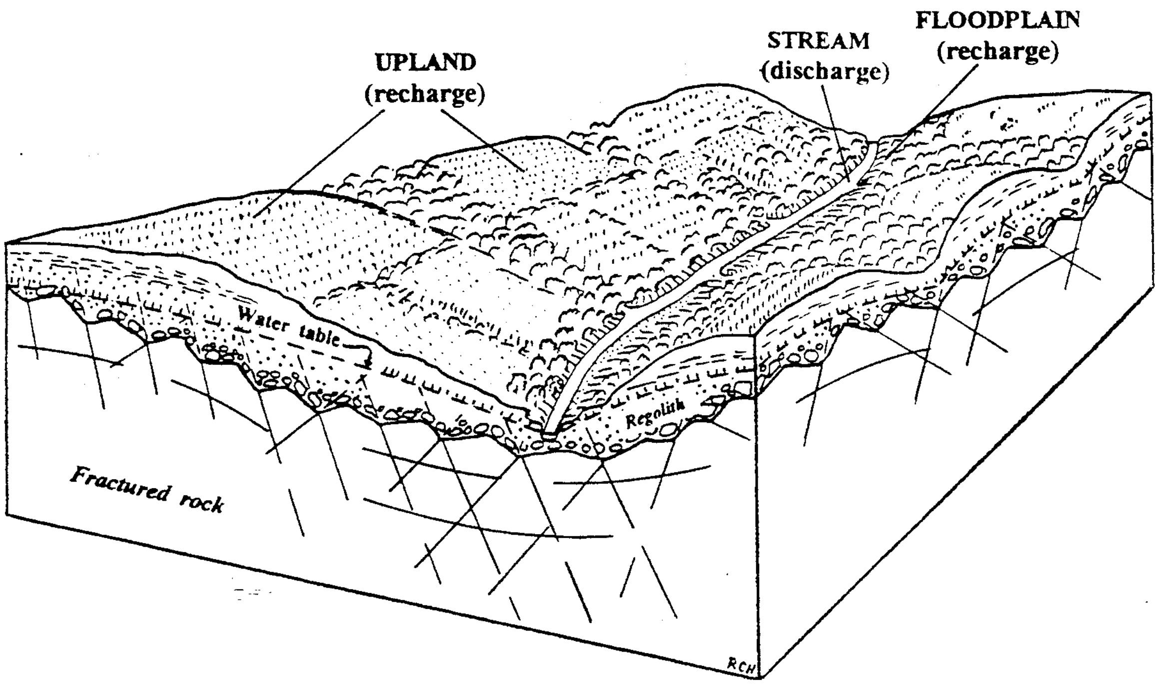


Figure 6.--Recharge and discharge areas during the growing season in a typical Piedmont setting.

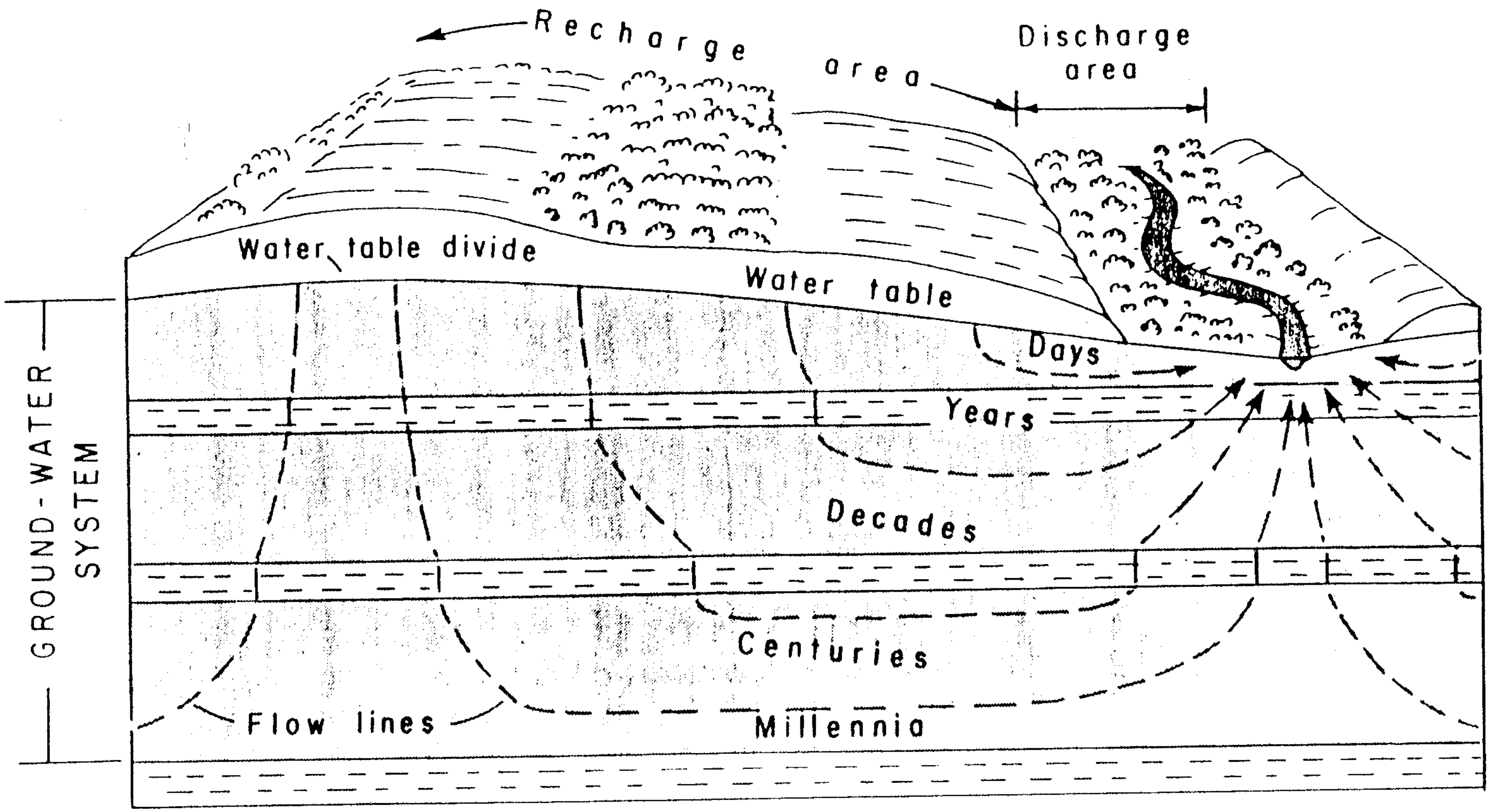


Figure 7.--Movement of water through the ground-water system from recharge areas to discharge areas. (From Heath, 1983, p. 14.)

IDENTIFICATION AND DELINEATION OF RECHARGE AND DISCHARGE AREAS

It is apparent from the preceding discussions that most of the land areas of the State are perennial ground-water recharge areas and that most streams and other surface-water bodies are perennial ground-water discharge areas. This basic observation permitted the topographic maps prepared and published by the U.S. Geological Survey to be used as the primary source of information in identifying and delineating recharge and discharge areas.

The Geological Survey publishes topographic maps at several different scales, but in this project maps of only three scales were used: 1:24,000, 1: 100,000, and 1:250,000. These maps and their uses were:

Map scale 1:24,000 *(1 inch = 2,000 ft or about 0.38 miles) – These are the* largest scale maps available for the entire State. However, because the number of these maps required to cover the State is nearly 1,000, it was not possible, in the scope of this project, to map the boundary of recharge and discharge areas on all these maps. Instead, 1:24,000 scale maps showing typical topography in different parts of the State were analyzed in detail to identify the boundary between recharge and discharge areas. The number of maps involved in this analysis actually totaled 3 13, or nearly a third of the maps required to cover the State. A large majority of these maps covered areas in the Piedmont and Mountains where the topographic conditions are more complex than in the Coastal Plain (see Figure 8A, page 15).

Map scale *1:100,000 (I inch = about 8,333 ft or about 1.58 miles) – The* streams shown on these maps are essentially the same as those shown on the 1:24,000 scale maps, which made them especially useful for mapping the areas between the 1:24,000 scale maps mentioned in item 1 (see Figure 8B, page 16).

Map scale *1:250,000 (1 inch = about 20,833 ft or about 3.95 miles)* – Maps at this scale were used in the compilation of information on the boundary between recharge and discharge areas as determined from the larger scale maps. These maps were then used to convert the information into digital form (see Figure 8C, page 17).

Topographic Maps and Ground-Water Discharge Areas

The following features shown on the topographic maps mentioned above proved to be especially useful in the delineation of recharge and discharge areas.

Streams and other surface-water features – These, as discussed earlier, are places of ground-water discharge. Both the 1:24,000 and 1:100,000 scale maps show, by different symbols, both perennial and intermittent streams and major drainage ditches.

Marshes and swamps – These are shown with a distinctive symbol on all USGS topographic maps and indicate areas in which either the capillary fringe or the water table are at or close to the land surface most of the time and in which standing water occurs in depressions during wet periods. Most of these areas are wetlands and, as such, are protected from development under Section 404 of the Federal Clean Water Act. Except during droughts - that is, long, excessively dry periods - these are areas in which ground-water discharges. This fact contrasts with the claims made by some supporters of wetland protection that wetlands are ground-water recharge areas.

Land-surface contours – Contour lines show the elevation of the land surface and the spacing of the lines indicates the slope of the land surface. In areas where streams have well-developed floodplains, as is generally the case in the Coastal Plain, the outer edges of the floodplain are clearly evident where the contour lines begin to be more closely spaced. In contrast, in many parts of the Piedmont and Mountains, the relatively even spacing of contour lines from ridge lines to streams indicates little or no floodplain development.

Woodland – This is shown as a green overprint on USGS topographic maps. Where the woodland overprint occurs on the floodplain of streams, it strongly suggests that much of the area is subject to flooding or to a wet condition resulting from a shallow depth to the water table frequently enough to prevent the area from being used for crops or other purposes that require nominally dry conditions.

It is readily apparent that the common aspect of the four features described above is that they all relate to ground-water discharge areas. In other words, these features were used to identify areas in which ground-water discharge occurs. Figures 8 shows the delineation of discharge areas in a typical Coastal Plain area in Lenoir County, beginning with the 1:24,000 scale map (Figure 8A, page 15), and how the same area appears on the 1:100,000 scale map (Figure 8B, page 16), on the 1:250,000 scale map (Figure 8C, page 17), and on the published 1500,000 scale map (Figure 8D, page 18). The procedure that was followed in drawing the boundary of discharge areas – that is, the boundary between recharge areas and discharge areas – involved the assumptions and actions described below.

1. *All perennial streams and other perennial surface-water bodies were automatically assumed to be discharge areas. The upstream termination of discharge areas on tributary streams posed a minor problem. Study of 1:24,000 scale maps showed two different situations. The first were those where the woodland overprint continued upstream beyond the termination of the perennial stream segment. In these, the discharge area was terminated at the end of the perennial stream reach. The second situation was where the*

perennial stream continued beyond the woodland area. This was interpreted to show that the stream was entrenched to a sufficient depth to permit the area to be cultivated up to the bank of the stream. In these areas, the floodplain discharge area was terminated at the end of the woodland overprint (see action 3).

2. *All areas shown on the topographic maps as being occupied by marshes and swamps were assumed to be discharge areas.*

3. *All relatively flat areas adjacent to streams and which are bordered by a steeper topographic slope were assumed to be current (modern) floodplains. These areas were assumed to be discharge areas if less than about ten feet above the streams "low-water" elevation and if occupied by woodland. The boundaries of these areas were drawn along the outer edge of the floodplain - that is, along the base of the steeper slope. Cleared (non-wooded) areas that extended onto the floodplain were usually not included in the discharge area on the assumption that they are either higher or better drained than the wooded areas.*

4. *At many places, floodplains exist on only one side of a stream. It was necessary in these areas to also draw a boundary alongside the stream in order* ***that the discharge area would be a closed*** *polygon* ***that could be*** used *later to determine the area occupied by both discharge areas and recharge areas.*

5. *When the boundaries of the discharge areas had been identified on 1:24,000 or 1:100, 000 scale maps, they were transferred to the 1:250,000 scale maps. As* ***noted earlier, all other areas are assumed to be recharge areas.***

Finally, it is important to note that the discharge areas, as mapped, include both perennial and intermittent ground-water discharge areas. To the extent that intermittent discharge areas are, at times, also recharge areas, the mapped discharge areas also include areas in which there is intermittent recharge. These areas include floodplains and wetlands where some recharge may occur during rains when the top of the capillary fringe is below land surface. However, because discharge, even in these areas, is an essentially continuous process, it was thought to be more appropriate to map them as discharge areas than to include them with the recharge areas.

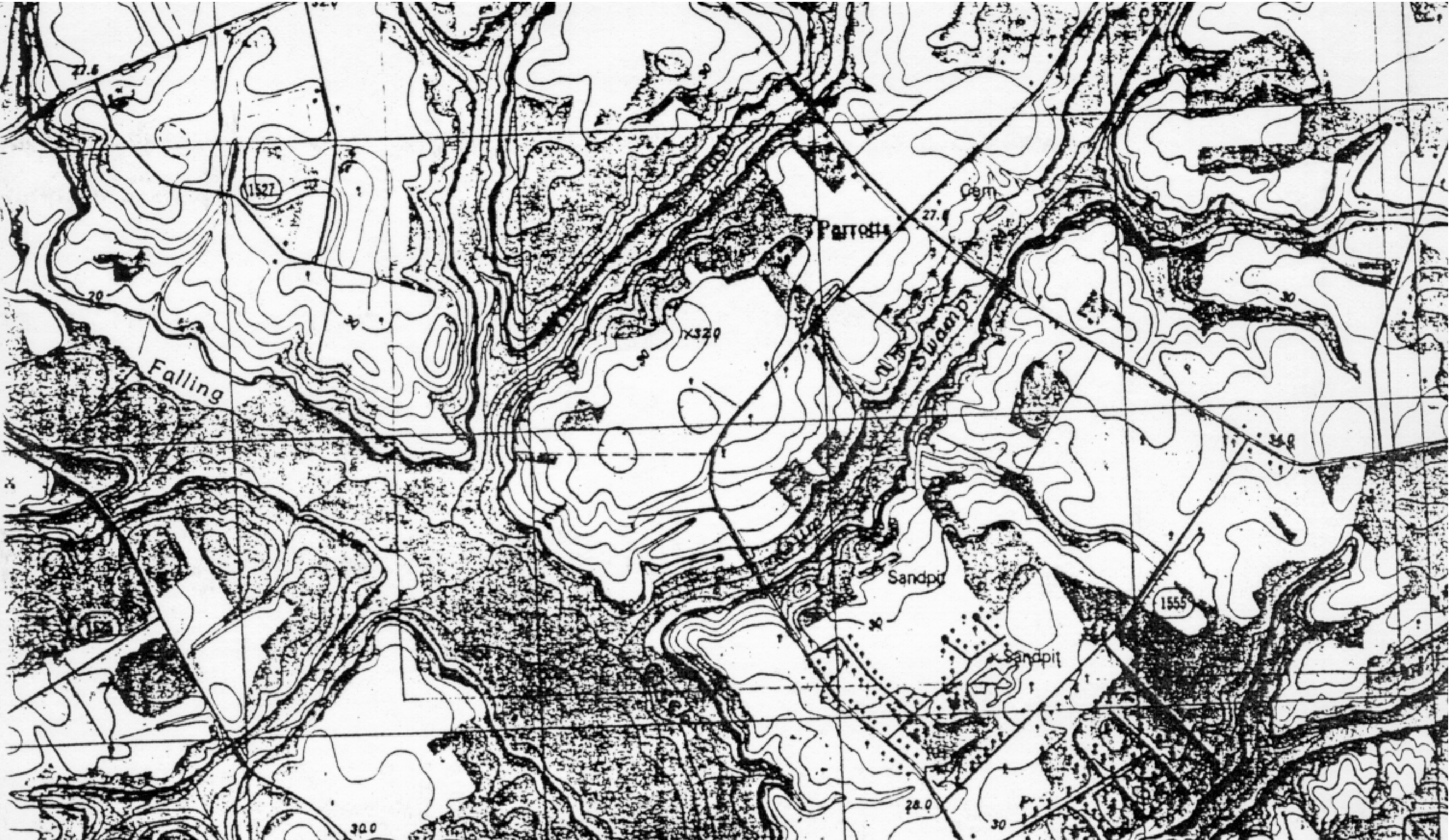


Figure 8A.--An area on the Falling Creek 1:24,000 scale topographic map showing the delineation, with prominent black lines, of the ground-water discharge area in the valley of Falling Creek and its tributaries. The dark shaded areas are woodlands.

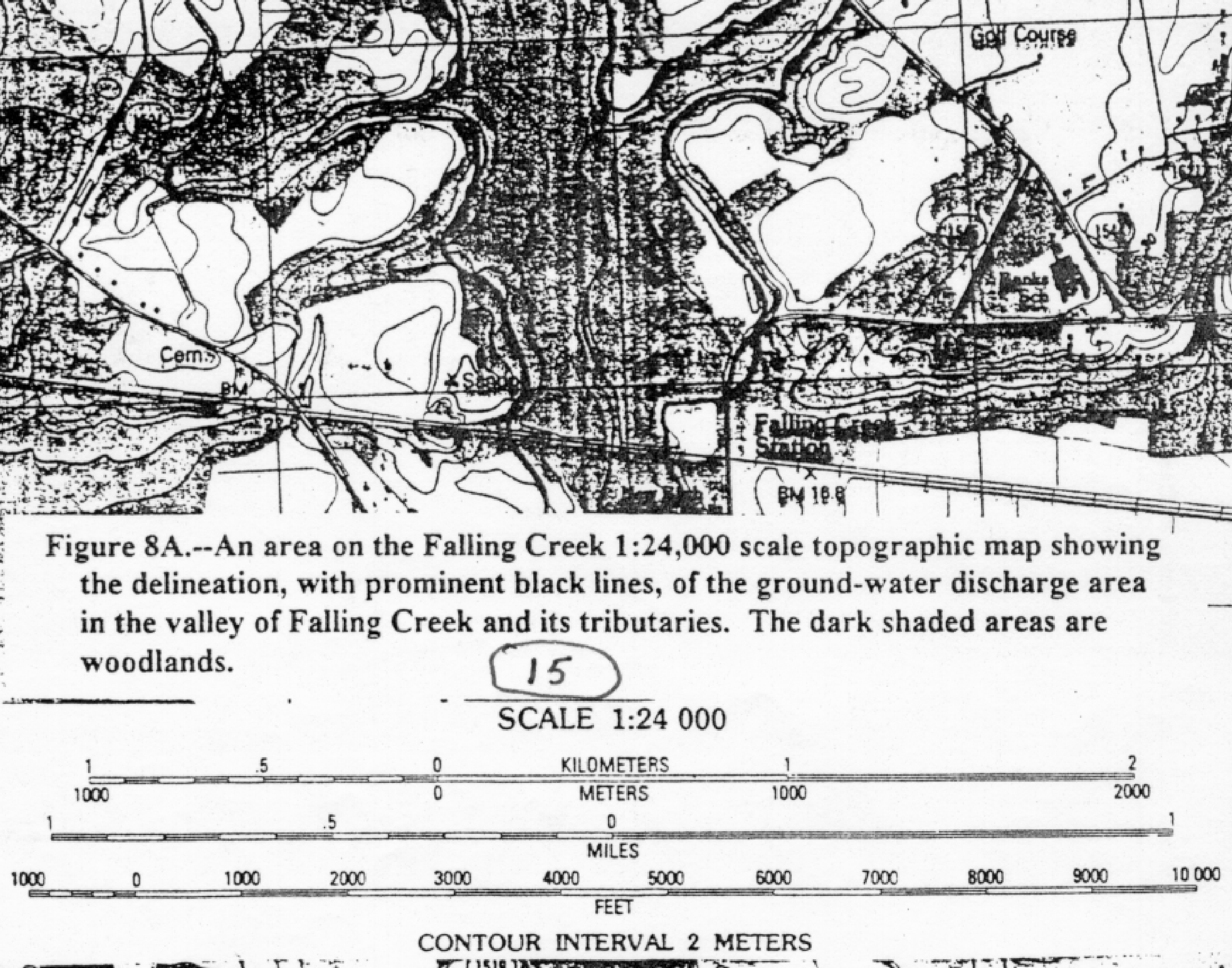


Figure 8B.--A part of the Kinston 1:100,000 scale planimetric map showing how the ground-water discharge area delineated on Fig. 8A appears at a scale of 1:100,000. The shaded areas are woodlands.

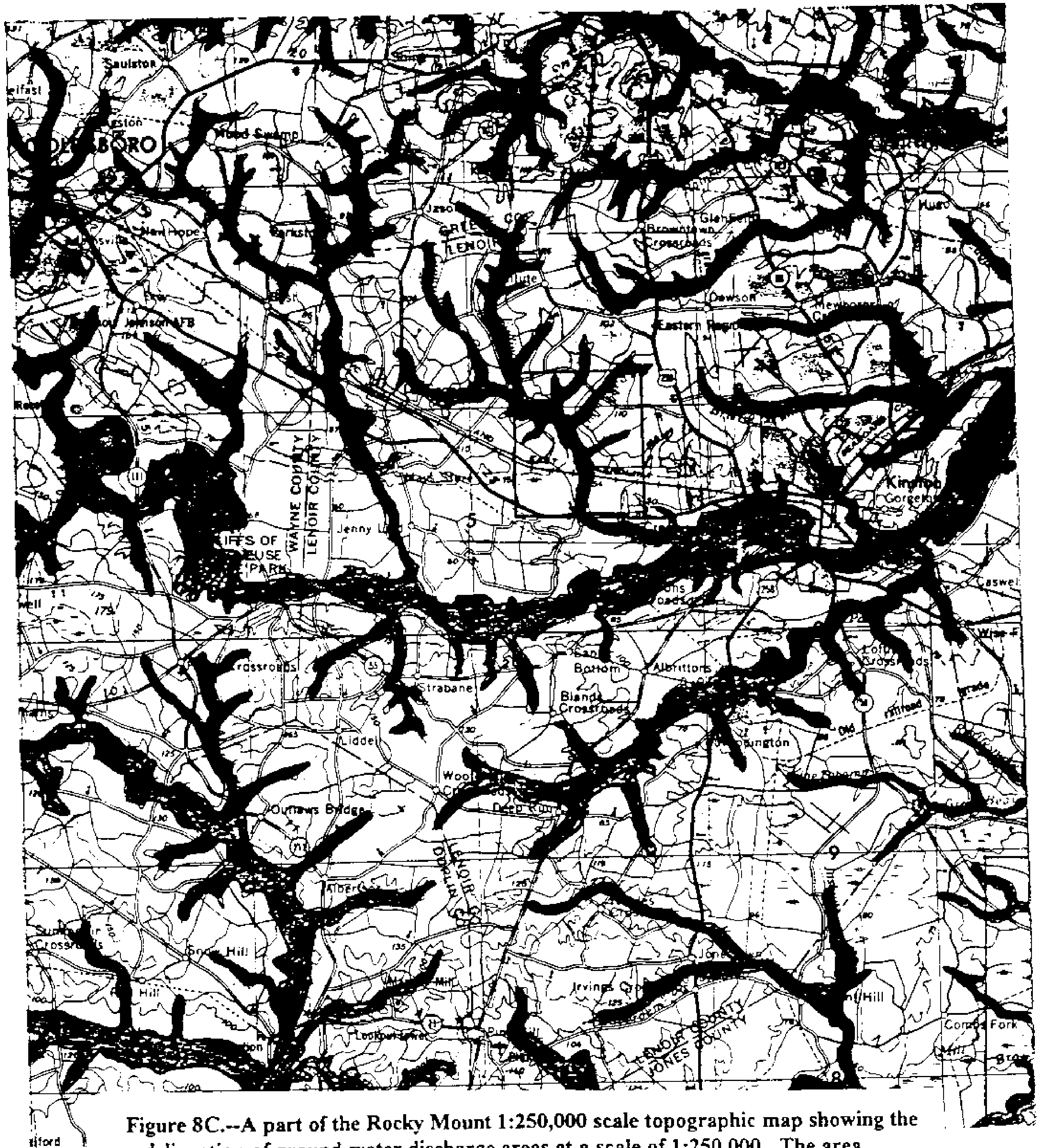


Figure 8C.--A part of the Rocky Mount 1:250,000 scale topographic map showing the delineation of ground-water discharge areas at a scale of 1:250,000. The area covered by Fig. 8A is west of Kinston.

Scale 1:250,000

5 0 5 10 15 20 Statute Miles

5 0 5 10 15 20 25 30 Kilometers

5 0 5 10 15 Nautical Miles

CONTOUR INTERVAL 50 FEET
WITH SUPPLEMENTARY CONTOURS AT 25 FOOT INTERVALS

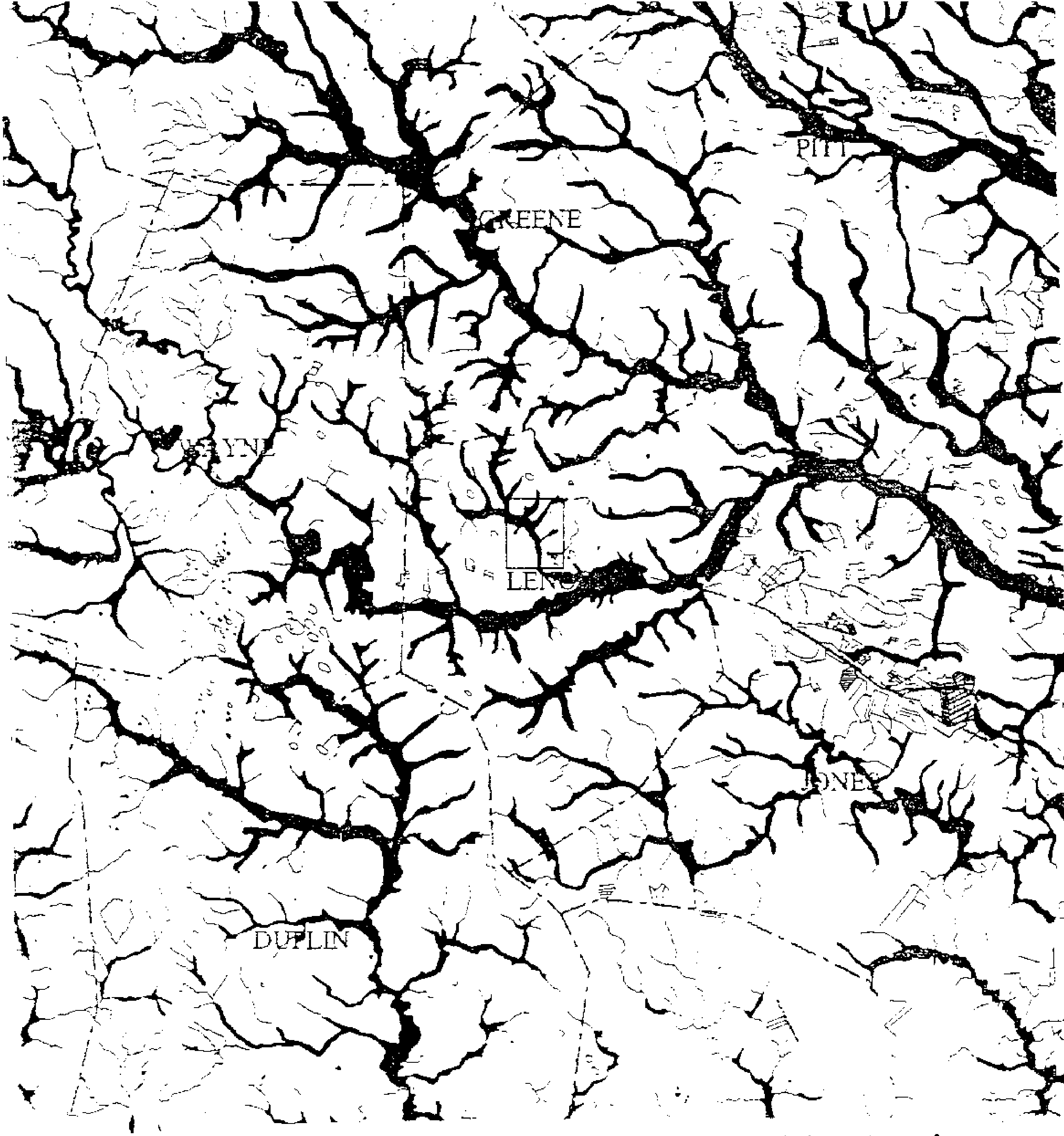


Figure 8D.--A part of the map entitled "Principal Ground-Water Discharge Areas of North Carolina" showing how the area delineated on Fig. 8A appears at a scale of 1:500,000. The area on Fig. 8A is the bordered area in Lenoir County.

SCALE 1:500,000

FACTORS THAT CONTROL RECHARGE RATES

Recharge of the ground-water system, as already noted, is a complex process that is also discontinuous because it occurs only when water is available. The rate of recharge differs widely, both from place to place and from time to time, in response to the factors that control recharge. The factors that control recharge include the following.

> ***Climate – The*** amount and seasonal distribution of precipitation, which determines the amount of water available for recharge; the duration and intensity of individual rainfall events, which affect the amount of water that percolates into the ground and the amount that runs off over the land surface; and the air temperature, wind, and amount and intensity of sunlight, which control surface heating and the evaporation of water from water surfaces and the soil zone.

> ***Vegetation – The type,*** density, and growth stage of the vegetative cover, which determine how much of the precipitation is intercepted by leaf surfaces, and how much of the water that has previously infiltrated into the soil zone is transpired by the vegetation during growth.

> ***Soil characteristics – The*** permeability of the soil and of the underlying layer (B-horizon) which, together with the rate of precipitation, determine how much of the precipitation percolates into the ground and how much runs off laterally through the soil zone or over the land surface.

Precipitation is of course the ultimate source of all recharge. However, there are certain water losses that **have** first cull on the precipitation and which therefore must be satisfied before any recharge can occur. Viewed in this light, recharge is, in effect, the *residual* water left over after the water losses have been satisfied.

The water losses include, in order of occurrence, the water required to wet all surfaces exposed to the precipitation and the replacement of the soil moisture that had been depleted since the last precipitation, both as a result of direct evaporation of water from the soil zone and the withdrawal and evaporation of water from the soil zone by growing vegetation in the process referred to as **transpiration. These** losses depend on the air temperature, on the stage of plant growth, and on the depth to the water table.

The rate at which the evaporative losses referred to above are satisfied not only depends on the amount and intensity of precipitation (factor 1), but also on the permeability of the soil and the underlying material (factor 3). If the intensity of the precipitation exceeds the rate at which water can infiltrate into the soil zone, water either ponds on the land surface or nms off through surface depressions. From the standpoint of ground-water recharge, runoff over the land surface must then also be viewed as a water loss that reduces the amount of water available for recharge.

The general concepts discussed in the preceding paragraphs can be stated in the form of the following simple equation which emphasizes the point made earlier that ground-water recharge represents the residual left over after the water losses that have first call on precipitation have been satisfied. The equation is:

Ground-water recharge = Precipitation – (Evaporative losses + overland runoff)

Each of the factors that affect ground-water recharge mentioned above will be discussed in more detail in the following sections.

Recharge and Climate

Precipitation and air temperature are the two aspects of climate that most directly affect ground-water recharge. The relation between precipitation and recharge is complex because it not only involves the total annual and the seasonal occurrence of precipitation but also the number and characteristics of individual rainfall events. Average annual precipitation in North Carolina ranges from about ***40*** inches to about 80 inches. As shown in Figure 9, page 21, the driest areas are in the vicinity of Asheville and in two areas in the Piedmont along the northern boundary of the State. The wettest areas are along the southeastern coast and in the mountains in an area that forms an arc around the Asheville Basin. Significantly, from the standpoint of ground-water recharge, the precipitation throughout most of the Piedmont and Coastal Plain ranges only from about 44 to about 52 inches a year.

Based on average annual precipitation alone – that is, if all other factors that affect recharge were the same throughout the State – we would expect the rate of recharge in the wettest areas to be about twice that in the driest areas. However, all of the other factors are not the same, as will be discussed in the sections on ***recharge and vegetation*** and ***recharge and soil characteris tics.***

The monthly variation in precipitation is another aspect that must be considered in relation to ground-water recharge. Figure 10, page 22, shows the normal monthly precipitation at

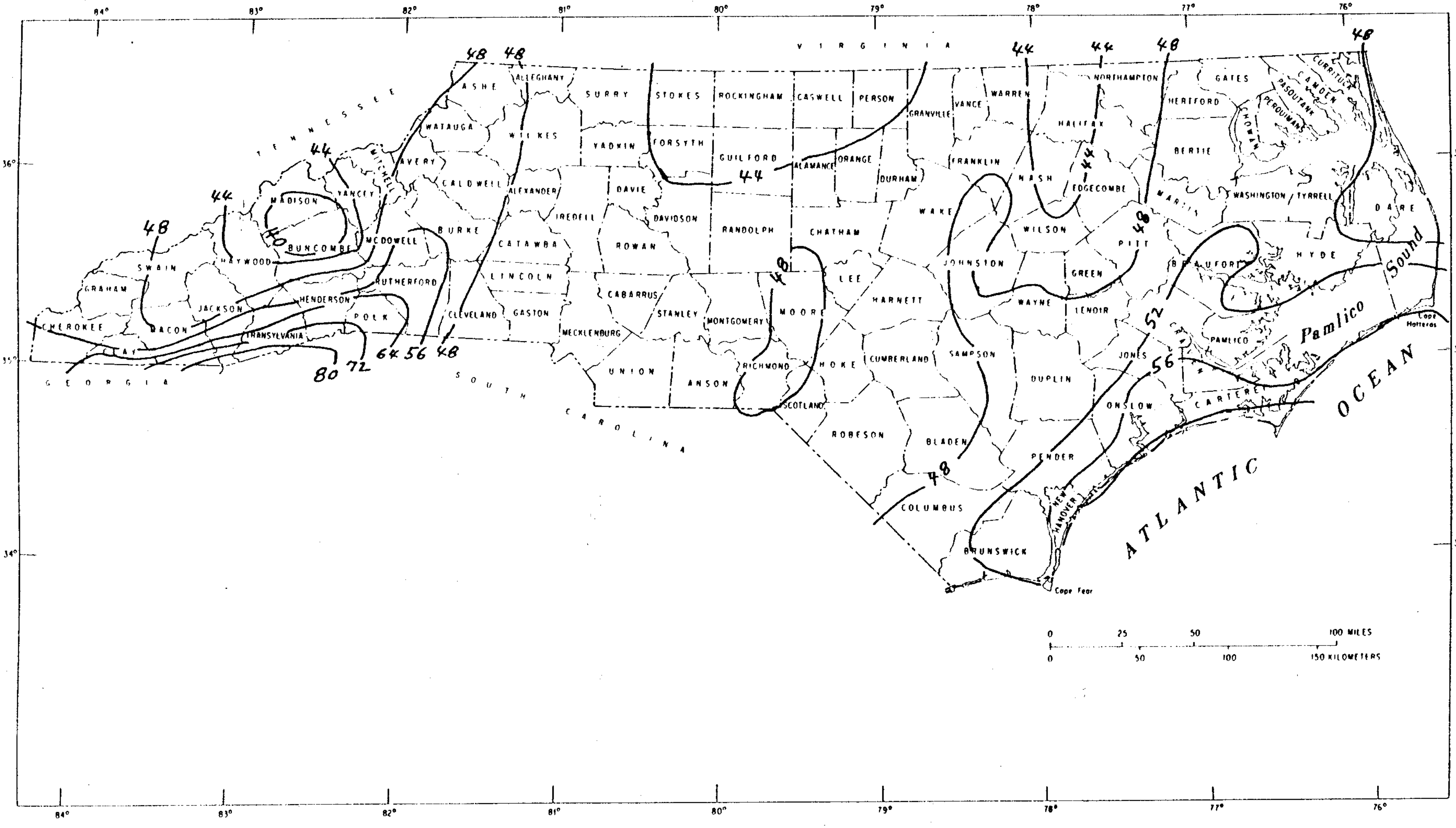


Figure 9.-- Map of North Carolina showing mean annual precipitation, in inches.

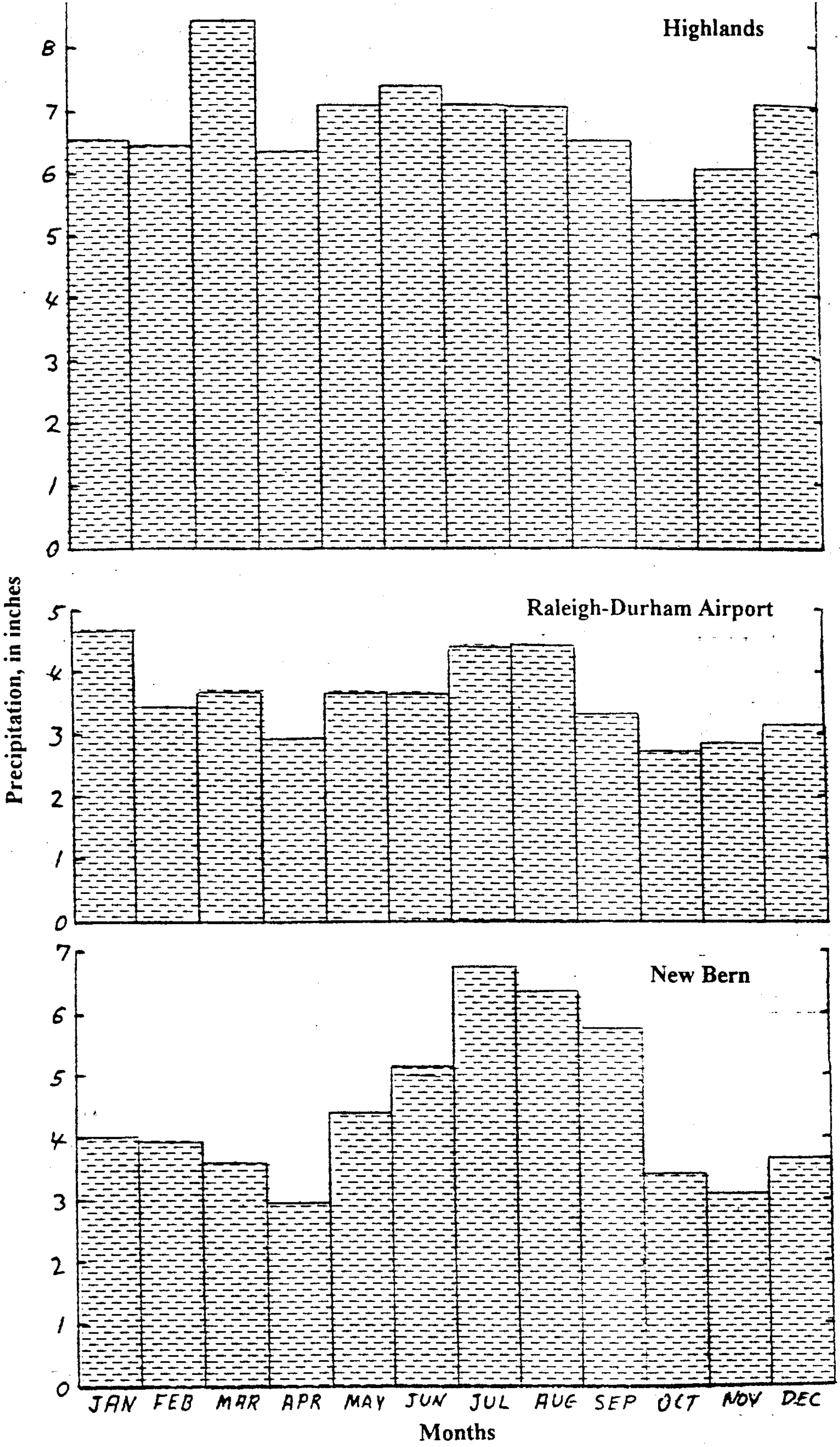


Figure 10.--Normal monthly precipitation at Highlands, Raleigh-Durham Airport, and New Bern. The normal annual and normal monthly average precipitation at these stations, in inches, are: Highlands - 81.52 and 6.79; Raleigh-Durham Airport - 41.46 and 3.46; and New Bern - 53.11 and 4.43.

Highlands, Raleigh-Durham Airport, and New Bern Weather Stations. Highlands was selected because it is located in the high-precipitation area in the southwestern mountains. The other two stations are representative of conditions in the Piedmont and Coastal Plain, respectively. Relative to ground-water recharge, the two most significant features of Figure 10 are the tendency for precipitation to exceed the normal monthly average during the summer and to be less than the normal monthly average during the fall. These seasonal tendencies are most marked at New Bern, in the Coastal Plain. The somewhat higher precipitation in the summer is, of course, beneficial to agriculture because it reduces the need for irrigation of crops. The somewhat lower precipitation in the fall, on the other hand, tends to delay the replenishment of ground-water storage.

The number of events and other characteristics of rainfall are also of significance relative to ground-water recharge. According to the records of the National Weather Service, precipitation of 0.0 1 inch or more occurs in North Carolina from about 110 to about 130 days each year - that is, on average about one in every three days. Many of these rains are too small to wet exposed surfaces and therefore are of no consequence to recharge. The minimum amount of ram that will result in recharge depends on the leaf area of the vegetation and other surfaces that must first be wet and on the soil-moisture deficit that has developed since the last rain. The minimum amount thus depends on the season and is much larger in the summer than in the winter. However, except at the end of a long dry spell, rains of 0.5 inch or more are likely to result in some ground-water recharge, even during the summer. Therefore, the number of days in which rain of 0.5 inch or more occurs is of more significance to recharge than the number of days of measurable rain (more than 0.0 1 inch). The annual number of such days ranges from about 30 at Asheville and Raleigh to about 35 at New Bern. These numbers indicate that precipitation sufficient to result in ground-water recharge will occur, on the average, every 10 to 15 days.

Air temperature is the second climatic factor that affects recharge. Air temperature is important from the standpoint of recharge in two respects; it exerts a primary control on evaporation of water from both water bodies and wet surfaces and it affects plant growth which, in turn, affects the evaporation of water by plants. Needless to say, air temperature follows an annual cycle with the result that its effect on recharge also follows an annual cycle.

Air temperature varies much less across the State than does precipitation (Figure 11, page 25). The average annual air temperature, for example, ranges only from about 64°F along the southeastern coast to about 50°F in the northwestern comer of the State (Carney and Hardy, 1964, Figure 4). Significantly, average annual air temperature throughout most of the Piedmont and Coastal Plain only ranges from about 60 to 64°F. Because of this relatively small range,

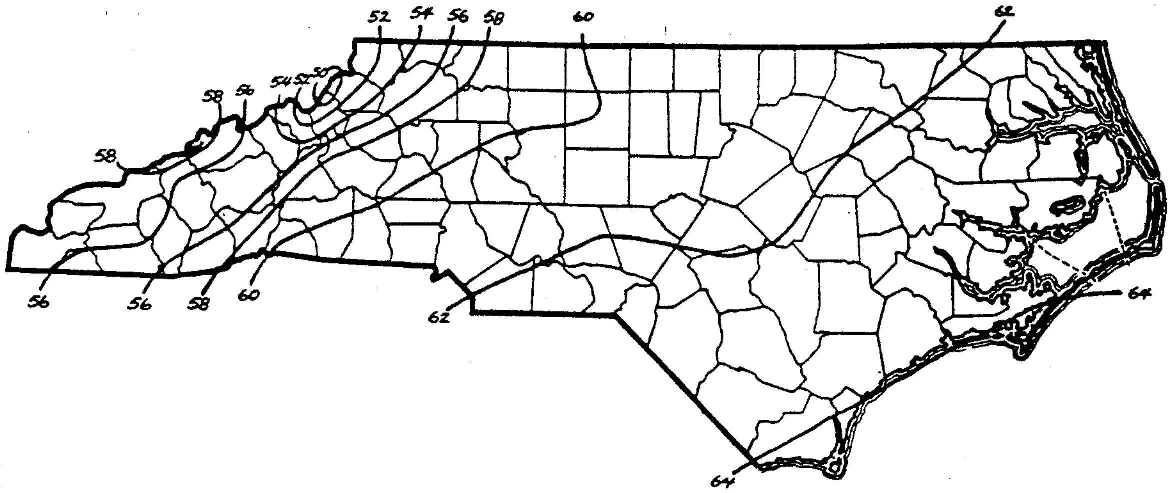


Figure 11.-- Map of North Carolina showing average annual air temperature, in degrees F.

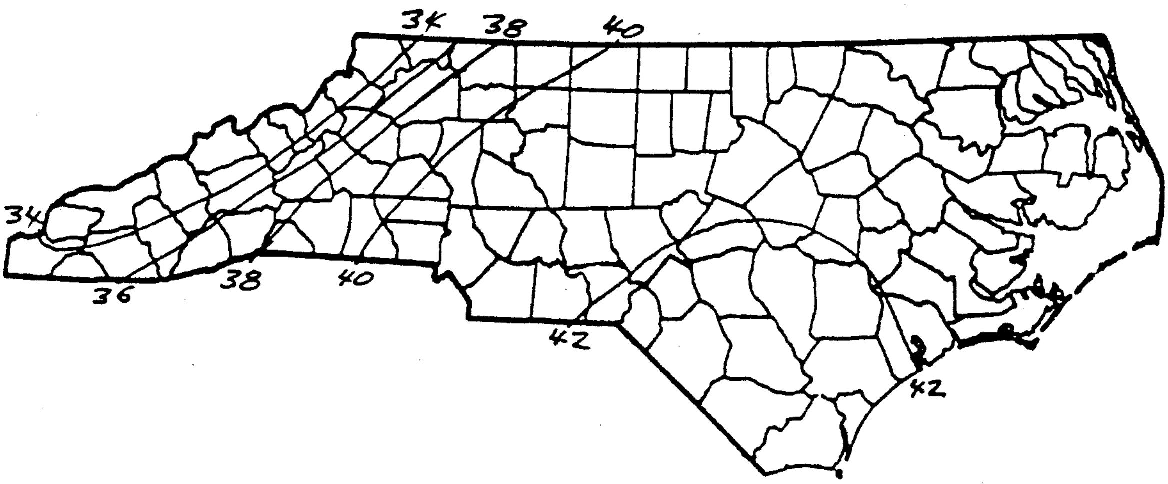


Figure 12.-- Map of North Carolina showing average annual evaporation, in inches, from free water surfaces.

differences in air temperature across the Piedmont and Coastal Plain probably have a relatively negligible effect on evaporative losses, and therefore, on ground-water recharge. Average annual air temperatures in the mountains are at least several degrees lower than those in the Piedmont and, as a result, evaporative losses are significantly less in the mountains than in either the Piedmont or the Coastal Plain.

The general relation between air temperature and evaporation is indicated by Figure 12, page 24, which shows the mean annual evaporation from free water surfaces – that is, from lakes, reservoirs, streams, farm ponds, and other surface-water bodies. Note that evaporation ranges from only about 38 inches in the western Piedmont to somewhat more than 42 inches in the southeastern comer of the State. Due to the higher elevations and cooler air temperatures, evaporation in the mountains is lower and ranges from about 32 inches in the northwestern comer of the State to about 36 inches along the Blue Ridge Front.

These values of evaporation from surface-water bodies are related in an important, but often overlooked, way to ground-water recharge. When these values are compared with mean annual precipitation (Fig. 9, page 21) it is immediately obvious that, in terms of averages, precipitation exceeds the surface-water evaporation every place in the State. The significance of this is that where there is no surface outflow from any waste-receiving pond, or *evaporation* pond, the difference between precipitation and evaporation, plus the water or waste added to the minimum pond, represents ground-water recharge. The smallest difference between precipitation and evaporation from free water surfaces, about 3 to 4 inches, occurs in the areas of low precipitation in the northern Piedmont. The excess of precipitation over evaporation is about 6 inches in the Asheville area, about 12 inches from Brunswick County to Carteret County, and more than 25 inches in the mountainous area in the southwestern part of the State.

Water losses due to evaporation, being related to air temperature, obviously vary widely with the seasons of the year. This variation can be illustrated with the data obtained by the U.S. Geological Survey on evaporation from Hyco Lake in Person County in the north-central Piedmont. Hyco Lake occupies 4,350 acres (6.8 mi^2) and is used to dissipate waste heat from a large coal-fired electric power station (Giese, 1976). In order to calculate the forced evaporation resulting from the thermal loading, it was first necessary to calculate the natural evaporation – that is, the evaporation that would have occurred if heated water had not been added to the lake. The calculated average monthly natural evaporation for the 8-year period from 1967 through 1974 is shown in Figure 13 page 26, and ranged from 1.1 inches in January to 5.8 inches in July. The

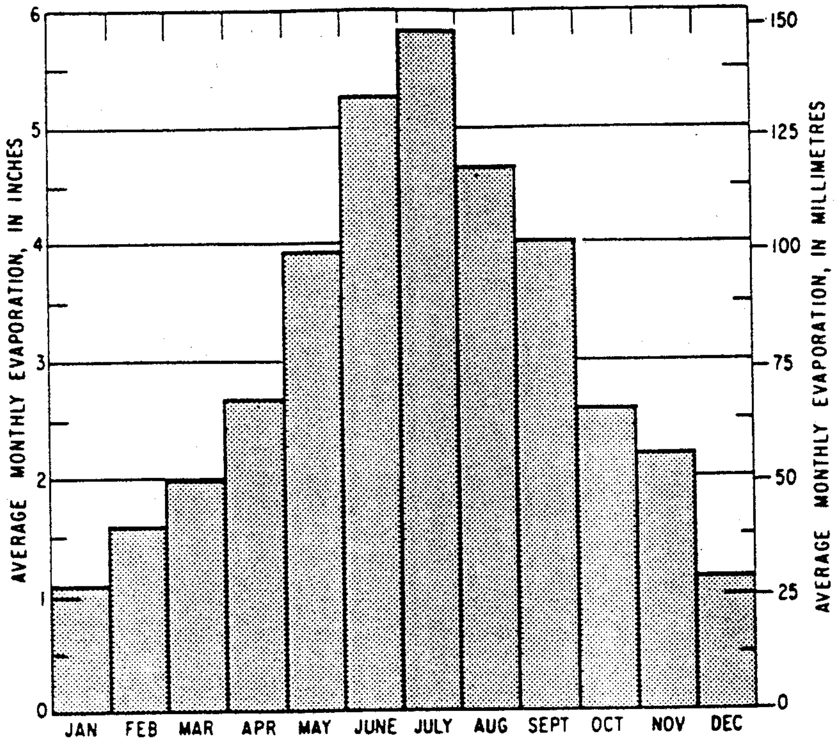


Figure 13.– Average monthly natural evaporation from Hyco Lake, North Carolina. (From Giese, 1976, Fig. 13.)

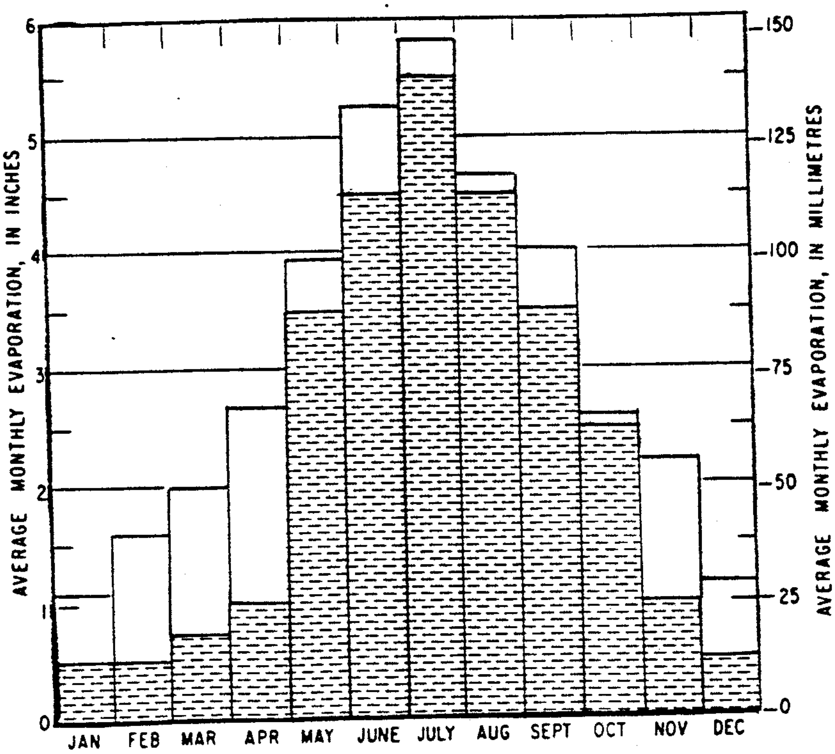


Figure 14.– Estimated water losses due to interception and transpiration (shaded area) compared to evaporation from Hyco Lake (unshaded area).

average annual evaporation for the period was 37.0 inches and ranged from 3 1.5 inches in 1974 to 43.6 inches in 1970.

Figure 13 is indicative of the evaporative loss of water from both water surfaces and from ground-water discharge areas where the water table is at or close to the land surface. As noted earlier, these losses in wet areas must be replaced before ground-water recharge can occur. As a result of the seasonal aspect of these losses, most recharge occurs in the late fall, winter, and early spring.

Recharge and Vegetation

Vegetation affects ground-water recharge in at least two ways. The first of these involves the precipitation that is *tied up in wetting* leaves and other plant surfaces at the beginning of a precipitation event, in the process referred to as **interception. The** second involves the depletion of soil moisture by vegetation during rainless periods in the growing season.

The amount of precipitation intercepted by plant and other surfaces depends on the area of the exposed surface and thus, for vegetation, depends on the kind, density, and growth stage of the vegetation. The extreme values are readily apparent and range from a cultivated field that has not yet been planted, to a mature deciduous forest in July and August during the hottest part of summer. In the case of the cultivated field, even a trace of precipitation will reach the land surface. In the case of the deciduous forest, the first 0.1 inch or more of the precipitation may be intercepted by leaves and other exposed surfaces (Anderson and Burt, 1990, page 12). The term *interception* is strictly applied only to precipitation that is caught and retained on vegetation and other structures and subsequently evaporated without reaching the ground. A broader, and possibly more useful, application of the term would also include precipitation caught and retained on surface litter and evaporated without reaching the soil surface. The precipitation required to wet an intact layer of surface litter probably equals that intercepted by the leaves. In fact, Anderson and Burt (1990, page 12) note that the storage capacity of surface litter is typically about 10 mm (0.5 inch) and evaporation from surface litter is from 1 percent to 5 percent of gross rainfall.

The importance of interception, from the standpoint of ground-water recharge, is that replenishment of soil moisture cannot begin until the interception losses are satisfied at the beginning of each rain. This means that during the growing season rams of less than about 0.2 inch, which are separated by periods long enough to permit surface drying, will have little or no effect on soil moisture and, consequently, on ground-water recharge.

Relative to the second effect of vegetation on ground-water recharge – that is, the depletion of soil moisture by growing vegetation – it is clear that recharge cannot occur until the soil moisture has been replenished to the point where gravity drainage will occur. Thus, any depletion of soil moisture after gravity drainage ceases, whether by direct evaporation from the soil zone or by the transpiration of vegetation, must be eliminated by the infiltration of precipitation before gravity drainage can resume, and before recharge can occur.

Significant depletion of soil moisture by vegetation obviously occurs only during the growing season, or between the last killing frost in the spring and the first killing frost in the fall. It begins slowly in the spring, as plant growth starts, and reaches a peak in mid-summer when air temperatures are highest and forests and crops have reached their maximum growth stage. It is not possible, with the methods now available, to separate evaporation from free water surfaces and the soil zone from plant transpiration. However, studies of evapotranspiration suggest that during summers with normal rainfall, when soil moisture is not excessively depleted as during summer droughts, the transpiration from forests and mature crops closely approaches the rate of evaporation from free water surfaces. The general concepts regarding transpiration discussed above can be illustrated as shown in Figure 14, page 26.

The effects of both interception and transpiration on ground-water recharge are obvious from records of water-level fluctuations in shallow observation wells designed to show the effect of climate on ground-water storage. Such observation wells are screened across the zone through which the water table fluctuates in an unconfined aquifer composed of relatively permeable sand, or other permeable material, and where the water table is within a few to several feet of the land surface. Figure 15, page 29, shows a sketch of the general annual pattern of the fluctuation of the water table in such an aquifer. The important features of this sketch include the decline of the water table that begins about the end of April or about a month after the last killing frost. At this time evaporation from the soil and transpiration from vegetation have reached the point where they are beginning to equal the infiltration from precipitation.

The decline in the water table continues, though at a somewhat decreasing rate, until the first killing frost in the fall which, in most of the State, occurs about the end of October. From this time until the following spring, soil moisture remains high and each significant rain is followed by a rise in the water table as recharge reaches the top of the capillary fringe.

Figure 15, as noted, is a sketch that shows the general annual pattern of fluctuation of the water table. Figure 16, page 30, is a hydrograph showing the actual fluctuation of the water table

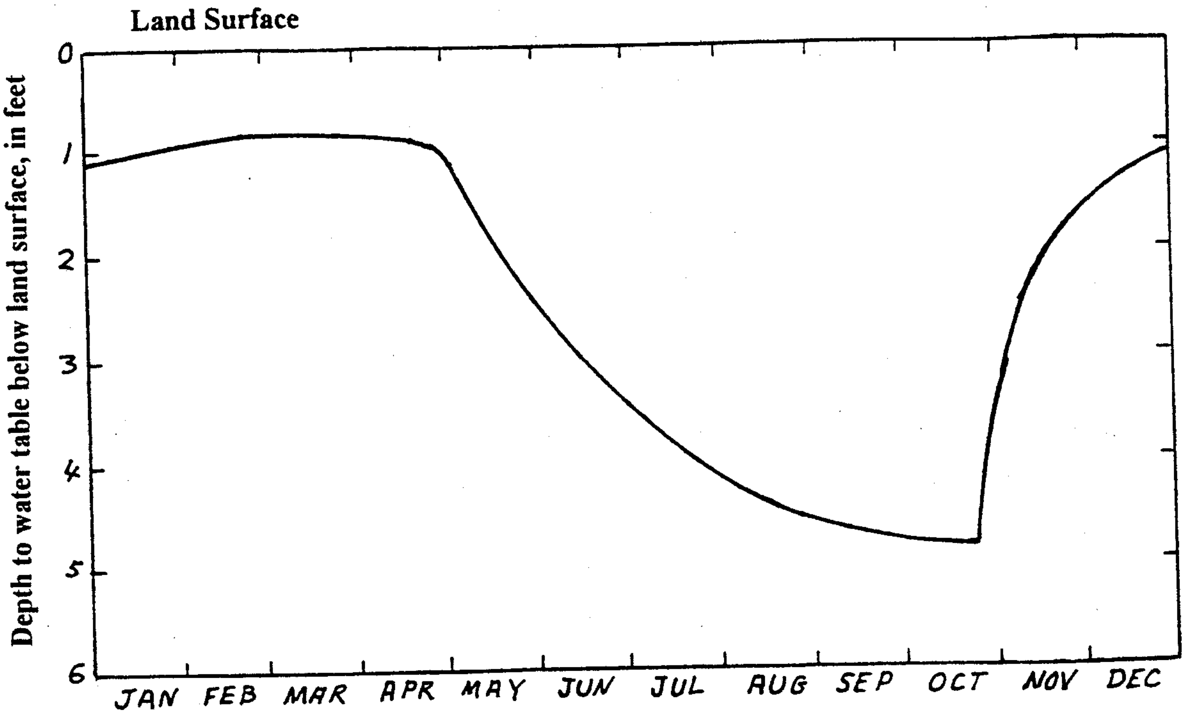


Figure 15.-- General pattern of the annual fluctuation of the water table in a shallow surficial aquifer.

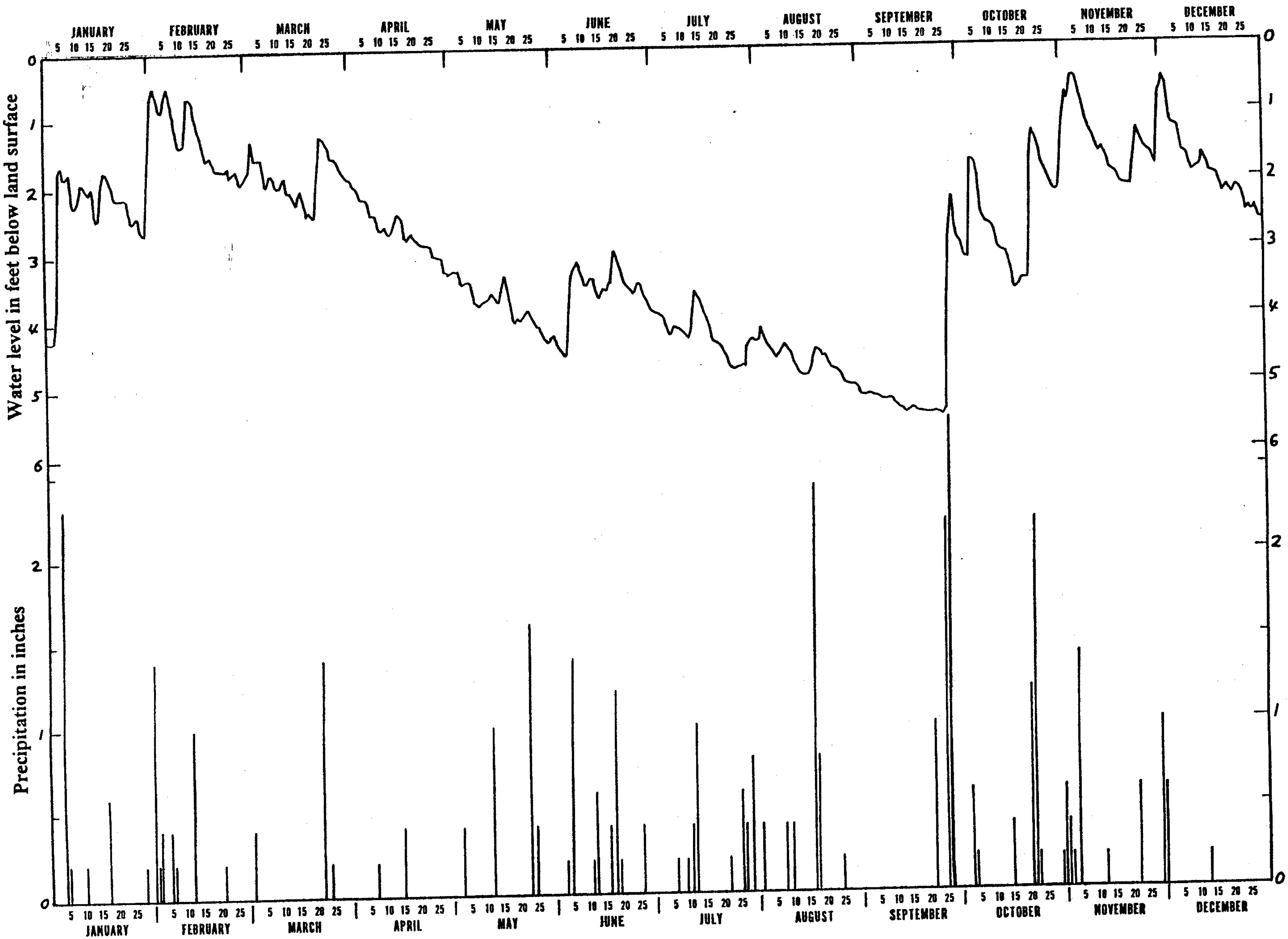


Figure 16.--Fluctuation of the water table in 1985 in U.S. Geological Survey observation well NC-141, Pasquotank County, and daily precipitation at Elizabeth City.

in 1985 in U.S. Geological Survey observation well NC-141 located near Elizabeth City in the northeastern comer of the State. The major difference between the sketch in Figure 15 and the hydrograph in Figure 16 is the actual response of the water table to individual rains which is apparent on Figure 16.

It is obvious from the preceding discussion in this section and from Figures 15 and 16 that recharge of the ground-water system differs widely between winter and summer, or between the non-growing and the growing seasons. These differences have not yet been studied in detail and clearly will vary widely from year to year. However, Daniel and Sharpless (1983, page 20-25), using the streamflow-hydrograph-separation method described by Wilder and Simmons (1982), calculated the monthly ground-water discharge for a IO-year period to three streams in the upper Cape Fear River basin. Although the total ground-water recharge may be somewhat larger than that which reaches streams, due to **evapotranspiration** losses directly from the top of the capillary fringe on floodplains and other areas with a shallow depth to the water table, the work by Daniel and Sharpless clearly shows the expected seasonal variations in ground-water recharge. As shown in Table 1, the ground-water discharge during the six-month May to October (growing season) period of large evapotranspiration losses ranges, for the three streams, from only 26 to 37 percent of the total ground-water discharge.

Table 1. Average daily and seasonal ground-water discharge to three unregulated streams in the upper Cape Fear River Basin, 1971-80. (Based on Daniel and Sharpless, 1983, Figure 7)

USGS *station name (type of bedrock)*	*Drainage area (mi^2)*	*Ground-water discharge (gpd/mi^2)*			*May- Oct discharge as percent of total*
		Avg. daily	*May-Ott*	*Nov- Apr*	
Reedy Fork near Oak Ridge (granite and gneiss)	20.5	5 10,000	370,000	660,000	36
Big Alamance Creek near Elon College (sheared granite and volcanics)	116	350,000	180,000	5 10,000	26
East Fork Deep River near High Point (granite, gneiss, and volcanics)	14.8	410,000	320,000	540,000	37

Recharge and Soil Characteristics

The third factor mentioned earlier that affects ground-water recharge is soil characteristics. As treated in this discussion, soil characteristics include not only soil composition and structure but also modifications of the land surface that affect the infiltration of precipitation. These modifications include structures, such as buildings and parking lots, that prevent infiltration and also grading and other activities that change the soil structure and therefore the infiltration characteristics of the soil.

The soil characteristics most favorable for ground-water recharge exist in virgin forests in which the soil zone contains an intricate network of openings previously occupied by the roots of living trees and by openings left by burrowing organisms. These openings are exceptionally efficient in conveying water from the land surface into and across the soil zone so that, even on the relatively steep forested mountain slopes in the western part of the State, there is little or no surface runoff.

At the other extreme, nearly all manmade structures make the land surface impermeable and therefore prevent the infiltration of precipitation into the soil zone. The effect of structures then, is to reduce the size of ground-water recharge areas and to increase the rate of runoff on the land surface. In his classic study of the effect of urban development on floods in the Piedmont Province of North Carolina, Putnam notes that the addition of impervious surfaces in urban areas is accompanied by ditching and the installation of curb and gutters, drams, and storm sewers all of which increase the rate of runoff and flood peaks (Putnam, 1972, page 17).

Impervious areas in North Carolina range from about 1 percent in rural areas to 50 percent or more in central business districts. Impervious areas in suburbs range from about 10 percent in areas with lots one acre or larger to about 25 percent in areas with half acre or smaller lots. The impervious surfaces in urban areas probably average about 30 percent and thus, statewide, represent a significant reduction in the size of the areas in which ground-water recharge can occur. *(Another aspect of the effect of urbanization on ground water, and one that has not yet been adequately studied, involves the deterioration in ground-water quality in urban areas due to leaking storm and sanitary sewers and underground storage tanks. Not only is the natural recharge in urban areas reduced, but much of the recharge that does occur is of undesirable quality.)*

Another aspect of urbanization that also adversely affects ground-water recharge is the grading and other soil-disturbing activities related to the development of lawns, An indication of the extent to which soil-disturbing activities can affect infiltration rates is shown by research conducted in the

Piedmont by Kays (1979). The infiltration rates measured by Kays for different land uses in areas underlain by Cecil sandy loam are shown in Table 2. The decrease in infiltration rates shown in Table 2, as land use changes from an undisturbed forest to highly disturbed and compacted lawns, is believed to be representative of the changes that occur for other soils with the exception of the sandy soils that underlie the Sand Hills and parts of the Coastal Plain. Because the infiltration capacity of these sandy soils depends more on their large permeability than on root holes and other secondary soil structures, it is unlikely that soil-disturbing activities would result in changes as large as those shown in Table 2.

Table 2. Infiltration rates and relative recharge rates for different land uses on Cecil sandy loam. Based on work by Kays (1979).

Land use	*Mean final infiltration rate(inches/hour)*	*Relative recharge rates*
Forest (undisturbed)	12.4	62
Slightly disturbed woodlands	4.4	22
Former farmland	1.9	9.5
Disturbed and revegetated lawns	0.5	2.5
Highly disturbed lawns	0.3	1.5
Highly disturbed and compacted lawns	0.2	1

The importance of the infiltration rates shown in Table 2, from the standpoint of ground-water recharge, is that they show the rather profound effect of soil-disturbing activities on infiltration and therefore on recharge rates. The relative recharge rates in the last column were calculated by dividing the infiltration rates in the middle column by the infiltration rate for highly disturbed and compacted lawns. Thus, the value for highly disturbed and compacted lawns is 1 and the value for undisturbed forests is 62. The profound effect of urbanization on reducing ground-water recharge and, conversely, on increasing flood peaks is readily apparent from a comparison of the relative recharge rates for forests and for lawns. It is also important to note that even the conversion of an area from forest to farmland may result in more than a six-fold reduction in the infiltration rate and, presumably, also in the recharge rate.

The preceding paragraphs in this section deal with the effect on infiltration and recharge of modifications of the soil (land) surface and soil structure. The composition of the soil obviously also affects infiltration rates. Composition, as used in this discussion, refers to the inorganic mineral grains and the non-living organic matter that comprise the soil.

The soils that form the surface of the State have been divided into approximately 300 named series (Daniels, and others, 1984, page 1). The primary reason for dividing the soils into such a large number of units is to aid farmers in their utilization of the land. The conditions that form soils involve not only composition but also landscape position and drainage characteristics, which relate primarily to the depth and fluctuation of the water table.

The inorganic mineral component of soils consists largely of quartz particles that range in size from silt to sand – that is, particles that range in diameter from 0.000 15 inch to 0.079 inch – and complex silicate minerals composed mostly of clay-size particles – that is, particles with diameters less than 0.00015 inch in diameter.

The rate at which water will infiltrate into a soil depends on the soils hydraulic conductivity which, in turn, is controlled by the grain size and sorting (range in grain size) of the mineral component and the soil structure. Soil structure, in the sense used here, refers to the non-porous openings in the soil, such as those due to the clumping of soil particles, and those left by decayed roots and burrowing organisms. Soil structure is exceedingly important in the infiltration of water, as shown in Table 2. It is the structure that is modified or destroyed when land use is converted from forests to other purposes, such as cultivated fields or urban areas.

In the absence of the soil structures mentioned above, the hydraulic conductivity, and the infiltration rate, of mineral soils depends on the grain size and sorting of the particles comprising the soil. Values of hydraulic conductivity, and other hydraulic characteristics, of 69 of the more important soils in the State were determined by Lutz (1970). In the collection of samples, Lutz avoided openings left by roots and organisms so that his values of hydraulic conductivity involve only the openings between the soil particles and the openings formed by the clumping of soil particles.

As is pointed out in the following paragraphs, the parent material forming the soils of the Coastal Plain differs in origin from the parent material forming the soils of the Piedmont and Blue Ridge. This difference is reflected in differences in the values of hydraulic conductivity reported by Lutz, as shown in Table 3. The values reported in Table 3 are all for the B horizon because, with only a few exceptions, this horizon has the smallest hydraulic conductivity and therefore the greatest effect on ground-water recharge.

Table 3. Selected values of B horizon soil hydraulic conductivity (Lutz 1970).

Province	*Number ofsamples*	*Hydraulic conductivity (in/hr)*		
		maximum	*minimum*	*mean*
Coastal Plain	41	100+	0.19	9.76
Piedmont	21	13.8	0.2	2.21
Blue Ridge	23	8.5	0.41	2.25

It is not possible in this discussion to deal with the very large range in grain size and sorting of the soils that form the surface of the State. At the present state of our knowledge of the effect of soils on ground-water recharge, it is probably sufficient to combine all soils into one of three groups: (1) sandy soils, (2) sandy and silty soils, and (3) clayey soils. Sandy soils are those composed primarily of coarse to medium-size sand grains (diameters from 0.0098 to 0.079 inch). Sandy *and silty* soils are those composed primarily of fine-grained sand and coarse and medium-grain silt (diameters from 0.0098 to 0.00062 inch). *Silty and clayey* soils are those composed primarily of fine-grained silt and clay-size particles (diameters less than 0.00062 inch). Also included in this group are the organic soils of the Tidewater Region of the Coastal Plain which, like mineral soils composed of silt and clay, have a very small infiltration rate.

The soils underlying the Coastal Plain, being developed primarily from unconsolidated marine and fluvial sediments, can fairly easily be divided into the three types mentioned in the preceding paragraph. The areas underlain by each of these are shown in Figure 2 1, page 45.

The unconsolidated surficial layer in the Piedmont and Blue Ridge regions of the State differs markedly in origin from that of the Coastal Plain. This layer, except where it is composed of alluvium laid down by streams, was formed by the chemical and physical disintegration of the underlying fractured bedrock, in the process referred to by geologists as **weathering. The** surficial layer is commonly referred to as **regolith** and consists at the land surface of a relatively porous and permeable soil zone several inches to a few feet thick. The soil zone grades downward into clay-rich, relatively impermeable **saprolite** that commonly retains the textural characteristics of the bedrock from which it is derived. The saprolite, in turn, grades downward through a relatively into unweathered bedrock.

The hydraulic conductivity of the soil and the underlying saprolite controls the rate of ground-water recharge and depends on the mineral composition and structure of the underlying bedrock. Thus, crystalline intrusive igneous and metamorphosed igneous rocks tend to form relatively permeable soils whereas those composed of silt and clay-size particles, such as the rocks of the Carolina Slate Belt, tend to form clay-rich, impermeable soils. Nevertheless, nearly all of the bedrock units underlying the Piedmont and Blue Ridge contain some clay-forming minerals which result in the hydraulic conductivity of the B horizon in these regions being less than in the Coastal Plain, as indicated by a comparison of the mean values in Table 3.

The Piedmont and Blue Ridge have been divided into the northeast-trending geologic belts shown in Figure 17, page 37. In each belt, the different rock units are similar in general appearance, metamorphic rank, structural history, and relative abundance of igneous, metaigneous, metasedimentary, and metavolcanic rocks. Daniel (1987) determined, in a statistical analysis of more than 6200 well records, the average yield of wells in each belt, as shown in Figure 18, page 38.

The belts shown in Figure 17 are bordered on the east by the Coastal Plain. The records analyzed by Daniel included wells located near the western edge of the Coastal Plain which draw water from the underlying fractured bedrock. Daniel included these wells in his analysis.

The average yield of the wells in the different belts (Figure 18) is believed to reflect largely the effect of differences in mineral composition of the rock units and geologic structure. These characteristics are believed to also have an effect on soil hydraulic conductivity and on ground-water recharge. However, it would be unrealistic to assume that recharge rates differ significantly between belts with similar average yields. Therefore, for the purpose of subdividing the Piedmont and Blue Ridge into areas having similar recharge rates, the 13 belts and zones of the Piedmont and Blue Ridge shown in Figure 17 are assigned to the four areas shown in Figure 2 1, page 45. It should be noted that the one exception to the assignment of belts to recharge areas is the Asheville Basin. As shown in Figure 9, page 2 1, the Asheville Basin is an area of low precipitation which is believed to result in a smaller recharge rate.

It is apparent from the preceding discussion that soil composition and structure have a significant effect on infiltration rates and on ground-water recharge.

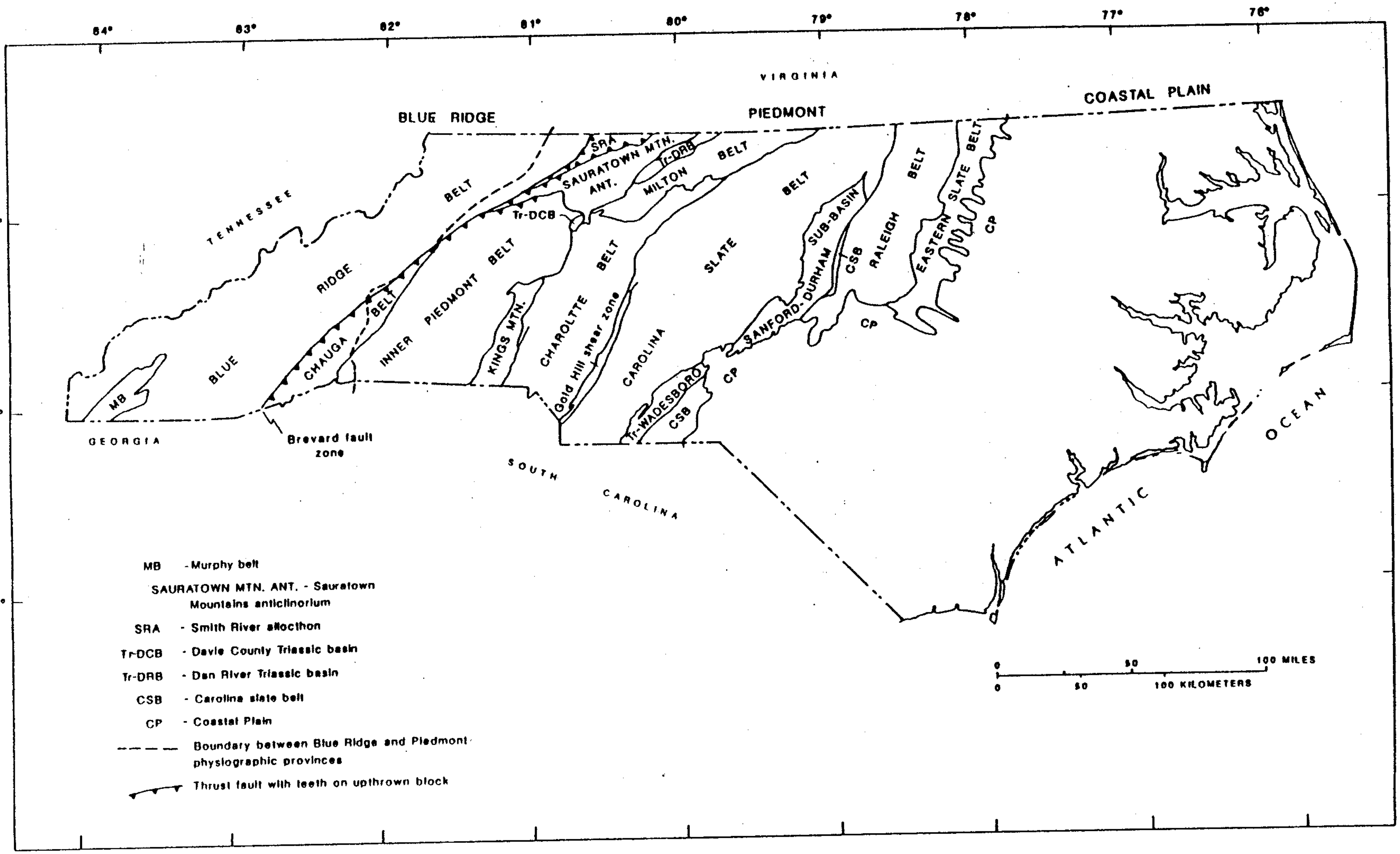


Figure 17.--Geologic belts, terranes, and some of the major structural features of the Piedmont and Blue Ridge provinces of North Carolina. (From Daniel, 1987.)

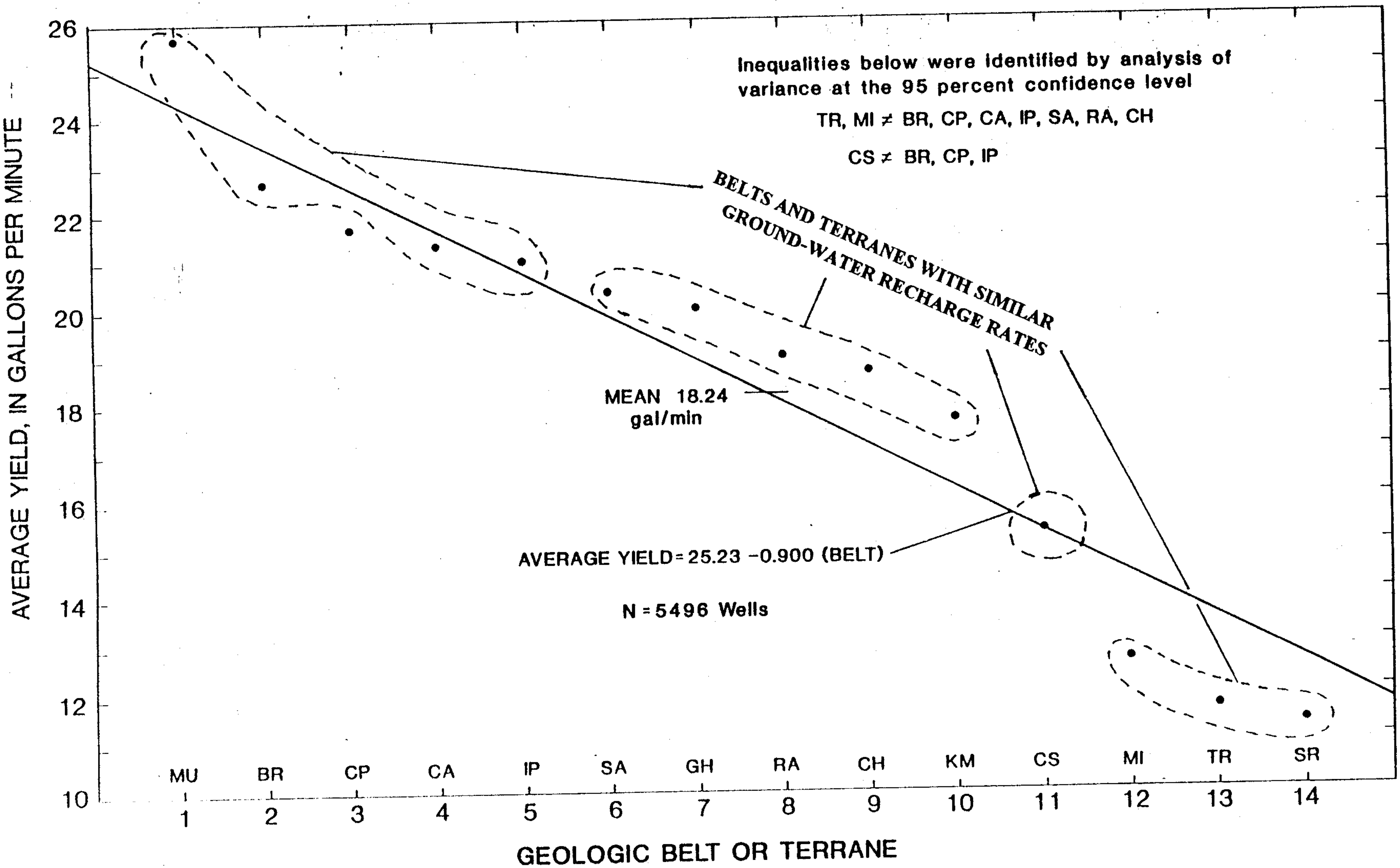


Figure 18.--Average yield of wells of average construction in the geologic belts and terranes of the Piedmont and Blue Ridge provinces of North Carolina. The average yield of wells drawing from bedrock near the western boundary of the Coastal Plain (symbol CP) is also shown. (From Daniel, 1987.)

RECHARGE OF THE GROUND-WATER SYSTEM

Recharge of the ground-water system is affected by numerous complex and, to some extent, interrelated factors. The factors related to climate and vegetation, as has been seen, vary both seasonally and from year to year. The factors related to soil characteristics are much less variable but, nevertheless, may change gradually from year to year as, for example, when forests are converted to cultivated land and both forests and cultivated land are converted to urban uses. All these changes tend to either reduce the rate of recharge or reduce the size of recharge areas. Recharge of the ground-water system therefore not only varies seasonally and from year to year, but is also undergoing a gradual reduction year after year as a result of changes in land use.

A map of the State showing estimated recharge rates was included in the report on the State's wellhead-protection program (Heath, 1991). That map was intentionally generalized in the Piedmont and Blue Ridge to avoid unnecessarily complicating the methodology proposed for the wellhead-protection program. That consideration is not involved in the work related to this report and it seems desirable to take a second look at the Piedmont and Blue Ridge relative to refining the estimates included in the wellhead-protection report. However, before dealing with this topic, it is desirable to discuss the units in which recharge rates are reported.

Expression of Recharge Rates

It is common practice to report recharge rates both as a depth of water (thickness of a layer) on the land surface per unit of time, such as in units of inches (or millimeters) per year, and as a volume per unit of time per unit area, such as in units of gallons per day per square mile.

Recharge rates reported in units of depth per unit of time permits recharge to be compared directly with precipitation. Because precipitation in the United States is still reported in inches, it is most convenient to also report recharge in inches and, specifically, as inches per year. Recharge reported as a volume per unit of time per unit area permits recharge to be compared with the rate of ground-water use. Ground-water use is commonly reported in units of gallons per day and it is therefore common practice to report recharge rates in units of gallons per day per square mile (gpd/mi^2).

Relative to the conversion from one unit to another, it may be noted that a recharge rate of one inch per year equals 47,610 gpd/mi^2 or, rounded, 48,000 gpd/mi^2. A recharge rate of 21 inches per year equals about 1,000,000 gallons per day per square mile (1 mgd/mi^2).

Estimated Recharge Rates

Any attempt to estimate ground-water recharge rates in North Carolina must include consideration not only of the factors discussed earlier but other related information. One of the most important related items of information involves the average annual runoff through streams. This runoff includes ground-water discharge, referred to as **baseflow,** as well as **overland runoff,** runoff through the soil zone, referred to as **interflow,** and precipitation directly on streams and other surface-water bodies. Therefore, because streamflow includes more than just ground-water discharge, average annual ground-water recharge is almost invariably considerably less than the average annual streamflow.

Figure 19 shows the average annual runoff through streams in North Carolina, based on long-term, continuous streamflow records compiled by the U.S. Geological Survey. The runoff unit shown in Figure 19 is inches, which permits it to be compared directly with Figure 9 which shows precipitation in inches. Such comparison shows that the areas of low precipitation in the northern Piedmont and the Asheville area (Buncombe and Madison Counties) are also among the areas with the smallest runoff.

Referring back to the conversion factors mentioned in the previous section, it may be noted that the runoff rate of 14 inches/year in the central and eastern Piedmont equals about 670,000 gpd/mi^2 and the runoff rate of 40 inches/year in the southwestern part of the State equals about 1,900,000 gpd/mi^2. From the discussion earlier in this section, it is obvious that the ground-water recharge in these areas must be substantially less than these amounts.

Moving from precipitation and streamflow to ground-water recharge rates, one of the first attempts in North Carolina to quantitatively estimate ground-water recharge was in connection with the study of the ground-water resources of the Cape Hatteras National Seashore (Winner, 1975). Using both a water-budget approach and an analysis of the decline in ground-water storage during a winter rainless period, Winner estimated that ground-water recharge to the surficial sand aquifer in the Cape Hatteras area is about 340 million gallons per year per square mile. This amounts to an average recharge rate of about 932,000 gallons per day per square mile, or about 19.6 inches per year. That is, of the average rainfall at Cape Hatteras of about 55 inches, 19.6

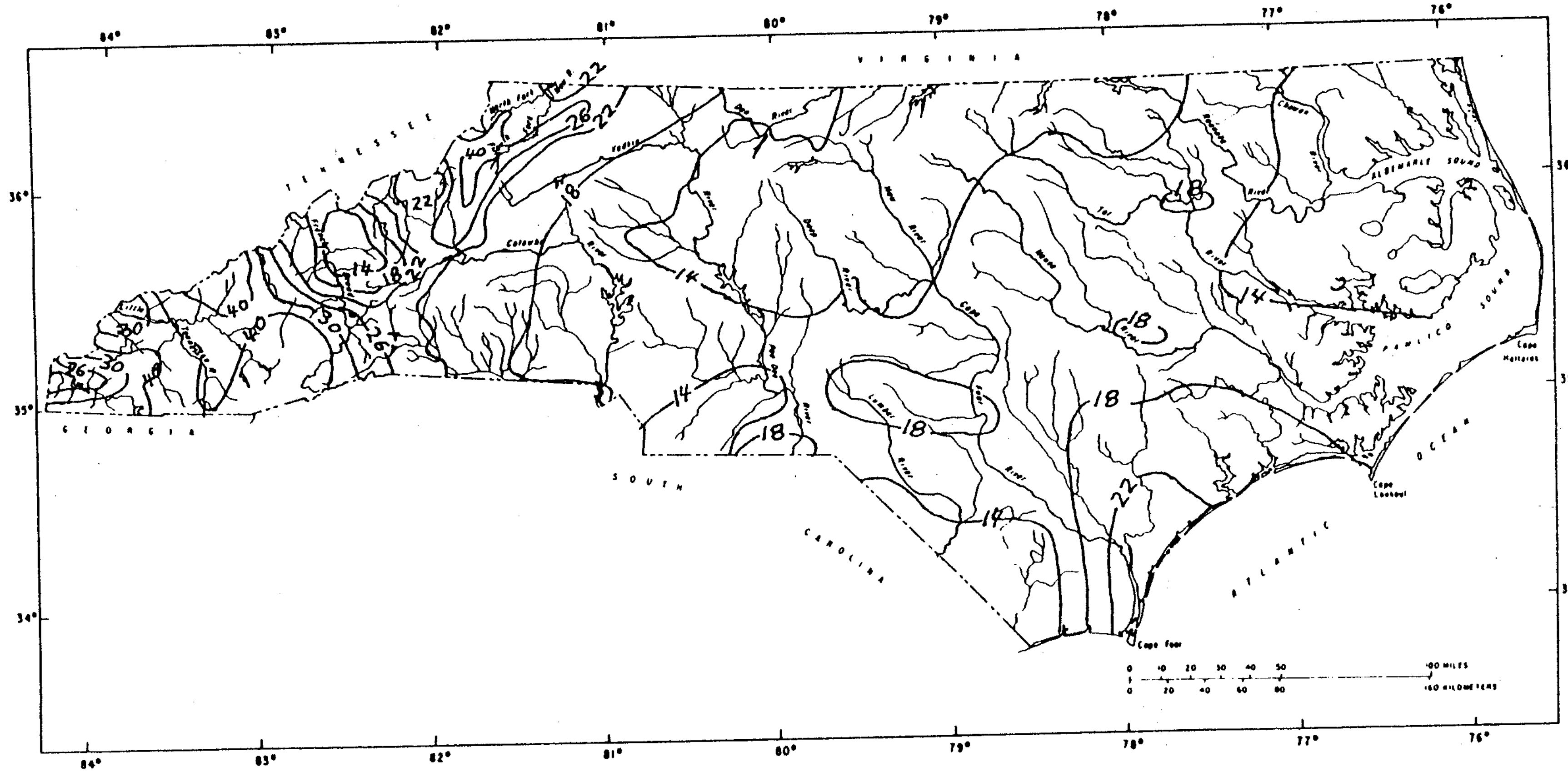


Figure 19.--Average annual streamflow in North Carolina, expressed as depth in inches on the land surface. (From U.S. Geological Survey.)

inches or about 36 percent of the precipitation reaches the ground-water system as recharge. This study and other studies conducted in East Coast States indicate that under the optimum conditions of a humid climate, very permeable surficial sands, and a depth to the water table of at least several feet, average annual ground-water recharge is about 20 inches or about 950,000 gpd/mi^2.

Estimates of ground-water recharge, similar to those made for Cape Hatteras, have not been made on the mainland where the composition and stratification of the surficial aquifer is, in most places, far more complex than it is on the Outer Banks. Fortunately, however, the U.S. Geological Survey has estimated the rate of ground-water discharge to streams in connection with studies of stream-water quality. These estimates are based on the method described by Wilder and Simmons (1982, p.A8-A12) which involves the separation of hydrographs of daily streamflow into the two components of ground-water discharge and overland flow. The results of this work are summarized in Table 4 for the stream basins shown on Figure 20, page 43. Although these

Table 4. Total runoff, overland runoff, and ground-water discharge compiled by the U. S. Geological Survey for selected stream basins in North Carolina

Map No.	*Stream name* and location	Drainage area *(sq. mi)*	*Avg. annual tot. runoff (in/yr)*	Overland *runoff (in/yr)*	Ground-water discharge: Percent *of* total runoff	inches per *year*	gallons per day *per mi²*
1	French Broad R. at Marshall	1,332	25.1	6.9	73	18.2	867,000
2	Second Broad R. at Cliffside	220	19.2	6.8	65	12.4	590,000
3	Jacob Fork at Ramsey	25.7	26.4	13.9	47	12.5	595,000
4	Sugar Creek near Fort Mill S.C.	262	23.8	16.2	32	7.6	362,000
5	Rocky R. near Norwood	1,372	13.2	9.9	24	3.3	157,000
6	Yadkin R. at Yadkin College	2,280	17.7	8.1	54	9.6	457,000
7	Reedy Fork near Oak Ridge	20.6	15.4	6.1	60	9.3	443,000
8	E. Fork Deep R. near High Point	14.8	15.1	8.9	41	6.2	295,000
9	Big Alamance Cr. near Elon Col.	116	13.4	7.1	47	6.3	300,000
10	Haw R. near Moncure	1,689	12.5	8.7	31	3.8	181,000
11	Neuse R. near Clayton	1,150	13.8	7.9	43	5.9	281,000
12	Neuse R. at Kinston	2,692	13.9	9.4	32	4.5	214,000
13	Turner Swamp near Eureka	2.1	14.4	7.7	47	6.7	319,000
14	Cape Fear R. at Lillington	3,464	13.7	9.5	31	4.2	200,000
15	Cape Fear R. at Lock No. 1	2,522	13.7	8.1	41	5.6	267,000
16	Lumber R. at Boardman	1,228	14.5	6.8	53	7.7	367,000
17	Tar R. at Tarboro	2,183	13.9	8.3	40	5.6	267,000

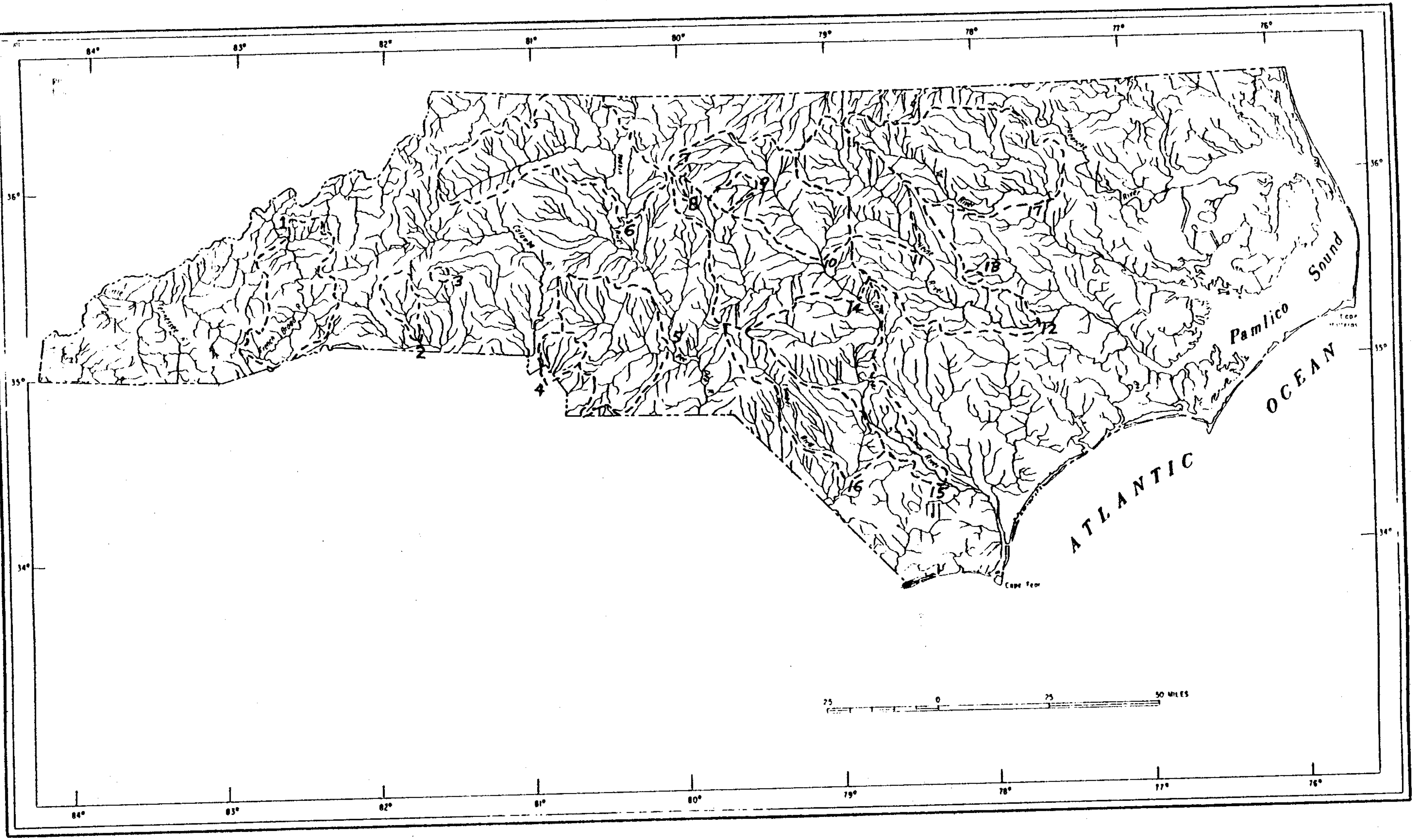


Figure 20.--Map of North Carolina showing drainage basins for which streamflow hydrographs have been separated by the U.S. Geological Survey into overland runoff and ground-water discharge components .

estimates are of the amount of ground water discharging to streams, they are based on the period of record, which at many of the stations exceeds 20 years, and are believed to represent long-term average annual ground-water recharge (Harned and Daniel, 1987).

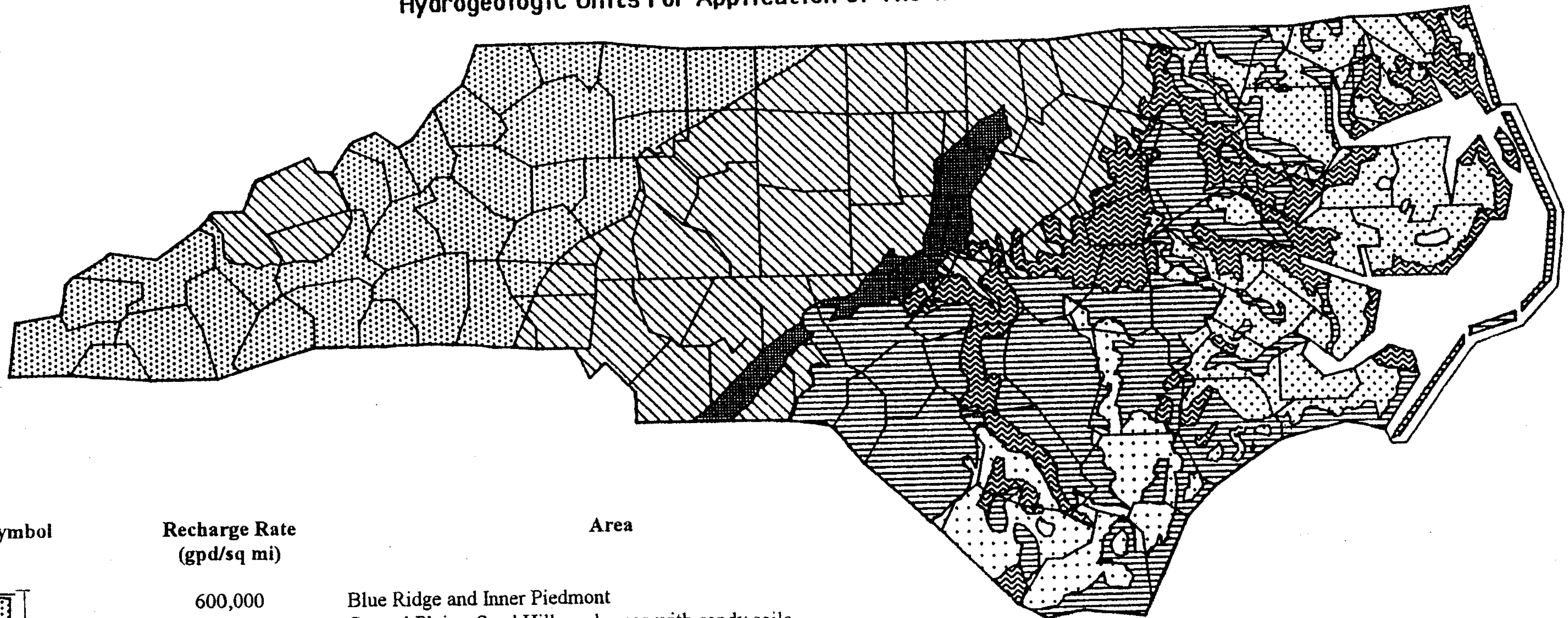
The values in the last column in Table 4 express ground-water discharge (actually considered to be ground-water recharge) in units of gallons per day per square mile and can, therefore, be compared directly with the value of 932,000 gpd/mi^2 estimated for Cape Hatteras. The effect of the factors that affect ground-water recharge, which were mentioned earlier, are clearly evident from the values in Table 4. For example, most of the French Broad River drainage basin is a mountainous area with a higher precipitation rate and lower air temperatures than the Piedmont area to the east. This is reflected in the ground-water recharge rate of 867,000 gpd/mi^2. Differences in climate (precipitation and air temperature) are not as marked between the Piedmont and Coastal Plain as between the Blue Ridge and Piedmont and the differences in ground-water recharge between basins in both the Piedmont and Coastal Plain area are believed to reflect mainly differences in the composition and structure of the surficial layer and differences in land use.

The values of ground-water recharge shown in Table 4 served as an important source of information for the recharge rates shown on Figure 2 1, page 45. In considering, and using, these values, it is important to realize that, depending on the total amount and the seasonal distribution of precipitation, the actual recharge may be as much as 50 percent more or less than the values shown. It is also important to realize that differences in land use in any area may also result in large differences in recharge rates. Thus, recharge per unit area in a mature forest may be at least several times more than that in pastures and cultivated fields, and the recharge in these areas may also be several times larger than in urban areas. Because of these and other factors, the recharge rates shown on Figure 2 1 have been intentionally rounded to reflect what are believed to be average values for the range in climatic and soil conditions. Note on Figure 21 that the Asheville Basin is combined with the Charlotte and Raleigh Belts and related zones because precipitation in the Asheville area is less than in the remainder of the Blue Ridge.

EXTENT OF RECHARGE AND DISCHARGE AREAS

One of the objectives in preparing this report was to estimate the amount of ground-water recharge. This involves determining the size (extent) of both recharge and discharge areas and, using the size of the recharge areas and the recharge rates shown on Figure 2 1, determine the *average annual* ground-water recharge.

Map of North Carolina Showing The SubDivision of The Surficial Aquifer Into Hydrogeologic Units For Application of The Wellhead-Protection Program



Map Symbol	Recharge Rate (gpd/sq mi)	Area
	600,000	Blue Ridge and Inner Piedmont Coastal Plain - Sand Hills and areas with sandy soils
	400,000	Asheville Basin, Charlotte and Raleigh Belts and related areas Coastal Plain - Areas with sandy and silty soils
	300,000	Carolina Slate Belt and Eastern Slate Belt
	200,000	Coastal Plain - Areas with silty and clayey soils
	150,000	Triassic Basins and related areas

Figure 21

The land area of the State – that is, the area exclusive of the sounds and estuaries – encompasses 49,530 mi^2 (Table 5). This area includes lakes, reservoirs, streams, and other surface-water bodies to which ground water discharges. It also includes the floodplains and the other areas identified as ground-water discharge areas on the map entitled *Principal ground-water discharge areas in North Carolina. The* total of all these places of ground-water discharge (or non-recharge) is estimated to be about 6,000 mi^2. Subtracting this from the total land area, leaves a remainder of about 43,5 00 mi^2 occupied by ground-water recharge areas.

Area1 Aspects of Discharge Areas

Table 5, page 48, contains data that will be used in this discussion and in the following discussion related to ground-water recharge. Most of the values contained in this table were generated by the North Carolina Center for Geographic Information and Analysis (NCCGIA) utilizing the data compiled by the U. S. Geological Survey from it's 1: 100,000 scale maps.

As pointed out previously, places of ground-water discharge include springs, stream channels, sides and bottoms of lakes and reservoirs, the shorelines of estuaries, sounds, and the ocean, and floodplains and other low areas where the top of the capillary fringe is within several feet of the land surface. As also noted, some areas are at times discharge areas and, at other times, recharge areas. Because of these and other factors, it is not possible to determine precisely the extent of ground-water discharge areas. In fact, it is important to note that some discharge areas, including small streams, and the ocean shoreline and the shorelines of estuaries, reservoirs, and large lakes can, for practical purposes, best be treated as discharge lines rather than as areas. It is well recognized, of course, that ground water discharges into surface-water bodies through a seepage face but where the thickness of this face is very small compared to its length, it is the length that is important.

Based on the data in Table 5, the total length of ground-water discharge lines is about 60,000 miles. This total was derived as follows:

Shorelines..		10,794 miles	(ocean, estuaries, large lakes and reservoirs)
Large Streams	– right bank	1,802	
	– left bank	1,898	
Small streams...		**40,089**	
Drainage canals.....................		2.633	
	Total.	57,2 16 miles of perennial ground-water discharge lines	

The above total was rounded upward to 60,000 miles to include the effect of intermittent streams and drainage ditches not in recharge areas.

In addition to the **ground-water discharge lines** discussed above, there are two other types of areas that need to be considered in this discussion. The first are the floodplains and other land areas mapped as **ground-water discharge areas** on the discharge-area map. The second are the areas occupied by lakes, reservoirs, large ponds, and streams which, if not discharge areas, are at least non-recharge areas. For convenience, these will be referred to as **non-recharge areas** and they include not only the surface-water features mentioned above but also the impervious parts of urban areas in which recharge does not occur.

Ground-water discharge areas shown on the discharge-area map, which do not include surface-water bodies, total 4,3 16 mi^2. (See Table 5.) This is about 9 percent of the land area of the State. Non-recharge areas total about 1,700 mi^2. This total was derived from data in Table 5 and from NCCGIA as follows:

Natural lakes, large ponds, and reservoirs..	560 sq mi
Streams, large..	193
small..	152
Urban areas..	840
Total	1,745 sq mi

The 840 mi^2 assigned to urban areas is 30 percent of the total urban area shown in Table 5, based on the earlier discussion of *Recharge and Soil Characteristics. The 2,800* mi^2 shown in Table 5 as being occupied by urban areas is based on data supplied by cities and towns to the North Carolina League of Municipalities. The incorporated area reported by 372 municipalities totals 2,533 mi^2. This value was rounded upward to 2,800 mi^2 to account for the 148 towns that did not report their areas. The value for small streams is based on an assumed average width of 20 feet.

No great accuracy is claimed for any of the items in the above list, with the possible exception of the values for lakes, large ponds, and reservoirs and large streams. However, it is believed to be worthwhile to call attention to the great length of the seepage faces through which ground water discharges (60,000 miles), and to the size of the mapped ground-water discharge areas (4,3 16 mi^2), and the size of the areas in which recharge does not occur (1,745 mi^2) which, together, total about 6,000 mi^2, or about 12 percent of the land area of the State.

Table 5. Areas in North Carolina pertinent to analyses of ground-water recharge and discharge.

Category	*Area (sq mi)*	*Length (miles)*	*Remarks*
Total area of State	52,727		From NCCGIA
Sounds and estuaries	3,197		do
Total land area	*49,530*		do. Includes lakes, reservoirs, and other inland water bodies
Surface-water bodies	560		do. Includes lakes, ponds, and reservoirs
Streams – perennial		41,939	do. Length includes single-line streams plus 1/2 of right +left banks
large – right bank		1,802	do. Streams with both banks shown on 1: 100,000 scale maps
– left bank		1,898	do.
small		40,089	do. Single lines on maps
Drainage canals		2,633	do.
Streams - intermittent		13,886	do.
Drainage ditches - intermittent		3,808	do.
Shorelines (estuarine, islands, lakes, reservoirs, and ponds)		10,794	do.
Forests	29,5 17		World Almanac, 1993, p. 638
Urban areas	2,800		Estimated by League of Municipalities
Cultivated areas	16,653		land area – (surface-water bodies +forests + urban areas)
Floodplains and other mapped ground-water discharge areas	4,316		Determined by NCCGIA from the ground-water discharge map

Finally, from the standpoint of water management, it is important to note that, on one hand, drainage canals and dredged channels facilitate ground-water discharge and, on the other hand, the expansion of urban areas and the conversion of forest to cultivated land and to urban areas reduces both the size of recharge areas and the rate of ground-water recharge.

Some Quantitative Aspects of Recharge

Table 6 contains a summary of the key items of information related to recharge rates, extent of areas with different recharge rates, and total recharge. The area1 extent of the different recharge areas shown in the table are based on a 1: 1 ,OOO,OOO scale map on which the boundaries between areas with different recharge rates were drawn. The total area1 extent of all the recharge areas is estimated to be about 43,500 mi^2.

Table 6.--Summary of data on recharge **areas.**

Recharge area	*Recharge rate (gpd/sq. mi)*	*Area1 extent (sq. mi)*	*Total recharge (Mgd)*
Piedmont and Blue Ridge			
Blue Ridge and Inner Piedmont	600,000	9,429	5,657
Asheville Basin Charlotte and Raleigh Belts and related areas	400,000	6,152	2,46 1
Carolina and Eastern Slate Belts	300,000	5,792	1,738
Triassic Basins & related areas	150,000	2,192	329
Coastal Plain			
Sand Hills and sandy soils	600,000	8,789	5,273
Sandy and silty soils	400,000	3,589	1,436
Silty and clayey soils	200,000	7,557	1,5 11
Grand Total		43,500	18,405

One of the objectives in compiling the data in Table 6 was to permit the estimated Statewide total ground-water recharge to be compared to precipitation, streamflow, and evapotranspiration.

The total ground-water recharge shown in Table 6 is 18,405 Mgd which amounts to about 8.8 inches on the 43,500 mi^2 of recharge areas. It should be noted, however, that in order to compare the recharge to the other categories of data, it is necessary to pro rate the recharge over the total *land area* of 49,530 mi^2. The comparative data are shown below.

Category	*Statewide average* *(inches per year)*	*(Mgd per sq mi)*	*Percent of precipitation*
Precipitation	49	2.35	-
Streamflow	15	0.72	31
Evapotranspiration	34	1.63	69
Ground-water recharge	8	0.37	16

Because of inherent inaccuracies in the data in the above compilation, the values in inches per year are rounded to the nearest whole number. The value for precipitation was calculated from data supplied by Eugene Saunders, Office of the State Climatologist, for the current 30-year *normal* period, 196 l-1990. The value for streamflow is based on a Statewide total runoff of 35,000 mgd reported in the North Carolina Atlas (Clay and others, 1975, p. 163). The value for evapotranspiration is the difference between precipitation and streamflow.

As shown in the above compilation, ground-water recharge in North Carolina amounts to about 16% of the precipitation and to about 5 1% of the streamflow.

The preceding sections of this report deal with basic concepts related to ground-water recharge and the delineation of ground-water discharge areas, with the factors that affect recharge rates, and with the subdivision of the State into five areas on the basis of recharge rates. Ground-water recharge, as noted earlier, has been a topic generally ignored by ground-water hydrologists. This is unfortunate, both because recharge is the ultimate limit of ground water available for use and because the factors that control recharge also control pollution of the ground-water system from the land surface.

This report is the first to be devoted entirely to the subject of ground-water recharge in North Carolina. Although it helps focus attention on this important topic, it is important to note, in conclusion, that the studies now being undertaken by the State Groundwater Section and studies being conducted by other agencies should provide more accurate estimates of ground-water recharge and a better understanding of the effect on recharge of climate, vegetation, and soil characteristics.

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