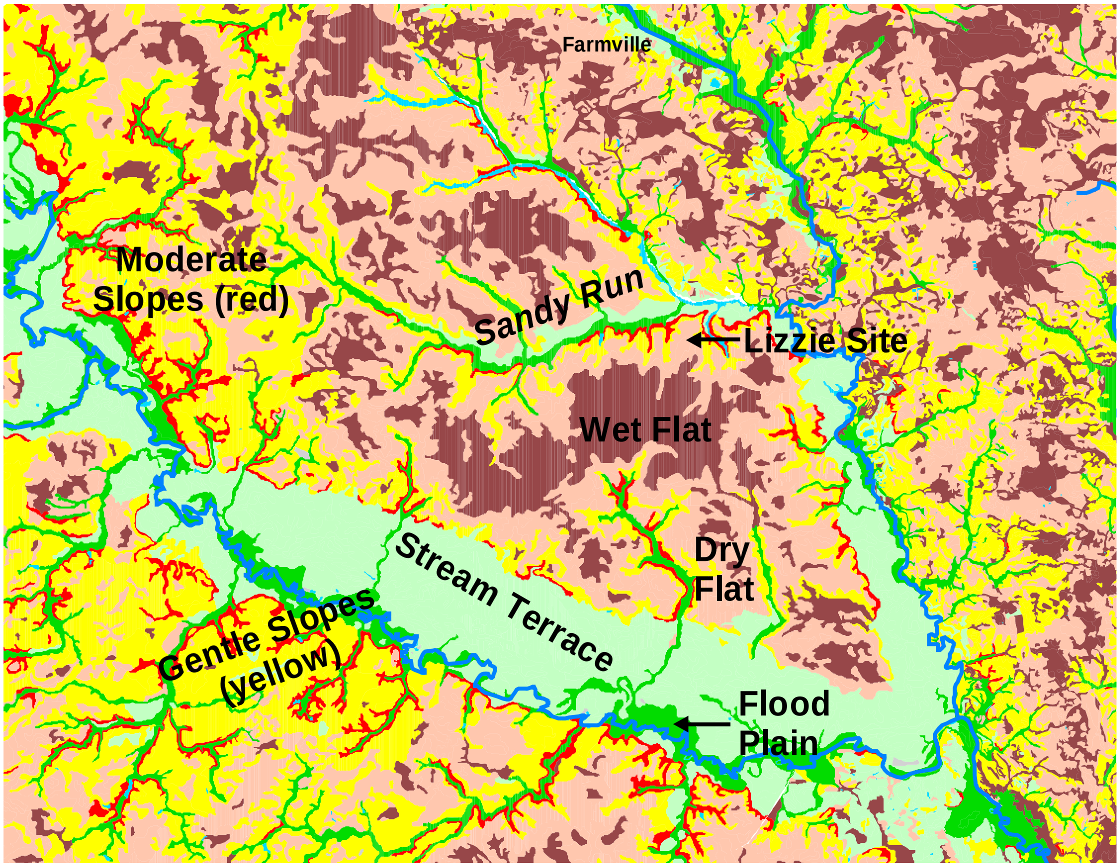
Methodology for Compiling Ground Water Recharge Maps in the Piedmont and Coastal Plain Provinces of North Carolina

Ground Water Bulletin Number 25

Internal Report



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GROUNDWATER SECTION
DIVISION OF WATER QUALITY

NONPOINT SOURCE MANAGEMENT PROGRAM
Section 319(h) of the Clean Water Act
319 GRANT

NCDENR

N.C. DEPARTMENT OF ENVIRONMENT AND NATURAL RESOURCES
RALEIGH, NORTH CAROLINA
SEPTEMBER, 2002

Methodology for Compiling Ground Water Recharge Maps in the Piedmont and Coastal Plain Provinces of North Carolina

Research to reduce nonpoint source pollution in North Carolina
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Forward

There is growing awareness that water quality problems in the Neuse River, and in North Carolina's other river basins, cannot be solved until the role of ground water in sustaining these river systems is better understood. This is the first in a series of reports by the DWQ Groundwater Section that examines the ground-water contribution to streamflow in the State's river basins. In this report we develop a methodology to map ground-water recharge in the Piedmont and Coastal Plain regions of the State.

Approximately 70 percent of the water flowing in our Coastal Plain rivers and streams originates as ground-water discharge. When rain falls across the landscape, a significant amount infiltrates into the ground, recharging the ground-water system. As this water passes through the soil zone, it accumulates nutrients and wastes that have been applied to the land. Many of these pollutants are transported through the ground-water system and are eventually discharged into nearby streams. The travel time for such pollutants to move from recharge areas to discharge areas sometimes takes decades.

The mapping methodology presented in this report focuses on the drainage basin, dividing the landscape into upland flats, valley slopes, and valley bottoms. This landscape approach to mapping provides insight into the dynamic relationship between ground-water recharge and discharge areas. It also illustrates the intricate pattern formed by the stream network as it advances into the heavily-farmed, upland-flat areas of the Coastal Plain. By developing new insights into the integral relationship between field and stream, and by quantifying the ground-water contribution to streamflow, we are focusing attention on the need for more effective management practices to better protect North Carolina's ground and surface waters.

Arthur Mouberry, P.E.
Chief, Groundwater Section

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SECTION 1

The Concept of Ground Water Recharge

PURPOSE OF REPORT

For several years the DENR-DWQ Groundwater Section has investigated ground water recharge and discharge in North Carolina. The objective of this ongoing investigation has been the compilation of regional maps showing rates of ground water recharge to the surficial aquifer, and discharge to the stream network, in different river basins. These maps integrate a ground water component into North Carolina's basinwide planning initiative by estimating the ground water contribution to streamflow at the sub-watershed scale. The purpose of this report is to describe the methodology we developed to compile these recharge maps.

OVERVIEW OF METHODOLOGY

The methodology is based on a conceptual understanding of ground water flow within a drainage basin, where water moves beneath the land surface from upland recharge areas to lower riverine areas of ground water discharge. Several factors govern the rate of ground water recharge. These include: depth to the water table; slope of the land surface; infiltration capacity of the unsaturated soil profile; regional geology; and mean rainfall. To estimate these recharge factors, and to differentiate landscape settings within the basin, detailed soil mapping units from individual county soil surveys were used to delineate *landscape units* having similar recharge characteristics. For each landscape unit, estimated ground water recharge rates were assigned. Independently, ground water discharge was calculated for selected gaged drainage areas using numerical models. These calculated discharge values were used to determine, or calibrate, recharge rates in the different landscape units. Mean rainfall rates were used to weight these recharge rates.

OUTLINE OF REPORT

The development and testing of the mapping methodology is presented in six Sections. Section 1 discusses the concept of ground water recharge and describes several methods to measure recharge. Section 2 reviews related recharge studies. Section 3 provides background on landscape classification, summarizes the methodology the USDA Natural Resources Conservation Service (NRCS) uses to map soils, and discusses the evolution of the mapping methodology presented in this report. Section 4 presents the methodology itself, describes how mapping problems were resolved, and briefly discusses the cartographic techniques used to compile the maps. Section 5 presents the stream baseflow separation methodology and how the discharge calculations were used to calibrate the recharge rates assigned to the landscape units using different model assumptions. Section six summarizes the report and discusses applicability and limitations in the methodology presented.

1.1 Ground Water Recharge Defined

SUBSECTION OUTLINE

Ground water recharge involves a complex set of interacting natural phenomena that result in highly variable recharge rates occurring over time and space. It is not the intent of this report to discuss these complexities. Rather, the report presents a methodology that can be used to estimate the average annual rates of recharge for the different landscape units found in the Coastal Plain and Piedmont regions of North Carolina, as well as other Mid-Atlantic and Southern States. In this subsection working definitions of ground water recharge and discharge areas are presented.

IMPORTANCE OF RECHARGE

Water, both on and beneath the land surface, originates as rainfall. This rain may run off the land surface into streams, infiltrate into the ground recharging the ground water system, or be lost to evaporation. Infiltrating water percolates through the ground water system and discharges into stream channels. The travel time for ground water moving through the surficial or water-table aquifer ranges from days to decades, depending on how close the infiltrating water is to the stream channel to which it discharges, and on the hydraulic properties of the aquifer. Travel time is measured in decades, centuries, and even millennia for the ground water percolating into the deeper confined aquifers of the Coastal Plain. Thus, the water flowing in streams is derived from two sources: overland runoff (including interflow between the land surface and water table) and ground water discharge. The ground water component of streamflow is termed base flow. In the Coastal Plain, base flow typically accounts for approximately 50-70 percent of the total water flowing in streams. Over the past 30 years increased nutrient loading of the State's stream networks has degraded the health of our streams. While several efforts have been initiated to control nutrient-laden runoff, we cannot effectively solve the nutrient problem until we understand the ground water contribution to streamflow, and its associated nutrient load.

FLOW PATTERNS

The movement of water through the ground water system is illustrated in Figure 1. Ground water recharge is defined in terms of the amount of water entering the saturated zone of the ground water system over some period of time. Ground water recharge is reported in units of volume, time, and area, e.g., gallons per day per square mile, or inches (cubic inches per square inch) per year. Ground water flows from topographically higher areas of recharge to lower areas of discharge along rivers and streams. In simplistic terms, one can interpret Figure 1 as the tendency of water to run downhill, or from ground water recharge areas to discharge areas. When sufficient rain falls on the upland areas, a portion of the water infiltrates into the ground, forcing the existing ground water deeper into the aquifer. However, in terms of ground water, the water generally flows, or is transmitted laterally much more easily than it can move vertically, due to the more restrictive properties of different sediment or rock layers. What this means is that ground water flows from recharge areas to riverine discharge areas, as illustrated in the figure.

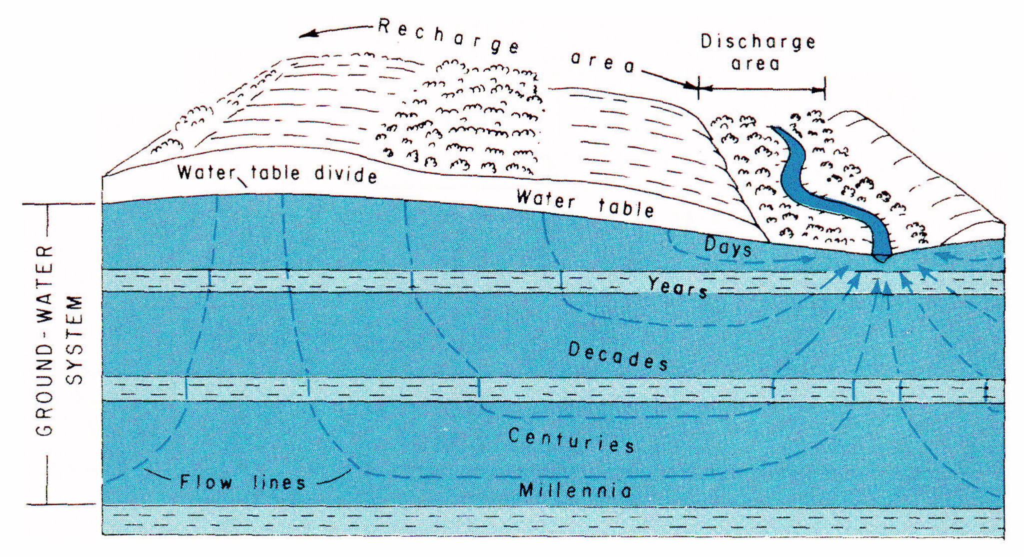


Figure 1. Idealized ground water flow pattern from recharge area to discharge area in a typical Coastal Plain landscape (Heath, 1983).

RECHARGE AREA DEFINED

Within a watershed the primary areas of ground water recharge occur on the interstream uplands where the direction of ground water flow is downward. According to Freeze and Cherry (1979, p. 194):

> *A recharge area can be defined as that portion of the drainage basin in which the net saturated flow of ground water is directed away from the water table.*

DISCHARGE AREA DEFINED

Primary discharge areas within a watershed occur along rivers and streams where the direction of ground water flow is upward. The Freeze and Cherry (1979, p. 194) definition of a discharge area states:

> *A discharge area can be defined as that portion of the drainage basin in which the net saturated flow of ground water is directed toward the water table.*

GENERALIZATIONS

Given the relationship between recharge and discharge areas, several generalizations can be made. First, rainfall may reach the water table anywhere by infiltration through pervious soil. However, it is in the upland recharge areas that the percolating water moves downward deep into the ground water system. Second, in discharge areas ground water is flowing towards the surface and may escape as a spring, seep, base-flow seepage to streams, or by evaporation and transpiration. Third, Figure 1 presents an idealized concept of a ground water system. In most watersheds conditions are more complex, with localized areas of recharge and discharge influenced by varying topography and changing aquifer properties. Nonetheless, with respect to the methodology presented in Section 4, the concepts illustrated in Figure 1 represent a sufficient foundation for mapping ground water recharge on a regional scale.

1.2 Factors Controlling Recharge Rates

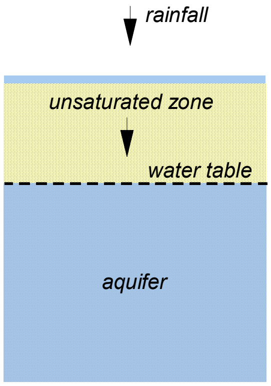
CONTROLLING FACTORS

Factors controlling the rate of ground water recharge include: depth to the water table; slope of the land surface; and the infiltration capacity of the soil profile. These factors are illustrated in the following paragraphs and are used in Section 4 to group soil mapping units into landscape units.

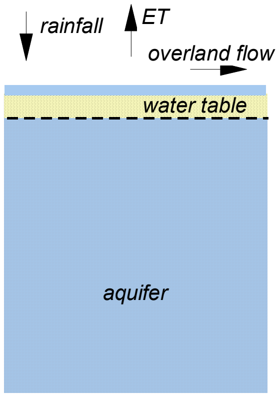
DEPTH TO WATER TABLE

The depth to the water table determines, in part, the amount of storage available in the unsaturated zone. If the water table is lower, then there is a larger storage capacity within the unsaturated zone, allowing the water table to rise as infiltrating water moves into the saturated zone. If the water table remains high over several months, water may pond on the surface and is lost to evapotranspiration (ET) or overland flow, reducing the water available to recharge the aquifer.

Lower Water Table



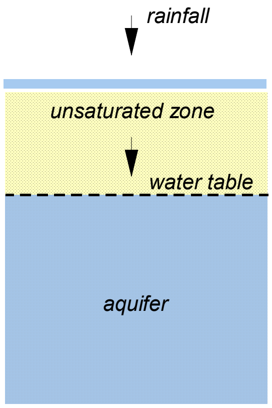
Higher Water Table



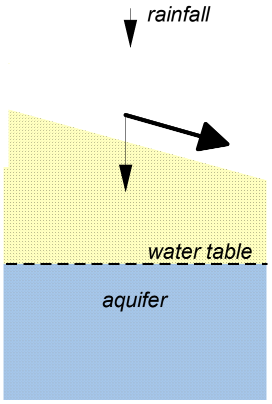
SLOPE OF THE LAND

The general slope of the land surface also influences the amount of water available to recharge the aquifer. As the land-surface slope increases, more water runs off, leaving less water available for recharge

Flat Surface

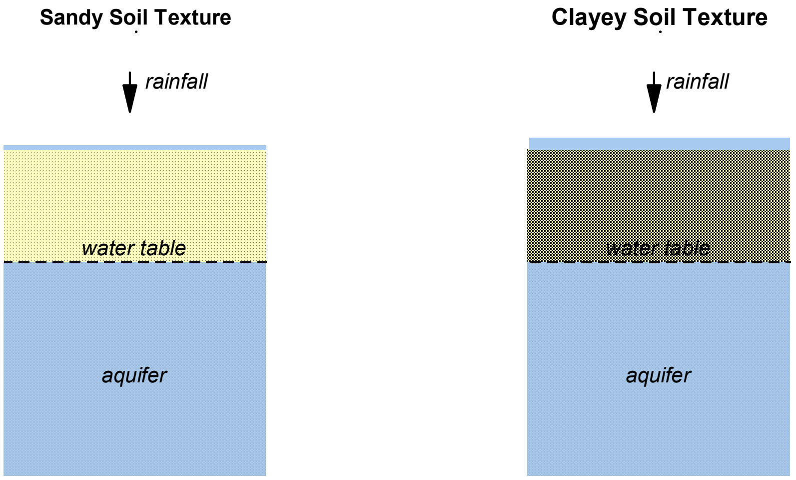


Slope Runoff



INFILTRATION CAPACITY

The infiltration capacity of the unsaturated soil profile is the third factor influencing ground water recharge. This factor is related to soil texture. A sandy-textured soil will percolate water at a higher rate than a more clayey soil.



OTHER FACTORS

These three recharge factors, and regional geology, are used to differentiate the drainage-basin landscape into landscape units having similar recharge characteristics. Other factors, such as land cover, preferential ground water flow paths, and soil moisture characteristics may be important in refining recharge estimates at a local scale, but these factors have proved adequate in developing our regional-scale recharge estimates.

EFFECTS OF LAND COVER

Land cover plays an important role in ground water recharge. At the extreme, no recharge takes place beneath an impermeable cover, such as a large, paved parking lot or central business district of an urban area. Heath (1994), citing the work of Kays (1979), determined that the relative recharge rate of an undisturbed forest was 62 times greater than a highly disturbed and compacted lawn. Using this compacted-lawn scale, the recharge rate for slightly disturbed woodlands was 22 times greater and former farmland 9.5 times greater. An early study of infiltration into the forest floor found that infiltration rates on fairly heavily grazed unimproved pasture were 59 percent lower than rates on similar soil types under hardwood stands protected from fire and grazing. When upland hardwood stands were annually burned, infiltration rates were reduced by 38 percent. When the hardwood litter was removed, infiltration rates were reduced 18 percent (Arend 1941). A Hawaiian study found that infiltration rates were higher for soils under forest cover than soils planted to sugarcane, pineapple, or used for pasture (Wood 1977). Section 3 discusses our early efforts to include land cover into the discharge mapping methodology. However, at the sub-watershed scale we have found that adequate recharge estimates can be made without incorporating land cover information.

1.3 Methods to Estimate Ground Water Recharge

OVERVIEW

Various physical, chemical, and radioactive isotope techniques are available for estimating ground water recharge (Rushton and Ward 1979, Allison 1988, Simmers 1988, and Sharma 1989). The following paragraphs provide a brief overview of the more common methods used to measure ground water recharge.

WATER BALANCE METHOD

The conventional method of estimating recharge using the water balance can be represented mathematically as:

$$\Delta S = P - R - E$$

where: ΔS is the increase in stored water (recharge); P is precipitation; R is runoff over the catchment; and E is the actual evaporation. Evaporation information is obtained either from direct measurement from open water evaporation pans, or calculated from meteorological data.

DIRECT MEASUREMENT

In the direct method recharge is typically measured using a lysimeter, or large-diameter cylinder carefully placed in the ground so as not to disturb the enclosed soil. Meteorological conditions, soil moisture, and the water level within the lysimeter are then periodically measured to determine the amount of water recharging ground water.

TRACER STUDIES

A variety of natural radioactive and chemical tracers are used to measure the movement of water through the subsurface area. By noting changes in concentration with depth, some estimates of the volume of water recharging the aquifer over set periods of time can be made.

HYDROGRAPH ANALYSIS

Well hydrographs showing water-table fluctuations over a period of a year can be used to calculate the net amount of water-table rise. If the porosity of the aquifer material is known, an estimate of water entering the saturated zone and raising the water table during the time period can be made.

STREAM FLOW SEPARATION

Water flowing in a stream originates either from surface runoff or ground water discharge. Techniques are available for separating the streamflow hydrograph runoff peak from the underlying baseflow, or ground water discharge component. This technique is discussed more fully in Section 5.

SUMMARY OF METHODS

None of these methods offer a precise means to determine ground water recharge. Using the water balance, evaporation and runoff are difficult to measure except in localized areas. Direct measurements and well hydrograph analyses are expensive and not necessarily representative of the surrounding area. Tracer studies lack precision, and preferred pathways may skew the migration of the tracer. Streamflow separation techniques are dependent on the availability of long-term monitoring data from stream gaging stations. In summary, the recharge estimating method selected depends on the objectives of the study. Our choice of the stream-flow separation method was determined in part by the availability of long-term streamflow records and the regional scale at which we are working

SECTION 2

Review of Related Studies

INTRODUCTION

This section briefly reviews regional ground water recharge and discharge studies conducted in New Jersey, Virginia, and North Carolina. These studies offer insight into how other States and agencies in the region have approached recharge estimation.

2.1 New Jersey Recharge Study

SUMMARY OF STUDY

One of the most comprehensive methodologies for estimating ground water recharge was developed for the State of New Jersey (Charles et al. 1993). This methodology is an outgrowth of the water balance method for estimating recharge and uses stream base flow estimates to calibrate recharge estimates. The method provides municipal planners with ground water recharge maps to support planning decisions. The foundation for this method is a series of relationships developed by the authors to relate recharge to local climate, soil type, land use/land cover and basin characteristics. To develop these relations the researchers used soil-water budgets, based on a monthly water-budget approach, to simulate recharge for all combinations of soils, land use/land cover, and climate, based on the equation:

recharge = precipitation – surface runoff – evapotranspiration – soil moisture deficit.

RESULTS OF ANALYSIS

The results of these analyses showed that estimates of long-term recharge could be made using factors representing the variables analyzed. These factors were assembled into tables keyed to the different soil, land use/land cover, and climate types found in the State. Using this method local planners can prepare recharge maps by dividing any particular area of study into a set of parcels using county soil surveys and land use/land cover categories developed by the researchers. For each parcel recharge can be calculated using the formula:

recharge = (recharge-factor **x** *climate-factor* **x** *basin-factor) – recharge constant.*

Each of the factors and constant is read from the appropriate table provided in the study report. In this method no recharge rates are assigned to surface water bodies, wetlands, nor hydric soils.

COMMENT ON METHOD

The salient question relative to this study is whether the generalized methods used to develop recharge estimates warrant the detailed development of precise factor tables and detailed land use/land cover measurements.

2.2 Virginia Discharge Study

SUMMARY OF STUDY

A USGS study of ground water discharge in the Coastal Plain of Virginia (Richardson 1994) used two approaches to estimate average annual discharge: (1) streamflow hydrograph separation at 16 gaged watersheds; and (2) a hydrogeologic area approach. In the hydrogeologic area approach areas with similar hydrogeologic characteristics were grouped together, and multiple-regression techniques used to determine the relation between these areas and ground water discharge. Data used to establish the hydrogeologic areas included: surficial geology; forest cover; soil-hydrology class; soil drainage; soil texture; and slope. Two categories of surficial geology were considered: (1) predominate uplands located above the 80-foot mean sea-level contour; and (2) predominate lowlands, located below 80 feet. Six resulting hydrogeologic areas were identified by Richardson in the Coastal Plain of Virginia: (1) well-drained uplands; (2) moderately well-drained uplands; (3) poorly drained uplands; (4) well-drained lowlands; (5) moderately well-drained lowlands; and (6) poorly drained lowlands. The results from the base-flow separation analysis at the 16 gaged stations estimated ground water discharge from 7.5 to 12.5 inches per year. Applying the hydrogeologic area methodology, ground water discharge in the Virginia Coastal Plain was estimated to range from 7.9 to 11.1 inches per year, with an overall average of 9.9 inches.

COMMENT ON METHOD

The Virginia study is similar to the one presented in this report, with the same base flow separation model used to estimate ground water discharge, and a methodology developed to classify the landscape into hydrogeologic areas. The fundamental differences between the studies lie in differentiating uplands from lowlands based on a single topographic contour, and in using the NRCS STATSCO database as a tool to identify soil properties. STATSCO maps are generalized soils maps compiled on a statewide basis at a 1:250,000 scale, with mapping units representing aggregate groups of up to 21 different soil series having similar properties. Most people who interpret soil properties from a STATSCO map derive a weighted average of a particular property from all the soils grouped within the STATSCO unit. The implicit assumption underlying the weighted average calculation is that all soils represented in a given STATSCO unit are distributed both evenly and proportionately throughout the unit.

NAMING CONVENTION

Although our study methodology evolved independently from the Virginia work, as an afterthought we initially decided to adopt the same term, “hydrogeologic areas,” to describe our landscape classification units. Our reasoning is that the science of relating ground water flow and transport to geomorphic settings is in its infancy, and much research still needs to be done before a defensible classification scheme is established. The term *hydrogeologic area* is descriptive, yet generalized enough to transitionally serve in a variety of studies. Several different researchers have used the term, “hydrogeomorphic unit.” However, in our final analysis, we opted for the more descriptive term “landscape unit.”

2.3 North Carolina Modeling Study

NORTH CAROLINA STUDY

In North Carolina the USGS developed a numerical model to simulate ground water flow in the Coastal Plain aquifer system (Giese, Eimers, and Cable 1991). As part of this modeling effort a ground water recharge map was developed to estimate recharge from precipitation to the surficial aquifer. This recharge map was modified from an earlier USGS report presenting a map of infiltration capacities of soils in the North Carolina Coastal Plain (Winner and Coble 1989, 1996). This earlier map, in turn, was compiled from information presented on a 1974 general soil map of North Carolina, published at a scale of 1:1,000,000 (Tant, Byrd, and Horton 1974). Winner and Coble compiled the infiltration capacities map by grouping soil associations having similar characteristics of drainage, sand-clay content, and permeability. In developing their ground water recharge map for model input, Giese, Eimers, and Coble assigned recharge rates of 12, 14, 16, or 20 inches per year to each node in their model grid. Assignment of recharge rates was based on: (1) soil characteristics from the 1974 general soils map; (2) recharge estimates to thick sandy soils by Heath (1980); and (3) estimates of baseflow to North Carolina streams (Wilder and Simmons 1982). This recharge map showed maximum recharge rates of 20 inches per year in the Sand Hills area of the State, and lowest rates in the lower Coastal Plain near the sounds where surficial soils have a high clay content. Numerical modeling results showed that most of the ground water recharge moved laterally, discharging to streams.

GENERALIZED WATER BUDGET

Giese, Eimers, and Coble (1991) also present in their report a generalized water budget for a typical location in the North Carolina Coastal Plain, assuming an annual average precipitation of 50 inches a year. This budget was modified from a water budget developed for northeastern North Carolina by Wilder, Robison and Lindskov (1978). Ground water recharge in this budget is estimated at 12 inches per year, with 11 of the 12 inches seeping to streams, while the remaining inch recharges lower aquifers. Overland flow to streams is estimated at 5 inches in the budget. Thus, this water budget allocates 16 of the 50 inches of rainfall to streams, with 11 of the 16 inches (~ 70 percent) being ground water discharge.

COMMENT ON METHOD

The Giese, Eimers, and Coble (1991) study represents one of the first efforts in North Carolina to use regional scale ground water modeling to quantitatively relate recharge from precipitation to ground water discharge to streams, and to recharge of the lower aquifers. In terms of recharge estimation, however, the regional scale of the model and generalized source of soils information effect model precision. Cell dimensions used in the model's finite difference grid ranged from 3.5 miles to 7.5 miles on a side, obscuring the finer ground water flow patterns surrounding the surficial stream and terrace network. ground water recharge was not a calibration variable in the model, as the model focus was on confined aquifers, and the model was not particularly sensitive to changes in recharge. There was also a feeling among some at the time that applied recharge rates may have been a little high (Jerry Giese, personal communication 1998).

2.4 Other Studies Providing Information on Ground Water Recharge

BASEFLOW SEPARATION

Harned and Davenport (1990) used the Rorabaugh streamflow separation method to estimate the ground water contribution to streamflow for the Neuse, Tar, and Roanoke rivers, as part of the Albemarle-Pamlico Estuarine Study (APES). At the Kinston station on the Neuse River they estimated ground water discharge at 70 percent of streamflow; at Tarboro on the Tar River discharge was estimated at 60 percent of streamflow, and at Roanoke Rapids on the Roanoke River (prior to reservoir regulation) discharge was 57 percent of streamflow. Overall, Harned and Davenport (1990) estimated average ground water discharge at 62 percent of total stream flow, with a range from 42 to 76 percent. McMahon and Lloyd (1995) used the Pettyjohn and Henning method to analyze 42 drainage areas in the Albermarle-Pamlico drainage basin, estimating ground water discharges in the range of 45 to 64 percent of streamflow. During a study of stream water quality, Wilder and Simmons (1982) used hydrograph separation techniques to separate ground water discharge from overland flow in selected stream basins in North Carolina. In this statewide study ground water discharge ranged from 31 to 73 percent of streamflow.

LOW-FLOW CHARACTERISTICS

Giese and Mason (1991), in a study of low-flow characteristics of North Carolina streams, observed that in the Coastal Plain:

> *The lower values for low-flow characteristics for clay soils as compared to sandy soils . . . result partly from the fact that a higher percentage of precipitation that falls on clay soils is rejected as recharge due to the low permeability of the clay and runs off directly to streams. Additionally, clay soils have much lower hydraulic conductivity than do sandy soils and, thus, contribute less water to base flow of streams than do sandy soils.*

STATEWIDE RECHARGE MAP

Heath (1991), as part of a wellhead protection applications manual, prepared a generalized, statewide, ground water recharge map of North Carolina based on broad geologic regions and differentiating coarse and fine-textured soils in the Coastal Plain region. Heath (1993) also prepared a 1:500,000-scale map of the principal ground water discharge areas in North Carolina based on features shown on USGS topographic maps at various scales. Features included streams and other surface-water features, marshes and swamps, land-surface contours, and woodland. The methodology used to prepare the discharge map is described more fully in (Heath 1994).

OTHER STUDIES

Liddle (1993) presents a good overview of other studies providing ground water recharge information, as part of a report on ground water discharge for the Albemarle-Pamlico Estuarine Study. The following Section examines the relationship between landscape and soils—the building blocks of our recharge methodology.

SECTION 3

Landscape and Soils

INTRODUCTION

To develop ground water recharge maps for the different river basins in North Carolina, we divided the basin landscape into a set of recharge units called *landscape units*. Section 3 reviews the historical foundation for landscape classification, and establishes a rationale for our landscape classification scheme. We introduce the ideas underlying landscape classification and their importance and utility in better understanding the movement of water and transport of pollutants through the basin. Since the underlying mapping units for the recharge maps are based on detailed county soils maps, we briefly review the methods used by the U. S. Department of Agriculture to develop these maps. Section 3 closes with an overview of our initial efforts to develop a recharge mapping methodology.

3.1 Landscape Classification Schemes

DRAINAGE BASIN CONCEPT

If the quality of North Carolina's Coastal Plain streams and ground waters is to be protected, better management of nonpoint sources of pollution is required. The key to protection lies in better understanding the *pathways* traveled by pollutants as they move from the land to the stream, or from source to sink. These pollutant pathways include: (1) *overland flow* from fields to streams; (2) *interflow* beneath the land surface through the unsaturated zone; and (3) *ground water flow* where water infiltrates into the ground, percolates across the water table into the surficial aquifer, and moves through the ground water system, discharging to streams. What is important to realize is that all of these pathways are enclosed within a drainage basin (Huggett 1975). This basin is a three-dimensional entity possessing a landscape that can be characterized in terms of landforms, such as upland flats, valley slopes, and valley or riverine bottom lands.

THE ROLE OF VALLEY SLOPES

The movement of water, pollutants, and sediments within the drainage basin is largely governed by the geometric configuration of the valley slope. Convex and concave topographic contour patterns influence the diverging and converging of flowlines. The major factors controlling water movement are soil and vegetation properties, topographic characteristics, and the underlying hydrogeology of the basin. The drainage basin thus provides a convenient topographic unit that can be subdivided by stream order. This enables us to establish a nested hierarchy of both valley slopes and stream catchments. (Gerrard 1981)

FLATS, SLOPES, AND BOTTOMS

Ruhe (1956) introduced the idea of common elements within the landscape, and Curtis, Doornkamp, and Gregory (1965) state that these elements consist basically of "flats" and "slopes" that may intersect at angles characteristic of physioclimatic areas. Using these flat and slope elements England and Holtan (1969) divided a Nebraska watershed into three landscape morphological units: (1) relatively uneroded upland soils; (2) the more severely eroded hillside soils; and (3) depositional bottom-land soils occurring on footslopes or along stream channels. These morphological units, which were called "hydrologic response units," form a landform sequence in a catchment of flat or convex uplands, rectilinear hillside slopes, and flat or concave lowlands. This elevation sequence differentiates soils of similar hydrological properties based on breaks and changes in slope.

HYDROLOGIC RESPONSE UNITS

England and Holtan (1969) proposed that the interaction between landform, soil type, native vegetation, microclimate, and land use can be used to group soil-land-use areas by hydrologic capacities. These hydrologic capacities represent the average paths of overland and subsurface flows. They conclude that the spatial distribution of soils and land-use areas having different hydrologic properties affects the magnitude and sequence of watershed processes, and that this recognition is critical to the proper functioning of mathematical models simulating the hydrologic response of watersheds.

IDENTIFICATION CRITERIA

Several criteria have been proposed in the literature to classify and differentiate landscape units. Gerrard (1981) cites the *IGU Manual of Detailed Geomorphological Mapping* (Demek 1972) for suggesting the following standard slope categories: 0°–2°, 2°–5°, 5°–15°, 15°–35°, 35°–55°, and 55° and above. He also points out that river-formed landscapes are similar the world over, in terms of both landforms and processes. Soils may not be identical, but the natural landforms and soil patterns are similar. Terraces are abandoned surfaces not related to the present stream, but composed of sediments laid down during a period of aggradation, and sometimes separated from the floodplain by a scarp.

THE ROLE OF SOILS

Within the drainage basin soils act as both potential regulators of water movement and as providers of a water-storage capacity. Soils do not exist in isolation, but are organized within the landscape, with particular soil sequences associated with particular slope forms. These types of relationships constitute the field of soils geomorphology, where a large body of research on slopes, landforms, and soil sequences exists, e.g., Daniels and Hammer (1992). In North Carolina the pioneering work of Daniels et al. (1984) provides an excellent overview of soil geomorphology throughout the State by geologic region. It is not the intent of this report to extend that research, but rather to utilize pertinent findings as the basis for developing ground water recharge maps. The building blocks for these maps are the individual soil mapping units drawn on county soil surveys. The following section provides an overview of the methodology used by the USDA Natural Resources Conservation Service (NRCS) to delineate these mapping units.

3.2 NRCS Soil Mapping Methodology

DEFINITION OF SOILS

Soils, in the context of this report, are mappable units on the land surface, that when interpreted correctly, can yield significant information relating landscape, surficial geology, and hydrology. In soil-science terms, soil formation is the product of flora and fauna acting on the weathered geologic deposits at the earth's surface. The interaction of physical, biochemical, and hydrologic processes produces the wide range of distinctive soil properties and characteristics. All soil classification and mapping is based on the USDA NRCS *Keys to Soils Taxonomy*, a modern soil classification scheme first published in 1975. County soil surveys published by the NRCS provide a wealth of information on the properties, characteristics, and areal distribution of soils found within a county.

HOW SOILS ARE MAPPED

Soils are classified and mapped on the basis of what can be observed and measured within the soil profile. Additional information, such as the origin of the parent materials, specific landscape position, whether or not human disturbance might have changed the profile, while important, does not affect how a given soil is classified. Soils are classified in order of increasing similarity by order, suborder, great-group, subgroup, family, and finally series. At the order level, soils are classified according to those properties which most affect their management. At the series level, the actual differences between soils can be slight. In terms of our recharge mapping project, differences between individual soil series with the same taxonomy are insignificant. Soils are identified in the field according to the specific qualifications of each taxa. Specific taxa requirements are very detailed, encompass a wide range of properties, and vary by soil type.

FIELD MAPPING

In practice, the soil mapper first identifies an area on the landscape having a common slope. After numerous shallow auger examinations, he or she determines whether this area should be divided into two or more mapping units. This decision takes into account numerous factors, including differences in profile characteristics and unit size. The minimum mapping unit size is dictated by the final published map scale. To name the soil mapping unit, the mapper evaluates the auger samples and determines the predominant soil and taxonomy, following the *Keys to Soil Taxonomy*. The *Keys* is a field guide used to identify and classify soils by a process of elimination. Finally, the mapping unit is named for the soil series which most closely matches the predominant soil type.

3.3 Evolution of Our Mapping Methodology

OUTLINE OF SUB-SECTION

The following paragraphs trace the development of our mapping methodology, detailing the approaches that were investigated before finalizing on the current techniques. We believe the simplicity of the methodology presented in Section 4 has merit and supports the notion of landscape units.

INITIAL DIRECTIONS

Beginning with the Groundwater Section's first mapping efforts, the intent of the recharge project has been to utilize the newly created digital soils coverages as a surrogate to map ground water recharge across the State. We also planned to use land-cover as a weighting factor for estimated recharge rates (NC Center for Geographic Information and Analysis 1994). However, the land-cover coverage that was available at the time of our analysis was predominately focused on types of vegetation, including ten forest cover types, but mapped most urban and residential areas as "unmapped municipal area." Also, few forested areas in the Coastal Plain would be considered undisturbed, in terms of recharge potential, since trees are frequently harvested and the land surface compacted during harvesting operations. In addition, most forested areas in the Coastal Plain occur in areas unsuitable for farming, primarily upland wet flats and flood plains. Since both wet flats and flood plains are mapped as distinct landscape units, account has been indirectly taken of forested areas in the methodology. After investigating several ways to employ the land cover data, this effort was abandoned, and the project concentrated on interpreting the detailed soils coverages.

EARLY MAPPINGS

Our initial mapping effort using soil surveys divided the landscape into upland, terrace, and floodplain units, and further differentiated these units by texture into areas of sand and loam, clay, and organics. The resulting maps, plotted for the central Coastal Plain, did not sufficiently delineate the landscape into meaningful areas of ground water recharge and discharge.

COMPREHENSIVE MAPPING

The second mapping iteration set an objective of identifying areas having similar recharge or discharge characteristics. To do this several soil properties were evaluated to determine their effectiveness in delineating distinct recharge and discharge areas. The soil properties investigated included: texture of control section, drainage class, permeability, hydrologic group, landscape position, slope gradient (surface slope range), and whether the soils were hydric or erodible. In conducting this investigation, it became apparent that several of these properties were highly correlated. Our final mapping methodology evolved by eliminating redundant soil properties, as discussed in the following section.

SECTION 4

Methodology Used to Compile Recharge Maps

FOUNDATION OF METHOD

The foundation of our methodology to differentiate landscape units having similar recharge characteristics rests on: (1) a fundamental understanding of ground water flow, from upland recharge areas to low-lying discharge areas along streams; and (2) factors controlling the infiltration of water into the ground water system.

APPROACHES TO MAPPING

Section 2 outlined two approaches to mapping areas with similar recharge characteristics: specific and generalized. The New Jersey mapping used aerial photographs to measure specific conditions on the ground at some selected point in time. Heath's recharge and discharge maps for North Carolina presented a more regional approach, using surrogate mapping to approximate areas having similar recharge and discharge characteristics. His statewide recharge map is based primarily on the North Carolina Geologic Map at a 1:500,000 scale, and a 1974 soils map differentiating soil texture at a 1:1,000,000 scale.

PROBLEMS IN APPROACHES

Three major problems are associated with these approaches: time, scale, and investment. The extensive mapping effort in New Jersey is estimated to take ten years (Hoffman, 1998, personal communications), and the costs of this effort are expected to be high. Also, over a ten-year period land uses will change, necessitating continuing updating of the recharge maps. The cost of implementing such a method in North Carolina would be significant, since New Jersey is less than a fifth the size of North Carolina. The problem with existing recharge maps in North Carolina is that the scale is so small that defensible estimates of ground water discharge into the State's river basins and subbasins cannot be effectively made.

NORTH CAROLINA CONSIDERATIONS

One of the major water quality problems facing North Carolina is nutrient enrichment of the State's waterways, particularly in estuarine areas. To help solve this problem, we need better information on the ground water contribution to stream flow. Estimates of ground water discharge to the stream system are needed at a regional scale, within a short time frame, and at reasonable cost. Such estimates need not be site specific, but rather generalized at the subbasin and sub-watershed level. In investigating alternative means to develop such estimates, we determined that the detailed soils maps found in county soil surveys offered the best available surrogate mapping upon which to develop ground water recharge maps.

SOIL MAP AVAILABILITY

Modern soil surveys have been published for about three quarters of North Carolina's 100 counties, and 74 of these surveys are available in digital format in the Arc/Info geographic information system (GIS) through the North Carolina Center for Geographic Information and Analysis. These Arc/Info coverages represent the building blocks for delineating landscape units.

RECHARGE FACTORS AND SOIL PROPERTIES

As previously discussed, there is a relationship between ground water-recharge factors and the properties of soil mapping units that can be used to develop recharge maps. The recharge factors considered in our methodology include: depth to water (available storage); slope of the land; and infiltration capacity of the unsaturated soil profile. Corresponding properties of soil mapping units include: drainage class, slope gradient; and texture. The soil drainage class property is a good indicator of water-table depth and can be used to estimate available water storage capacity in the unsaturated zone. The slope gradient property designates the predominate percent grades in the mapping unit and can be used as a general indicator of the land-surface slope. Soil texture reflects the grain-size distribution of the soil, and is a good initial indicator of the infiltration capacity or recharge potential for a particular soil. Also, county soil surveys contain descriptions of the landscape position(s) where each soil mapping unit is most commonly mapped. These descriptions allowed us to identify stream terrace and floodplain soils.

SOIL PROPERTIES AND TAXONOMY

In selecting which soil properties to incorporate into the mapping methodology, we chose only those properties actually measured in the field. Other properties assigned to a soil series are based on an analysis of soil samples collected at specific reference sites. Soil identification in the field is based on the properties (including texture) of diagnostic soil horizons observed at representative locations across the mapping unit. Soil drainage class is determined principally by observing the redoximorphic features or iron oxides present within the soil profile. Slope gradient is also a mapping unit property observed in the field. All of these observations are used to determine the appropriate taxonomy and assign the name of the predominant soil series to the soil unit being mapped. Once the mapped unit has been properly named, a variety of other generic properties are then assigned, based on the predominant soil series.

OUTLINE OF SECTION

The following subsections discuss how we identified landscape units and resolved various mapping problems, including stream terrace delineation and county edge matching of landscape units. We also discuss GIS procedures and techniques utilized in developing recharge maps.

4.1 Identifying Landscape Units

LANDSCAPE SETTINGS

In Section 3 we discussed landscape classification and our early attempts to map landscape settings. In our final version of the methodology, the landscape is divided into three settings:

- Upland flats;
- Valley slopes; and
- Valley bottoms.

This differentiation is based on land-surface slope and predominant landscape position of the soil mapping unit, and is similar to the technique employed by England and Holtan (1969). The distinction also provides an approximation of upland ground water recharge areas, transitional hillslope areas, and riverine discharge areas.

UPLAND FLATS

Upland flats are the nearly flat, dominantly depositional or constructional surfaces of 0 to 2 percent slope found on the broad interstream divides and interfluves in the Coastal Plain region. These areas are divided into wet flats and dry flats, based on the drainage class of the soil. Within wet-flat areas organic soils are differentiated from mineral soils.

VALLEY SLOPES

Valley slopes are a transitional landscape setting separating the flat uplands from the riverine terraces and floodplains comprising valley bottoms. This definition of valley slope follows that of Daniels et al. (1984). Valley slopes are divided into gently, moderately, steeply, and very steeply sloping areas. These slopes were formed as a response to the headward advancement and meandering of streams that incise and downcut the land surface. Within some areas of the lower Coastal Plain significant stream dissection of the land surface has not occurred and no valley slopes exist between upland and riverine areas. In the older Piedmont province, valley slopes are the dominant landforms. The significance of the valley slope landscape setting is that, to a great extent, the slope geometry controls the primary flow and pollutant pathways between field and stream.

VALLEY BOTTOMS

Valley bottoms, or riverine landforms, include floodplain and stream terrace areas. The soil mapping units found in these areas are usually described in county soil surveys as “mapped on” flood plains or stream terraces.

LANDSCAPE UNIT CRITERIA

The criteria used for combining soil mapping units into landscape units are listed in Table 1. Appendix A provides a detailed description for each of the soil properties mentioned in the table. Following this table each of the landscape units is described in more detail. Figure 2, on the following page, illustrates the relation between landscape settings and landscape units. This example shows the area surrounding the Groundwater Section’s Lizzie Research Station 12 miles west of Greenville, North Carolina.

Table 1. Criteria Used to Combine Soil Mapping Units into Landscape Units

Landscape unit	*Slope gradient–%*	*Drainage class*	*Soil texture*
Upland Flats (Coastal Plain)			
wet flats	0 – 2	poorly to very poorly	●
organic	●	●	organic
mineral	●	●	all other
dry flats	0 – 2	somewhat poorly to excessively	●
Valley Slopes			
gentle slopes	2 – 6*	●	●
moderate slopes	5 – 15*	●	●
steep slopes	15 – 25	●	●
very steep slopes	25+	●	●
Valley Bottoms (defined in county soil survey)			
stream terraces	●	●	●
floodplains	●	●	●

* *Slope ranges typically overlap in county soil surveys.*

UPLAND WET FLATS

Upland wet flats are poorly to very-poorly drained flat upland areas found generally on interstream divides. Locally these areas are sometimes referred to as “pocosins.” They remain wet for long periods of the year because the stream network has not yet advanced headward enough to effectively drain them. Unless these areas have been drained for farming or recently timbered, they are usually forested. Wet flat areas are subdivided into organic flats and mineral flats.

ORGANIC WET FLATS

Organic wet flats occur in the Lower Coastal Plain, predominantly on the Pamlico marine terrace to the east of the Suffolk scarp. Other large accumulations are found on the Talbot terrace, particularly in the Croatan National Forest. These organic flats have shallow water tables and little storage in the unsaturated zone available for ground water recharge. We identified organic wet flats solely by the presence of upland organic soils. Organic soils may also be found in floodplains, but in our methodology these organics have been included as part of the floodplains landscape unit.

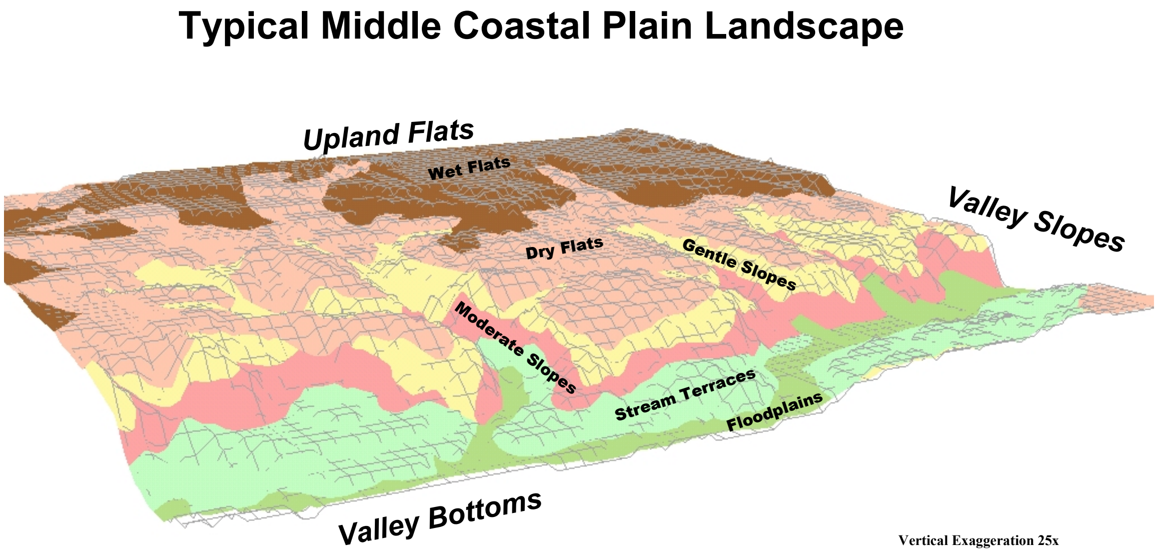


Figure 2. Relation between landscape setting and landscape units Lizzie Research Station, Greene County, NC.

MINERAL WET FLATS

Mineral wet flats are found both adjacent to organic flats and on the higher marine terraces where organic soils are not abundant. The water table in wet flat areas may be near land surface for several months during the year. Like the organic flats, broad mineral wet-flat areas may contain man-made drainage networks that have lowered the water table. In the lower Coastal Plain many mineral wet flats were once organic flats before the land was drained.

DRY FLATS

In the upland flats landscape setting, dry flats occur adjacent to and as a fringe around the wet flats, usually along an interfluve in the Coastal Plain. These flats are drier than the wet flats for several reasons. First, they usually contain headwaters of ephemeral and intermittent streams which lower the water table. Second, the slope of the land surface in these areas has increased slightly, increasing runoff. Third, because of the better drainage in the dry flats, the water table remains several feet below land surface for a good portion of the year.

TEXTURAL DIFFERENCES

With the increased average depth to the water table in the dry flats, textural differences within the soil profiles can potentially have a significant effect on rates of recharge. Thus, we subdivided the dry flats into coarse and fine textural classes. Coarse textured units include all those soils in which the predominant texture of the control section is sandy to loamy. Fine textured units include those soils where the texture is finer than loamy. The reason for this distinction is that the infiltration rate through the more permeable coarse-textured soil is can be considerably higher than through the fine-textured materials. Appendix A contains more detailed information about soil textural classes.

VALLEY SLOPES, OVERVIEW

Ground water recharge on valley slopes varies significantly, depending on the degree of slope. Runoff is greater on steeper slopes, thus leaving less water available to infiltrate into the ground. Valley slopes are divided into four landscape units with similar recharge rates based on slope-gradient groups.

GENTLE SLOPES

Wet and dry flats exist because these areas are relatively undissected by stream channels. As one moves toward the stream channel, the land-surface slope increases to 2 to 6 percent. These gentle slopes may form the shoulder of a more significant valley slope, or may extend to the stream terrace in areas with little relief. Where relief is minor, the dry flats may extend to the stream terrace with no intervening gentle slopes. The water table in gently sloping areas usually remains well below land surface for most of the year. Recharge in these areas may be somewhat limited due to the increased soil moisture demands of a thicker unsaturated zone. Gently sloping landscape units are also subdivided into coarse and fine textured units in the Coastal Plain, similar to dry flats. In the older Piedmont physiographic province, stream dissection of the ancient land surface has long ago eroded most upland flat areas. Thus, in the Piedmont and Mountain provinces, we do not use the upland flats setting, but instead classify all upland flat areas as gentle slopes. Also, all Piedmont and Mountain soils are considered to be fine textured.

MODERATE SLOPES

Valley slopes between 5 and 15 percent are classified as moderate slopes. In the Coastal Plain these moderately sloping landscape units form as narrow ribbons bordering stream terraces and flood plains. Some of these moderate slopes in the Coastal Plain reflect the outcropping of aquifer confining beds, where the stream channel has cut below the overlying surficial sediments. In the older Piedmont province, moderate slopes are a more dominant landscape component.

STEEP SLOPES

Valley slopes 15 to 25 percent are classified as steeply sloping landscape units. As the slope increases beyond 15 percent, little ground water recharge is expected. Only a few isolated areas in the Coastal Plain have slopes greater than 15 percent. These slopes are more common in the Piedmont, but still do not represent a significant portion of the landscape.

VERY STEEP SLOPES

The very steep slopes classification was not used in development of the original methodology, which focused on Coastal Plain and Piedmont provinces. This classification has been added to account for very steep slopes found in the Mountain province of North Carolina.

VALLEY BOTTOMS OVERVIEW

Valley bottoms include both the modern flood plain and adjacent stream terraces. The age and properties of these soils are similar in both the Piedmont and Coastal Plain. Thus, we used the same stream terrace and flood plain landscape units in both provinces. Within the Coastal Plain recent, or Holocene, stream terraces and flood plains lie within older paleovalleys. These paleovalleys may be composed of a series of relic marine terraces dating to the Plio-Pleistocene geologic period that step down in elevation and age into the modern stream drainages. These terraces formed during transgressions and regressions of the ocean shoreline within the paleovalleys. Geologically, these landforms are viewed as relic terraces, but in the terminology used in our modern landscape mapping, these relic terraces become valley slopes.

STREAM TERRACES

Stream terraces usually occur next to active flood plains along the broad riverine areas of major rivers and streams, but can occur in association with streams of all orders. These areas contain the most diverse assemblage of materials anywhere on the landscape, with the sediment texture ranging from very fine clays to very coarse sands and gravels, depending on the fluvial environment where the materials were deposited. These terrace landscape units function as both recharge and discharge areas depending on distance to the stream channel, elevation, and depth to the water table.

FLOOD PLAINS

Flood plains are areas that regularly flood, with duration dependent upon location and height above the stream. Flood plains are ground water discharge areas and as such are assigned a zero recharge rate.

OTHER MAPPING UNITS

Various combinations of other mapping units occur in different detailed county soil surveys, including: urban, pits and quarries, mines, udorthents (undifferentiated pits and fills), and water. Our recharge maps group these units into three categories: urban land, water, and undifferentiated. Some obviously urban-land mapping units (large, amorphous shaped polygons) were classified as an “urban complex” of various soil series. The location of these mapping units within a county coincided with known urban metropolitan areas. In such instances, we classified these polygons simply as urban land.

ESTUARINE MAPPING UNITS

Although our studies focus on ground water discharge to streams, for completeness we also classified the following estuarine landscape units: barrier dunes, back barriers, beaches, marine terraces, and (coastal) marshes. Recharge rates for these estuarine units were estimated, not calibrated, since these areas represent such a small amount of the total land area of a basin, and because the low coastal relief and tidal influences makes it difficult to delineate drainage areas and accurately measure discharge. Also, we classified all land area of Quarternary age east of the Suffolk scarp that was not associated with barrier islands as marine terrace or marsh, reflecting the significantly lower recharge rate expected in these low-relief settings.

4.2 Differentiating Geologic Regions

OVERVIEW

In the Piedmont Province of North Carolina it was necessary to modify the valley slope landscape units used in the Coastal Plain to account for the increased clay content found in Piedmont soils. This clay impedes the infiltration of water into the soil reducing ground water recharge. The Piedmont is composed of distinct geologic regions; the different bedrock underlying these regions has weathered to produce distinctive soils. In some geologic regions, such as the Slate Belts and Triassic Basin, soils are quite clayey and ground water recharge rates are significantly lower than in surrounding regions. Based on the calibration analysis discussed in Section 5, we were able to divide the Piedmont Province into three areas having distinct recharge characteristics: Triassic Basin, combined Slate Belts, and Other Piedmont. To identify valley slope landscape units located within these areas, a suffix was attached to each unit, e.g. gentle slopes SB (Slate Belt), gentle slopes TR (Triassic Basin), and gentle slopes other (all other Piedmont geologic regions). For consistency, valley slopes in the Coastal Plain were designated with a CP suffix.

PIEDMONT LANDSCAPE

The Piedmont landscape is characterized by rounded ridge tops, gentle to steep valley slopes, and bottom lands. Soil texture of the uplands is dominantly fine, so we made no textural subdivisions. In the Triassic Basin and the two slate belt geologic regions, gentle slopes dominate the upland areas. Moderate slopes are common in the Raleigh Belt, reflecting the more rolling nature of the landscape. Steeper slopes greater than 15 percent are found along the more incised streams. The steeply sloping landscape units represent five percent or less of the landscape. Upland flat landscape units are not extensive in the Piedmont and were incorporated in the gentle valley slopes.

DELINEATING GEOLOGIC REGIONS

Geologic regions within the Piedmont were delineated based on the geologic parent material or region associated with each detailed soil mapping unit. We acknowledge that the standard reference for delineating geologic regions in the State is the 1985 Geology Map of North Carolina (Brown and Parker 1985) compiled by the North Carolina Geological Survey. However, since our ground water discharge maps are developed from soil mapping units, we used the geologic parent material associated with each mapping unit to delineate geologic regions. This information is found in *North Carolina Soil Key* (North Carolina Soils Staff, 1994). Most of the mapping units grouped logically into distinct regions. Where there were outliers, the mapped line separating our geologic regions was drawn to reflect the predominant geologic property of the soil mapping units within the group.

4.3 Resolving Mapping Problems

PROBLEMS IDENTIFIED

In compiling the recharge maps, three significant problems were encountered: (1) delineating stream terraces in a consistent manner; (2) reconciling individual soil mapping units that occurred in both upland and valley bottom areas; and (3) edge matching landscape units along county borders.

STREAM TERRACE PROBLEM

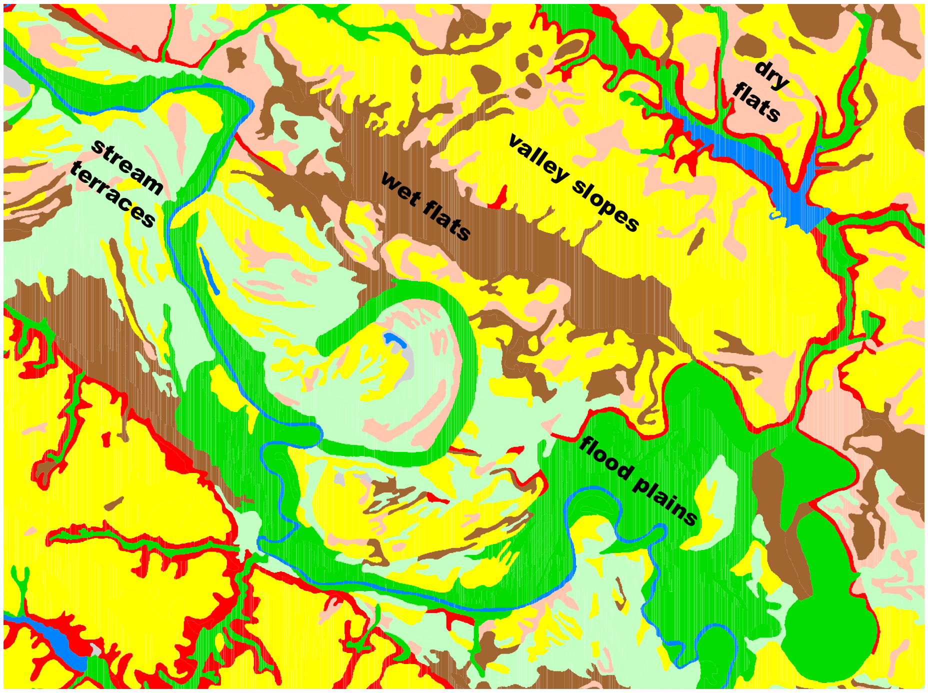
The most serious problem encountered in grouping soil mapping units into landscape units was differentiating Coastal Plain stream-terrace boundaries from upland and valley slope landscape settings. The problem involved individual county soil surveys that had been published at different levels of generalization. An example of this problem can be seen in the Greene and Pitt County soil surveys. Greene County soils were mapped in the late 1970s, and flood plain and stream terrace soil mapping units were generalized, showing a distinct boundary between upland and stream-terrace soil associations. The Pitt County soil maps, completed in the mid 1960s, include much more detail within the riverine system, making it more difficult to delineate the stream terrace boundary.

STREAM TERRACE SOLUTION

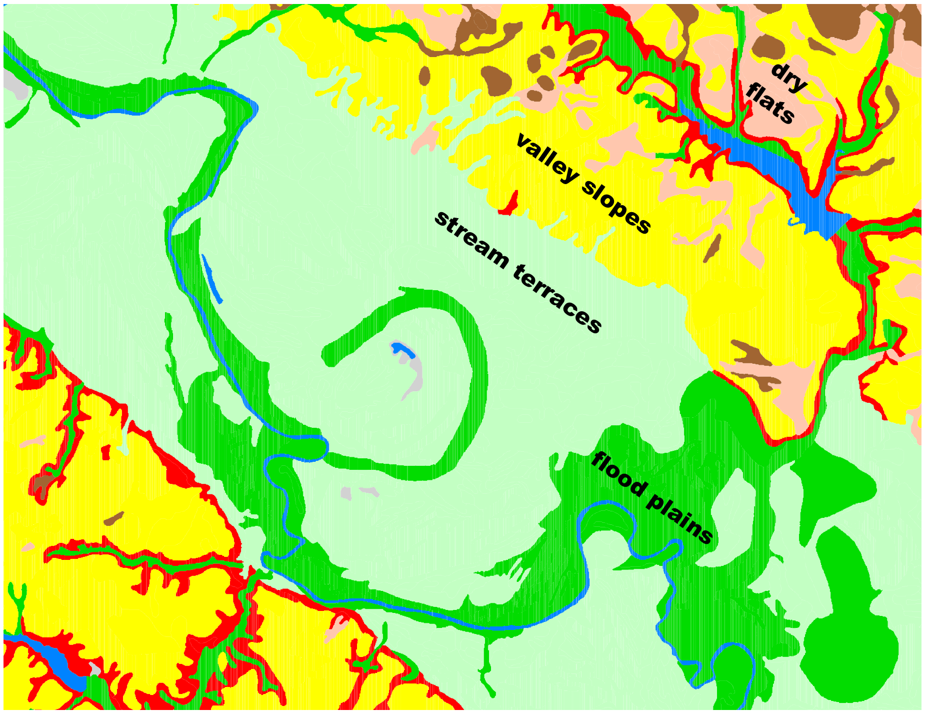
This problem and its resolution are illustrated in Figure 3, that shows a section of the Neuse River floodplain south of Goldsboro. To resolve the problem, stream-terrace boundaries along the major rivers and streams within each basin were manually delineated on a soil-polygon by soil-polygon basis on copies of the individual county soil surveys. Where steeper valley slopes existed, the delineation was more obvious, but in areas where the boundary was not as distinct, the delineation was determined by the predominance of upland versus stream-terrace mapping units. In order to achieve a smooth and continuous boundary on the recharge map, we drew the stream-terrace delineation along contiguous upland soil mapping units. In questionable areas, the border between upland and stream terrace areas was confirmed on 1:24,000 scale USGS topographic maps. All soil mapping polygons occurring between stream terrace boundaries were reassigned as stream terrace landscape units, if they were not flood-plain soils, water, urban land, or one of the undifferentiated mapping units.

LATER TERRACE SOLUTIONS

Subsequent to solutions discussed in the previous paragraph, we performed additional terrace editing to address three issues: (1) assure that similar terrace elevations occurred on each side of the stream channel, i.e., we would expect modern terrace-shaping fluvial processes to operate at similar elevations on both sides of the stream; (2) designate low-relief landscapes in the outer Coastal Plain as marine terraces, where the “upland flats-valley slope-valley bottom” landscape model did not fit well; and (3) differentiate low lying organic soils from upland wet flat organics. To assure similar terrace altitudes, contours from the National Elevation Data Set (NED), 30-meter digital elevation model (DEM) were plotted by river basin along major drainages, and individual soil mapping polygons were converted as described in the preceding paragraph. To handle low-relief landscapes, we determined that upland and terrace-mapped polygons below the 12-meter contour west of the Suffolk scarp should be classified as marine terrace. All organic soils not in upland settings were classified terraces organic.



a. Original Mapping



b. Modified Mapping

Figure 3. Example of the stream-terrace mapping problem, Neuse River south of Goldsboro, NC.

MULTIPLE-AREA PROBLEM

The multiple-area problem involves individual polygons with the same soil mapping unit name that occur on two different landscape positions, usually in upland and stream terrace areas. There are two variants of this problem. In the first situation isolated polygons from a soil mapping unit classified as predominantly stream terrace are found in an upland area. This problem was infrequently encountered and the soil mapping unit in question was most always coarse textured. The second situation involved polygons classified as predominantly upland units occurring along the stream terrace. These mapping units are mostly fine textured and have soil profiles similar to upland soils. The reason a soil mapping unit might appear in both upland and terrace areas is that the criteria used to classify the unit are similar in both areas, i.e., similar slope, textures, drainage class, and diagnostic horizons.

MULTIPLE-AREA SOLUTION

In the case where an isolated polygon of a stream-terrace soil occurred on an upland area, the individual polygons were reclassified to the appropriate upland landscape unit, if the suspect polygon had no apparent relationship to any drainage. For the situation of the upland unit located on a stream terrace, the polygon on the terrace was reclassified as a stream-terrace landscape unit, if there was no apparent connection between the isolated polygon and upland area. This multiple area problem illustrates the importance of grouping soil mapping units into landscape units on a county-by-county basis. The soil mapping units in each county need to be evaluated in terms of the landscape position descriptions provided in the individual county surveys.

EDGE MATCHING PROBLEM

The edge matching problem involved reconciling the boundaries of landscape units along county borders. The database underlying the landscape units originated from the individual county soil surveys mapped by different individuals at different times. In general we found a good match between landscape units at county borders. However, in a few instances there were obvious discontinuities. A second edge matching problem was that county borders, themselves, were not coincident, i.e., a small gap or overlap between counties existed. This surveying problem is inherent in the county database used for soil mapping units. Neither of these problems is significant, and the problem is more cosmetic in nature, jarring the eye as one scans between counties.

EDGE MATCHING SOLUTION

For different landscape units meeting at the county boundary, only the obvious problems were corrected. The solution was simply to adjust the polygon boundaries to achieve a more visually satisfactory match. These changes had no impact on the map nor on the analysis of the data at the scale of the recharge map. For survey gaps between counties, the soil survey county boundaries were aligned with a standardized North Carolina county boundary GIS data set. We used the “County Boundaries with Shoreline” GIS data set developed and distributed by the North Carolina Center for Geographic Information and Analysis. This data set utilizes mappings from the United States Geological Survey Digital Line Graph Program.

4.4 GIS Processing and Cartographic Techniques

SECTION OVERVIEW

The ground water recharge maps created using our methodology are vector maps produced using the Arc/Info geographic information system (GIS) software from Environmental Systems Research Institute (ESRI). In this subsection some of the mechanics underlying map production are explained. It should be noted, however, that the actual recharge maps produced in this project are not single Arc/Info coverages, but are instead a set of individual county coverages clipped to river basin boundaries. A single, consolidated recharge map coverage would be difficult to store, transport, and manipulate in many machines.

SOURCE OF DATA

The data used in recharge mapping is taken from detailed NRCS county soil surveys. The individual soils maps are rectified to a stable-base grid and digitized into a GIS computer system. The North Carolina Center for Geographic Information and Analysis (CGIA) oversees the compilation and quality assurance of most of this digitized data. When all of the individual soils maps in a county survey have been digitized, they are joined into a single Arc/Info coverage, placed in CGIA's corporate database, and made available to the public. Each county soils coverage contains the vector representation of each soil polygon mapped in the county, as well as various physical and soil properties associated with the soil mapping units.

CONVERTING MAP UNITS TO LANDSCAPE UNITS

Table 1 lists the criteria used to combine soil mapping units into landscape units. Using this table, and a lookup table associating soil series with geologic region, it was possible to classify each soil mapping unit within a county by landscape unit. This classification scheme was then entered into the computer, and each mapping unit polygon within a county soils coverage was assigned a landscape unit attribute.

DIVIDING COUNTY COVERAGES ALONG BASIN BOUNDARIES

Once landscape unit attributes were assigned to each county soils coverage, the individual county coverages were divided along river basin boundaries. CGIA maintains a river basin boundary coverage for the major river basins in North Carolina. This coverage follows the 14-digit hydrologic units as delineated by the U.S. Department of Agriculture, Natural Resources Conservation Service (1995) and maintains the integrity of these units. This basin coverage was used to divide the county soil coverages along basin lines. The 14-digit hydrologic units are explained more fully in Appendix B.

POLYGON EDITING

We used two methods to edit individual polygons. Initially, all polygons were edited within Arc/Info. Later, when faster personal computers and graphic cards with expanded storage became available, we used ESRI's ArcView 3.2 program and county shape files for editing and analysis. We also used Microsoft Excel to edit the ArcView *.dbf shape files.

SECTION 5

Methodology Used to Estimate Ground Water Recharge and Discharge

OVERVIEW OF METHODOLOGY

Section 4 presented the methodology used to divide river-basin landscapes into landscape units having similar recharge characteristics. In this section we describe the methodology used to estimate ground water recharge and discharge. These rates were determined by calibration with drainage areas where ground water discharge had been estimated using stream hydrograph separation techniques. Selected U. S. Geological Survey (USGS) gaged drainage areas were used in the calibration.

SECTION OUTLINE

This section first reviews hydrograph separation techniques, then describes the Rorabaugh-Daniel model used in our methodology. Next, selection criteria for the USGS gaged drainage areas used in the calibration process are outlined, and characteristics of the selected drainage areas are described. The Monte Carlo calibration procedure used to determine landscape unit recharge rates is then explained.

5.1 Stream Hydrograph Separation Methods

DESCRIPTION OF METHOD

Water flowing in streams is derived from both overland flow and ground water discharge. Stream hydrograph analysis examines the historic record in daily flow values recorded at stream-gaging stations similar to the station illustrated in Figure 4. A typical stream hydrograph records the sharp peaks associated with a wave of surface water run off following a rainfall event. As the wave passes the gaging station, the peak will gradually recede to leave only the ground water component of streamflow. The interval between run off peaks represents a period of ground water recharge that can be evaluated.

DATA AVAILABILITY

Daily streamflow values are available in several formats for most gaging stations in the United States maintained by the USGS via the world wide web (http://waterdata.usgs.gov/usa/nwis/sw/). The widespread availability of streamflow data with lengthy periods of record makes hydrograph separation an excellent ground water discharge estimation technique.

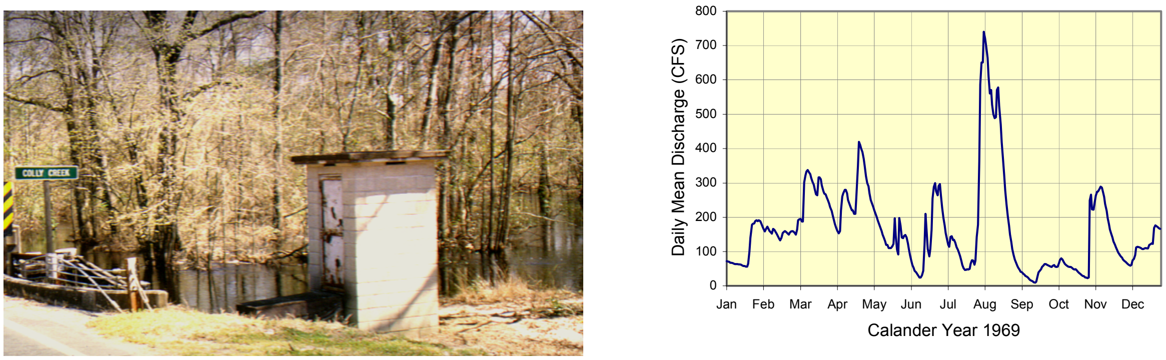


Figure 4. Example of a gaging station (02107500) and stream hydrograph, Colly Creek, Sampson Co. NC.

EARLY SEPARATION METHODS

Several different techniques of stream hydrograph separation have been used over the years. A manual process of separating the overland flow from base flow began with the work of Meinzer and Sterns (1929). Later Pettyjohn and Henning (1979) published an automated technique of hydrograph separation. Their computer program calculates baseflow using three different methods: (1) a fixed interval of time after the peak flow, (2) a sliding interval of time, and (3) a local-minimum method of estimation. Figure 5 illustrates these methods. The sliding interval produces slightly lower base-flow estimates than the fixed interval. The local minimum method is more conservative than the other two methods, always producing a smaller base-flow estimate. Daniel (1996) used a variation of the local-minima method to estimate recharge to the regolith-fractured crystalline rock aquifer system in Orange County, North Carolina. McMahon and Lloyd (1995) used the Pettyjohn and Henning method to analyze 42 drainage areas in the Albermarle-Pamlico drainage basin.

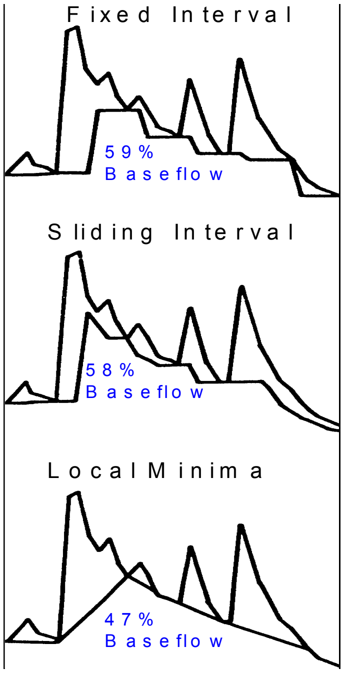


Figure 5. Manual techniques of stream hydrograph separation, from (Pettyjohn and Henning, 1979).

5.2 Rorabaugh-Daniel Model

MODEL EXPLAINED

The more advanced Rorabaugh-Daniel hydrograph separation model utilizes streamflow recession curves instead of straight lines. The model is based on the measurement of change in the total potential ground water discharge at a critical time after the peak streamflow by extrapolating from the pre-peak and post-peak recession periods. The critical time begins *N* days after the peak flow, where *N* is dependent on the size of the basin (Rutledge 1993). This technique generates an average master recession curve for periods of low evapotranspiration for the entire data set before estimating base flow. The estimation process extrapolates the pre-event base flow and post-event base flow to a calculated critical time after the peak of the event.

MODEL ASSUMPTIONS

Various assumptions must be met for the Rorabaugh-Daniel model to be executed effectively. First, several years of daily streamflow data are required. Second, there should be no major surface water diversions, such as reservoir storage or municipal water withdrawals and discharges. Third, rain events are assumed to be evenly distributed throughout the gaged drainage area. Fourth, pumping, leakage through confining layers (upward or downward), and evapotranspiration are all assumed nominal.

COMPUTER IMPLEMENTATION

A set of computer programs to implement the Rorabaugh-Daniel Model was developed by the U. S. Geological Survey (Rutledge 1993). The code that was available to the Groundwater Section is written in Fortran-77 and runs on a Unix workstation. Details of the Rutledge programs are provided in USGS WRI Report 93–4121, *Computer programs for describing the recession of ground-water discharge and for estimating mean ground-water recharge and discharge from streamflow records.* We used four of these modules in our recharge calculations:

- TRANS – a program that translates daily USGS streamflow records into a format that can be used by the other computer programs;
- STREAM – allows the user to screen the daily-values data file for periods of continuous record and calculates the mean flow rate;
- RECESS – determines the master streamflow recession curve during times when all flow can be considered to be ground water discharge; and
- RORA – uses the recession-curve-displacement method to estimate the recharge for each peak in the streamflow record; this method is applied to a long period of record to give an estimate of the mean annual ground water recharge.

We also had to write a short BASIC program to translate the streamflow data sets available from the USGS into the “2 and 3 card” format required by the TRANS module. Subsequent to our analysis, Rutledge updated his computer programs (Rutledge 1998).

RECHARGE VS. DISCHARGE

In his programs, Rutledge distinguishes between recharge and discharge calculations. The Rorabaugh-Daniel model (RORA program) estimates recharge from a displacement in the recession curve attributable to increased ground water discharge. He also provides a computer program, PART, that implements a variant of the Pettyjohn-Henning techniques, using streamflow partitioning to estimate a daily record of base flow under the streamflow record. Recharge estimates using the RORA program are larger than discharge estimates using the PART program. Rutledge (1993) attributes this difference to riparian evapotranspiration. In our analysis we have used the Rorabaugh-Daniel model exclusively, and have also equated recharge with discharge. This model is more rigorous than the simple, straight-line base-flow separation techniques, has wider acceptance, and more closely represents the ground water component of streamflow.

MODEL ILLUSTRATION

To illustrate use of the Rorabaugh-Daniel model, we describe how the gaged USGS drainage areas used in our recharge calibration analysis were selected. There are over 160 USGS automatic gaging stations at which streamflow is measured on North Carolina's rivers and streams. Also, historic records are available for numerous discontinued sites (Ragland et al. 1997). As an example, within the Neuse and Tar-Pamlico river basins, we identified 87 gaging stations at which discharge has been measured, from areas ranging in size from 3 acres to 4,470 square miles. The period of record for these stations ranges from 1 to 73 years.

STATION SELECTION

We evaluated all gaged drainages in the North Carolina Piedmont and Coastal Plain provinces as possible calibration sites. In selecting stations, we adhered to the model assumptions previously discussed and followed the criteria used in the USGS Appalachian-Piedmont Regional Aquifer System Analysis (APRASA), as cited by Rutledge (1993):

- drainage area 10 to 500 square miles; and
- period of record 15 or more years.

We also required selected stations to have a similar period of record, following Richardson (1994), and to be independent, i.e., not be a part of a smaller or larger drainage area being analyzed. Finally, each drainage area was required to have a well-defined topographic boundary. This criterion excluded stations in the relatively flat lower Coastal Plain where artificial drainage is extensive. Applying the above criteria, we were only to identify 13 stations meeting specifications. The records of selected drainage areas covered the 20-year period 1967 to 1986. The locations of these stations are shown in Figure 6, and station attributes are listed in Table 2.

MODEL RESULTS

The Rutledge (1993) implementation of the Rorabaugh-Daniel model was used to analyze streamflow records for each of the 13 gaging stations over the 20-year period. Results of this analysis are shown in Table 2. The model indicated that ground water discharge averaged about 7 inches a year in the Piedmont province and about 12 inches a year in the Coastal Plain.

USGS Gaged Drainage Areas Used in Recharge Calibration

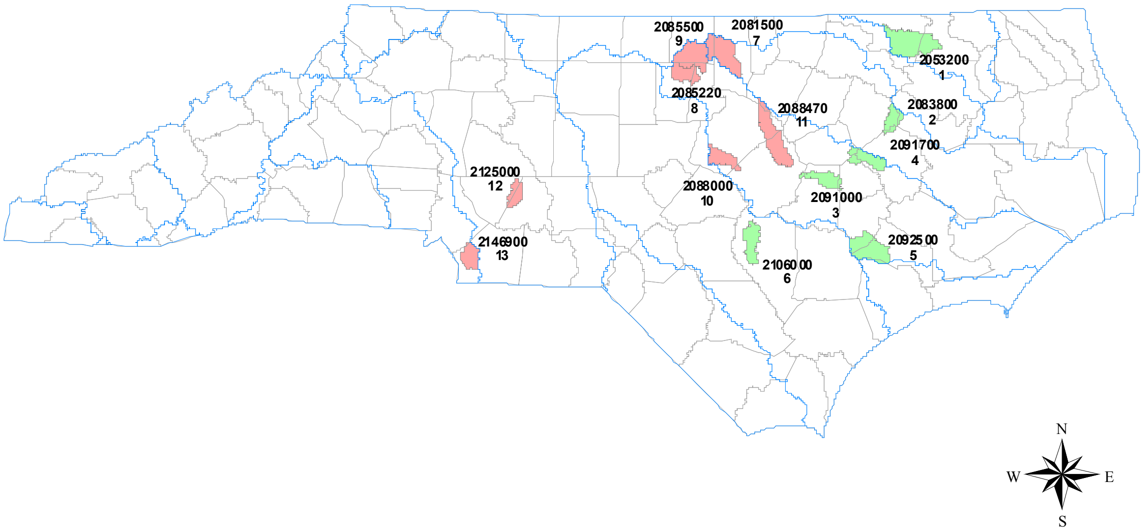


Fig 6. USGS gaged drainage areas used in stream hydrograph separation analysis.

Table 2. USGS Gaging Stations Analyzed in North Carolina River Basins

Fig. 6 Number	*USGS Station #*	*Station Name*	*Drainage Area (sq mi)*	*Baseflow (in/year)*	*Baseflow (cm/year)*
Coastal Plain Stations					
1	2053200	Potecasi Creek near Union	225	12.10	30.73
2	2083800	Conetoe Creek near Bethel	78.1	11.26	28.60
3	2091000	Nahunta Swamp near Shine	80.4	11.75	29.85
4	2091700	Little Contentnea Creek near Farmville	93.3	12.53	31.83
5	2092500	Trent River near Trenton	168	13.13	33.35
6	2106000	Little Coharrie Creek near Roseboro	92.8	12.42	31.55
		mean:		12.20	30.99
Piedmont Stations					
7	2081500	Tar River near Tar River	167	6.52	16.56
8	2085220	Little River near Orange Factory	80.4	5.89	14.96
9	2085500	Flat River at Bahama	149	6.60	16.76
10	2088000	Middle Creek near Clayton	83.5	8.72	22.15
11	2088470	Little River near Kenly	191.00	10.04	25.50
12	2125000	Big Bear Creek near Richfield	55.60	4.88	12.40
13	2146900	Twelve Mile Creek near Waxhaw	76.50	5.46	13.87
		mean:		6.87	17.46

ET CONSIDERATIONS

An underlying assumption of the Rorabaugh-Daniel model is that streamflow is analyzed to determine the master recession curve when evapotranspiration demands are low. We met this criterion by analyzing stream flow only during the months of November through February, when ET values are lowest in the Coastal Plain, as shown in Figure 7.

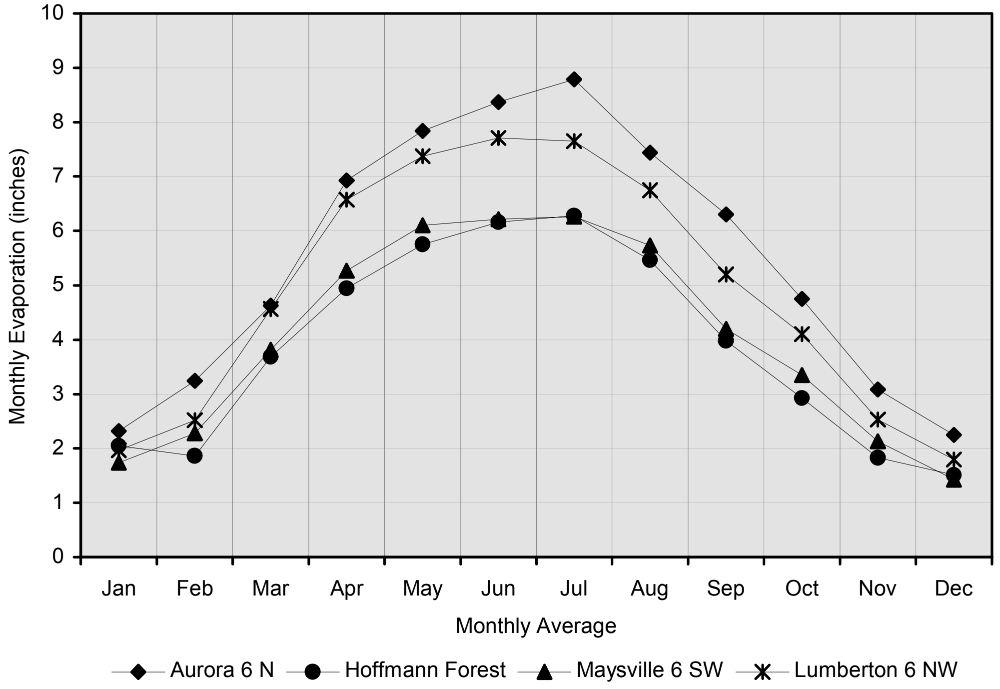


Figure 7. Average monthly pan evaporation from selected Coastal Plain weather stations.

DISCUSSION OF UNCERTAINTY

The Rutledge implementation of the Rorabaugh-Daniel streamflow hydrograph separation technique is a well-accepted model. However, we are unaware of any studies that have actually tried to compare model output with measurements of recharge at a watershed scale. Accountable model uncertainty arises in streamflow measurements and in estimating the near linear portion of the recession curve that represents baseflow. The USGS calculates daily mean stream discharge at a station using the daily mean stage and a stage-discharge relation curve. For the stations we analyzed in the Neuse and Tar-Pamlico basins, the USGS estimated the accuracy of the discharge data “good,” or within 10 percent. To determine uncertainty in recession-curve estimates, Daniel (1990) performed a master recession-curve variability test. He found that an induced variation of 25 percent in the curve resulted in a maximum variation in estimated recharge of only 6 percent. The average recharge rate variation was less than 3 percent.

5.3 Calibrating Recharge Estimates with Baseflow Model

PURPOSE OF CALIBRATION

The purpose of calibration was to refine initial landscape unit recharge estimates we had made to more closely estimate the net base flow calculations compiled for the gaged drainage areas shown in Table 2. In other words, if ground water recharge estimates for each of the landscape units described in Section 4 can be used to accurately estimate the known mean annual base flow in USGS gaged drainage areas, then we can infer that these same recharge values can be used to estimate base flow in similar ungaged drainage areas.

OVERVIEW OF PROCEDURE

The calibration procedure we followed involved six steps: (1) develop initial ground water recharge estimates for each of the landscape units; (2) calculate base flow at selected stream gaging stations; (3) establish an objective function to measure success of calibration; (4) establish decision rules setting logical relations among landscape unit recharge rates; (5) perform a Monte Carlo or iterative simulation to evaluate alternative recharge-rate combinations; and (6) perform a sensitivity analysis to select a final set of recharge rates.

1. INITIAL ESTIMATES

Initial recharge estimates were developed based on Heath's (1994) report on *ground water Recharge in North Carolina.* These initial values were then modified by our team using an iterative Delphi technique and preliminary base-flow information from a gaged drainage area.

2. BASE-FLOW CALCULATIONS

Base-flow calculations were made using the Rorabaugh-Daniel method at 13 gaged drainage areas, as described earlier in this section, and are listed in Table 2.

3. OBJECTIVE FUNCTION

In calibration we are trying to minimize the error between our recharge estimates and baseflow calculations. This error can be expressed mathematically as an objective function. For example, an estimate of annual base flow for a gaged drainage area can be made by summing the weighted recharge estimates for the individual landscape units over the entire drainage area. This base-flow estimate, expressed in inches or centimeters per year, can be subtracted from the modeled base-flow calculation for the drainage area to determine the error in base-flow estimation. This same procedure can be followed to calculate an estimated error for each of the gaged drainage areas. If there are $n = 13$ gaged drainage areas, and the estimation error for the i_{th} area is e_i, then a root-mean-square (RMS) objective function can be set forth. Our calibration goal, then, is to adjust the individual recharge estimates to minimize the aggregate RMS error.

$$RMS = \sqrt{\frac{\sum_{i=1}^{n} e_i^{\,2}}{n}}$$

4. DECISION RULES

In estimating recharge rates for the different landscape units, we established certain relationships, or decision rules, between areas, based on the recharge factors discussed in Chapter 1 and on general hydrogeologic knowledge. An example of a decision rule would be that recharge rates for wet flat mineral soils are greater than or equal to (>=) rates for wet flat organic soils. Below is a list of the seven decision rules used in calibration; these decision rules are applied in the Monte Carlo simulation.

1. *Coastal Plain (CP) dry flat recharge rates >= Coastal Plain gentle slope recharge rates*
2. *Coastal Plain recharge rates >= Piedmont recharge rates (same landscape position)*
3. *Triassic Basin (TR)recharge rates < Slate Belt recharge rates (same landscape position)*
4. *Slate Belt (SB) recharge rates < other Piedmont recharge rates (same landscape position)*
5. *gentle slopes recharge rates >= moderate slopes recharge rates (same geologic region)*
6. *moderate slopesrecharge rates >= steep slopes recharge rates (same geologic region)*
7. *wet flats mineralrecharge rates >= wet flats organic recharge rates*

5. MONTE CARLO SIMULATION

Monte Carlo simulation is used to evaluate different combinations of landscape-unit recharge rates. Early simulation results indicated that some landscape units having similar recharge rates could be combined into what we termed hydrologic areas or recharge units, as listed in Table 3 in the next section. The purpose of this simulation is to identify the optimal combination of rates that will minimize the objective function, or RMS error. Monte Carlo simulation is performed by randomly selecting a recharge rate for each landscape unit from a predefined range of rates. These selected rates are then used to calculate base flow for each of the gaged drainage areas, and to determine a RMS error. The simulated recharge rate units we used were centimeters per year (cm/yr) to maintain a meaningful set of integer values. Table 3 also presents final recharge rates in inches per year and gallons per day per square mile.

6. SENSITIVITY ANALYSIS

The final step in the calibration procedure was to conduct a sensitivity analysis. The purpose of this analysis is to determine how sensitive each of the landscape or recharge units is to a change in recharge rate. Knowing the sensitivity of each landscape unit, we were able to determine a final set of ground water recharge rates. The next section describes the different simulation models we evaluated in determining a final set of recharge units and ground water recharge rates.

SECTION 6

Alternative Simulation Models to Estimate Ground Water Recharge

OVERVIEW

In Section 6 we evaluate five simulation models for estimating ground water recharge in our 13 gaged drainage areas, as described in the previous section. The complexity of these models range from a naive uniform recharge model to the more detailed landscape/geology model previously described. Our purpose in evaluating these alternative models is to graphically illustrate which variables most effectively simulate the calculated recharge in each of the 13 drainages. Also, this section illustrates how the recharge methodology can be applied in individual drainages.

SECTION OUTLINE

The five simulation models evaluated are:

- Uniform recharge model;
- Weighted rainfall model;
- Soil permeability model;
- Simple landscape model; and
- Modified landscape model.

The section closes with an example applying the modified landscape model recharge rates in one of the 13 drainage areas.

6.1 Uniform Recharge Model

DESCRIPTION OF MODEL

The uniform recharge model naively assumes that ground water recharge occurs at a uniform rate throughout the entire watershed or drainage area. Our purpose in presenting this model is to establish a baseline to evaluate other models. This model can be expressed mathematically as:

$$R = R_{sim}$$

where the recharge rate, R, applied to the drainage area is simply equal to the simulated rate, R_{sim}.

OBJECTIVE FUNCTION

The objective function to be minimized can be expressed as:

$$\mathrm{RMS}=\sqrt{\frac{\sum_{N}(R_{\mathrm{calc}}-R)^2}{N}}$$

MODEL SIMULATION

To run the simulation, recharge rates, $R = R_{sim}$, between 15.0 cm/yr and 30.0 cm/yr were applied to each of the 13 calibration drainage areas in 0.1 cm/yr increments. The R_{calc} or baseflow value for each drainage area is shown in Table 2 on page 31. The error value for each drainage area is thus $(R_{calc} - R)$. For each recharge rate, R_{sim}, simulated across all drainages, a RMS was calculated. Figure 8 plots each of these RMS values as a function of the simulated recharge rate. The graph shows that the objective function was minimized at a recharge rate of 23.5 cm/yr. The root mean square (RMS) error for this recharge rate is 7.54 cm.

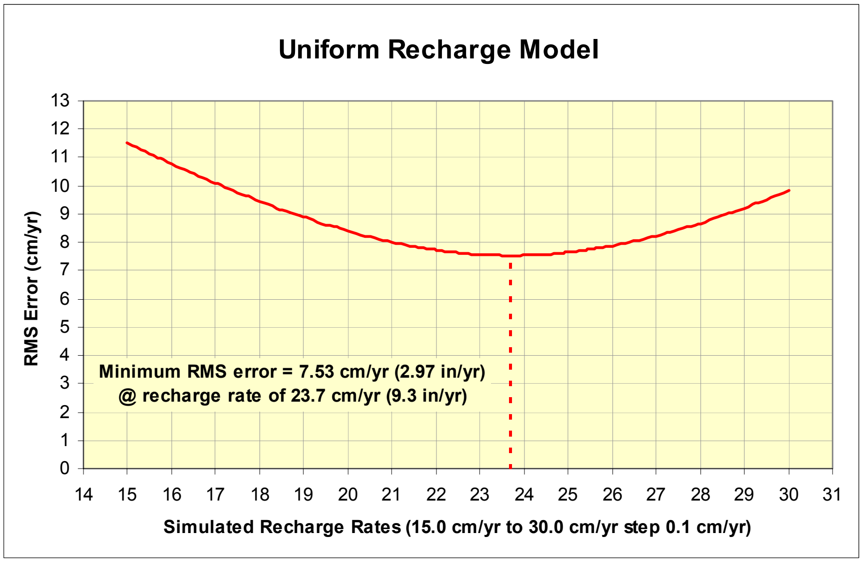


Figure 8. Uniform recharge model: simulation results.

6.2 Weighted Rainfall Model

DESCRIPTION OF MODEL

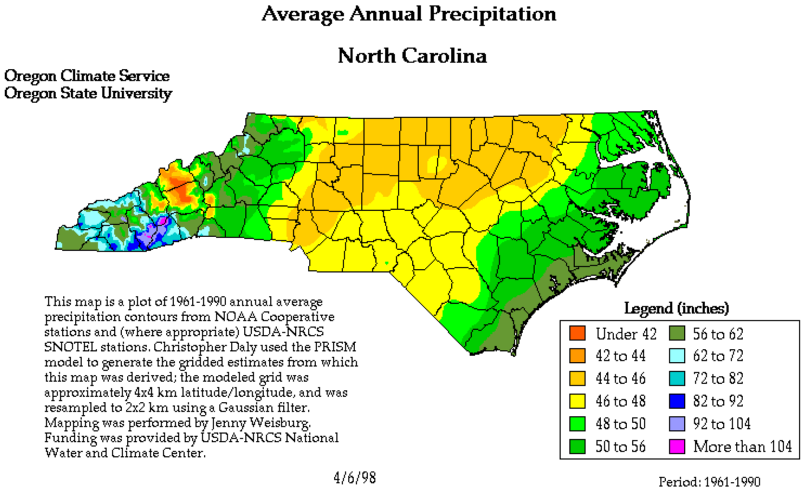
Obviously the uniform recharge model is a poor estimator of ground water recharge. Our second model, the weighted rainfall model, accounts for the variability in average yearly rainfall across the state, illustrated in Figure 9. North Carolina's average rainfall is about 50 inches/year, but ranges from under 42 inches to more than 100 inches in the Blue Ridge Mountains. The weighted rainfall model calculates an average annual rainfall for each of the 13 calibration drainages, then divides this local rainfall by 50 in/yr, creating a proportional weight W_{RF}:

$$W_{RF} = \frac{\text{local annual rainfall}}{\text{50 in/year}}$$

This weight is then incorporated into the uniform model:

$$R = W_{RF} \times R_{sim.}$$

In later landscape models rainfall weighting was incorporated into the model at the soil mapping unit level, as described by Hirth et al. (2002). Hirth examined monthly rainfall records from National Climatic Data Center (NCDC) data sources over the 30-year period 1967 to 1996 for 160 North Carolina and 42 bordering county rainfall data stations. Using a linear kriging algorithm in ArcInfo v7.1 (Environmental Systems Research Institute-ESRI) he developed a statewide 30-year mean annual rainfall lattice on a 500 square foot cell size. Annual rainfall values in the lattice were then spatially joined to the individual soil polygons, county by county.



Average Annual Precipitation

North Carolina

Oregon Climate Service
Oregon State University

This map is a plot of 1961-1990 annual average precipitation contours from NOAA Cooperative stations and (where appropriate) USDA-NRCS SNOTEL stations. Christopher Daly used the PRISM model to generate the gridded estimates from which this map was derived; the modeled grid was approximately 4x4 km latitude/longitude, and was resampled to 2x2 km using a Gaussian filter. Mapping was performed by Jenny Weisburg. Funding was provided by USDA-NRCS National Water and Climate Center.

4/6/98

Period: 1961-1990

Figure 9. Average annual precipitation in North Carolina.

MODEL SIMULATION

Simulation of the weighted rainfall model was run similar to the uniform recharge model. Simulation results are illustrated in Figure 10. Adding the weighted rainfall to the model slightly increased the RMS error, from 7.53 cm/yr to 7.65 cm/year, and reduced the modeled recharge rate from 23.7 cm/yr to 22.4 cm/yr. This shift would be expected since annual rainfall in most of the 13 calibration drainages is less than the statewide average of 50 inches a year.

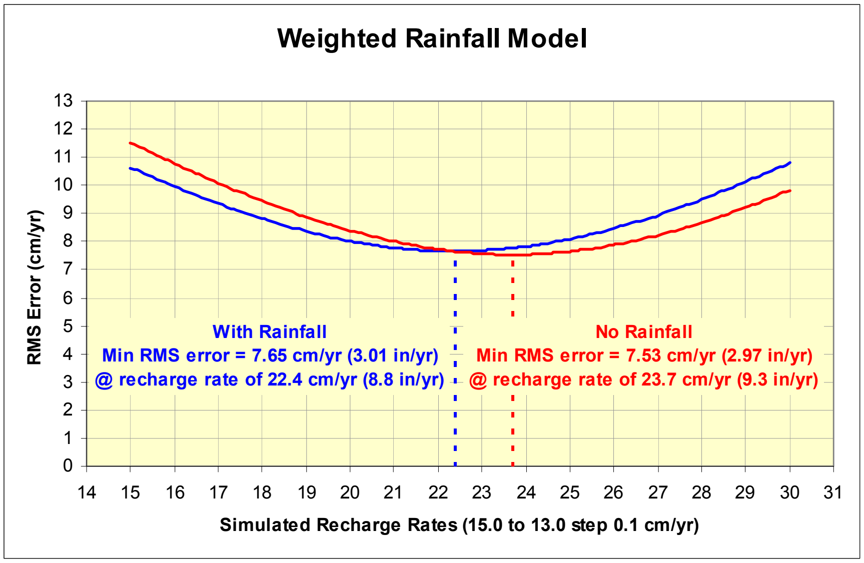


Figure 10. Weighted rainfall model: simulation results.

6.3 Soil Permeability Model

BACKGROUND ON MODEL

The soil permeability model was developed to investigate possible linkages between the Groundwater Section's recharge mapping project and a vulnerability assessment of public water supply wells completed by the U. S. Geological Survey under contract with the DENR Public Water Supply Section as part of the state's Source Water Assessment Program (SWAP). The USGS research (Eimers et al. 2000) focused on four characteristics contributing to vulnerability of the unsaturated zone: vertical hydraulic conductance, land-surface slope, land cover, and land use. To estimate conductance, researchers used a weighted estimate of saturated hydraulic conductivity, or average soil permeability. In each county soil survey, a saturated conductivity range is given for each soil series by soil layer, up to a maximum of six layers for the series. Conductivity is one of those variables that is measured at a single reference site, not in the field, as discussed on page 16. Permeabilities for individual soil layers can be combined into an harmonic mean average soil permeability or conductivity (HMK) by using the following formula:

$$HMK = \frac{\sum_{i=1}^{i=6} \left| deph_i - depl_i \right|}{\sum_{i=1}^{i=6} \frac{\left| deph_i - depl_i \right|}{\mu_i}}$$

where $deph_i$ and $depl_i$ are the high and low depths of soil layer i and μ_i is the average permeability for that layer. Permeability values are usually log-normally distributed, so average permeability for layer i is calculated as:

$$\mu_i = 10^{\frac{\log(permh_i) + \log(perml_i)}{2}}$$

where *permh* and *perml* are the high and low values of a permeability range given in the county soil survey for the particular soil series and layer.

DESCRIPTION OF MODEL

In our soil permeability model, we calculated an *HMK* value for each soil series in each of the 13 calibration drainages using the above formulas. We also determined the relative percent of each soil series within the drainage, *PSD*. The soil permeability model can thus be represented as:

$$R = \sum_{i=1}^{n} (HMK_i \bullet PSD_i \bullet R_{sim})$$

where n is the number of soil series within the drainage. In our simulations we actually ran two models, the second being a logarithmic transformation of the first, with HMK_{log} substituted for *HMK*:

$$HMK_{log} = \frac{\log_{10}(HMK \bullet 100)}{2}$$

MODEL SIMULATION

Because permeability rates are listed in units of in/hr in the county soil surveys, we used inches as our simulation units and converted the results to centimeters. For the permeabilities listed in the surveys, we simulated over a range from 2.0 to 10.0 inches of recharge a year in increments of 0.1 inches. For the logarithmic transform we simulated from 5.0 to 13.0 inches per year, again in 0.1 inch increments. The underlying assumption in this model is that the harmonic mean soil permeability can be used as a predictor of ground water recharge in a drainage area. Said another way, given an annual amount of rainfall in a drainage, recharge within the drainage will be governed by the differential infiltration capacities or permeabilities of the individual soil series within the drainage. Figure 11 illustrates the results of the soil permeability modeling. Neither model was an effective predictor of ground water recharge, with the log permeability model performing slightly better (min RMS error 6.6 cm/yr) than the regular permeability model (min RMS error 7.9 cm/yr). Given the poor model performance, we felt it was not necessary to apply rainfall weighting to these models.

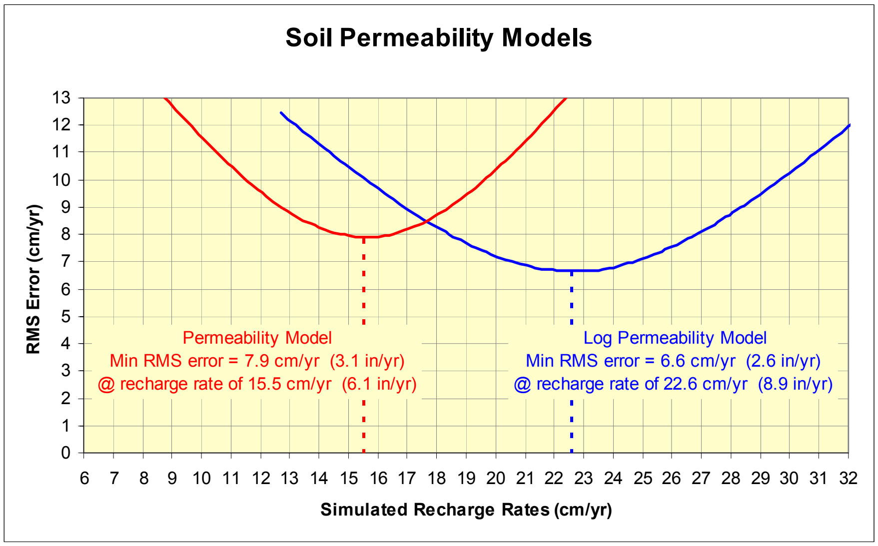


Figure 11. Soil permeability models: simulation results.

6.4 Simple Landscape Model

BACKGROUND ON MODEL

The simple landscape model incorporates the fundamental concept of ground water flow, illustrated in Figure 1 on page 3, where ground water moves from upland areas of ground water recharge to lower areas of ground water discharge. It also incorporates the drainage basin concepts we discussed in Section 3, and our interpretation of these concepts in terms of a landscape divided into upland flats, valley slopes, and valley bottoms, as discussed in Section 4. The factors controlling recharge rates discussed in Section 1 are used in the model as decision rules, and are listed on page 34.

DESCRIPTION OF MODEL

The simple landscape model uses a Monte Carlo iterative technique where different combinations of recharge rates are evaluated, with the goal to minimize the objective function, or RMS error. The model considered seven landscape settings (i = 1 to 7): wet flats organic, wet flats mineral, dry flats, gentle slopes, moderate slopes, steep slopes, and stream terraces, but did not differentiate between the Piedmont and Coastal Plain regions. In each of the 13 calibration drainages, the relative percent of area covered by each of these landscape units was calculated $(PSD)_i$. Also, for each landscape unit within the drainage, we calculated a mean annual rainfall based on the rainfall attribute in each soil polygon, as described on page 37, and weighted it with the statewide average rainfall $(W_{RF})_i$. For each set or combination of landscape-unit recharge values simulated $(R_{sim})_i$, we estimated a recharge value (R) for the drainage and compared it to the calculated value to determine our error:

$$R = \sum_{i=1}^{7} [(W_{RF})_i \bullet (PSD)_i \bullet (R_{sim})_i]$$

MODEL DETAILS

We developed a computer program, written in the Python programming language (Lutz and Ascher 1999), to perform the simulations. In earlier analyses we had developed expected recharge ranges for each of the landscape settings. In the program we read in the recharge values for each of the 13 calibration drainages calculated by the Rorabaugh-Daniel method. For each drainage area we also input the relative percent of each landscape unit within the drainage and the rainfall weight for that unit. The program then performed 150,000 Monte Carlo simulations. For each simulation a random number generator was used to select a recharge value within a predefined range for each of the seven landscape units, according to the decision rules previously established. A recharge value for each drainage area was then calculated using the above formula and an RMS error determined for that simulation. If the RMS value was less than 3, the RMS value and simulated recharge values for each landscape unit were written to an output file. Once the program finished, we imported the output file into an Excel spreadsheet and sorted the records by the RMS value. For the 500 records with the lowest RMS values, we calculated distribution statistics on the simulated recharge values for each of the landscape units. Due to the limited number of qualified drainage areas available for modeling, and because some landscape units occur less frequently than others, e.g., steep slopes, outlying or extreme recharge values can be found in individual simulations that have low RMS errors. For this reason, we selected median values (from the 500-record distributions) for our recharge estimate for each landscape unit. These individual median landscape-unit recharge estimates were then used to estimate a drainage area recharge. The drainage area estimates were then used to calculate a final RMS error for the simple landscape model.

MODEL SIMULATION

Figure 12 illustrates performance of the simple landscape model compared to the other models previously evaluated. In terms of our objective function, the model performs about three times more effectively in estimating ground water recharge in our 13 gaged drainage areas. However, when we used these model results to compare estimates within the individual drainages, we found a wide range of errors, as illustrated in Figure 13. In the Piedmont region it appeared the model both overestimated and underestimated recharge, indicating that additional model refinement was warranted. To a lesser degree we see this same dichotomy in the Coastal Plain drainages. Figure 13 displays drainage areas by number; the corresponding drainage area names are listed on page 31.

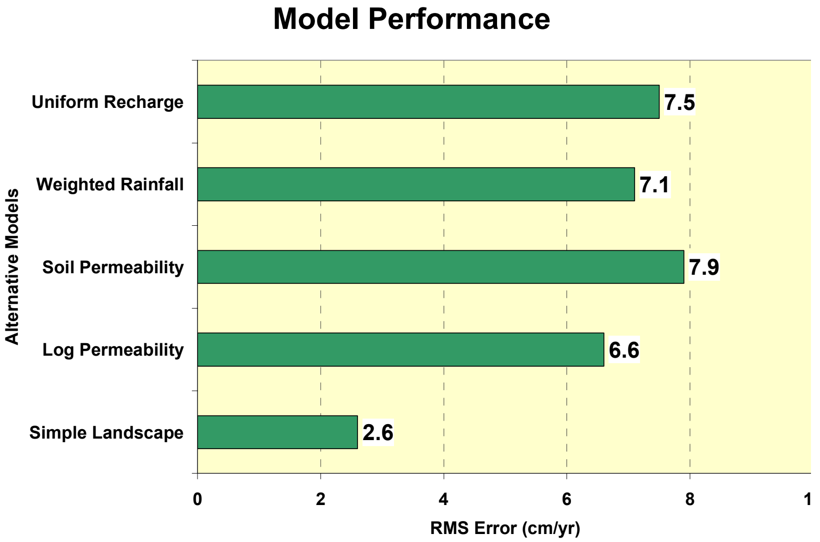


Figure 12. Comparing performance of alternative simulation models.

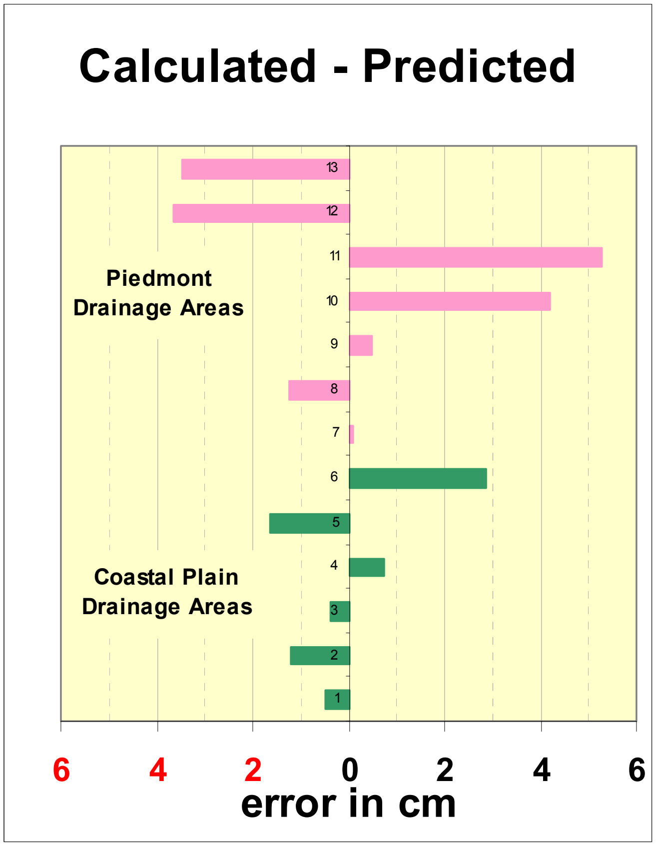


Figure 13. Simple landscape model individual drainage area performance.

6.5 Modified Landscape Model

BACKGROUND ON MODEL

Sub-section 6.6 discusses a variety of other models we investigated in trying to simulate ground water recharge. In investigating these models we realized that we could group several landscape units with similar recharge rates into what we termed *recharge units*. In many instances the landscape unit term sufficed as a recharge unit, as in the case of flood plains. In other cases, a generic recharge unit term was adopted, e.g., landscape units stream terraces-ct and stream terraces-ft were combined into the recharge unit stream terraces. Table 3 presents the complete list of recharge units we are proposing, and also the list of associated landscape units. The more detailed landscape units were retained as an attribute in the individual county soil coverages we created for use in landscape mapping and future research initiatives.

DESCRIPTION OF MODEL

The modified landscape model differentiated geologic regions in the Piedmont Province, as discussed on page 22. The model also used recharge units, rather than landscape units in the simulations, combining textural differences and grouping moderate and steep slopes into a single recharge unit, by geologic region. These aggregations simplified and minimized the number of recharge units needed to effectively simulate ground water recharge in the drainages. The basis for these groupings is discussed more fully in the next sub-section. We used the same landscape model in our simulations as described in the previous section, the only difference being that recharge for a differing set of recharge units was simulated, rather than landscape unit recharge. The set of recharge units simulated includes:

- upland flats-organic
- upland flats-mineral
- gentle slopes CP [*Coastal Plain*]
- gentle slopes SB [*Slate Belt*]
- gentle slopes TR [*Triassic Basin*]
- gentle slopes other
- other slopes CP
- other slopes SB
- other slopes TR
- other slopes
- stream terraces

MODEL SIMULATION

The modified landscape model simulation generated a minimum RMS error for our objective function of 0.40 cm/yr, with an average absolute error for the individual drainages of 0.31 cm/yr, and maximum error of 1.02 cm/yr, as illustrated in Figure 14. We also conducted a sensitivity analysis on these 11 recharge units by individually varying the simulated rates for each unit over the range ± 5 cm/yr and observing the effect on our RMS error objective function. These results are plotted in Figure 15. We considered these results sufficient for our modeling effort. Our final recharge rate estimators for individual recharge units are listed in Table 3 on page 45.

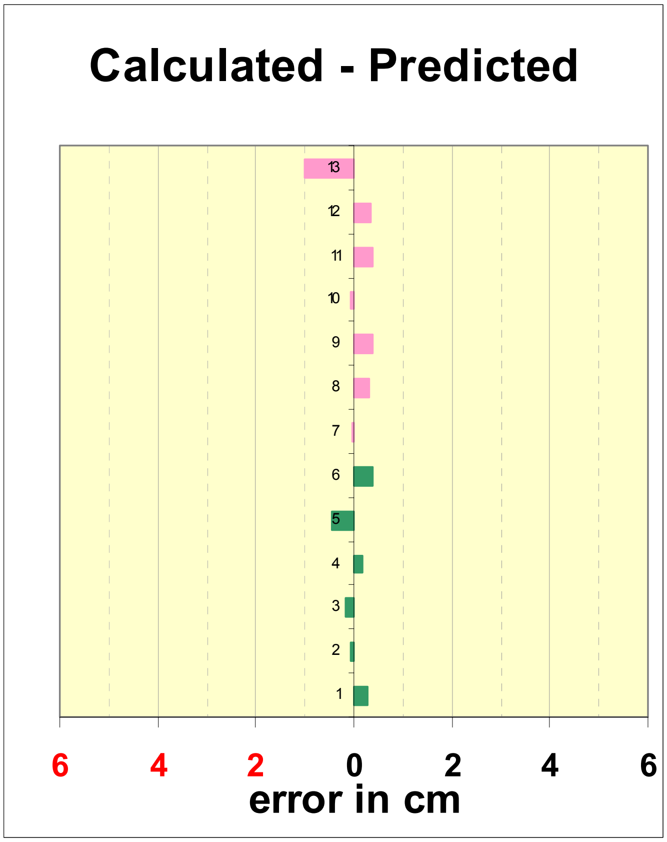


Figure 14. Modified landscape model individual drainage area performance.

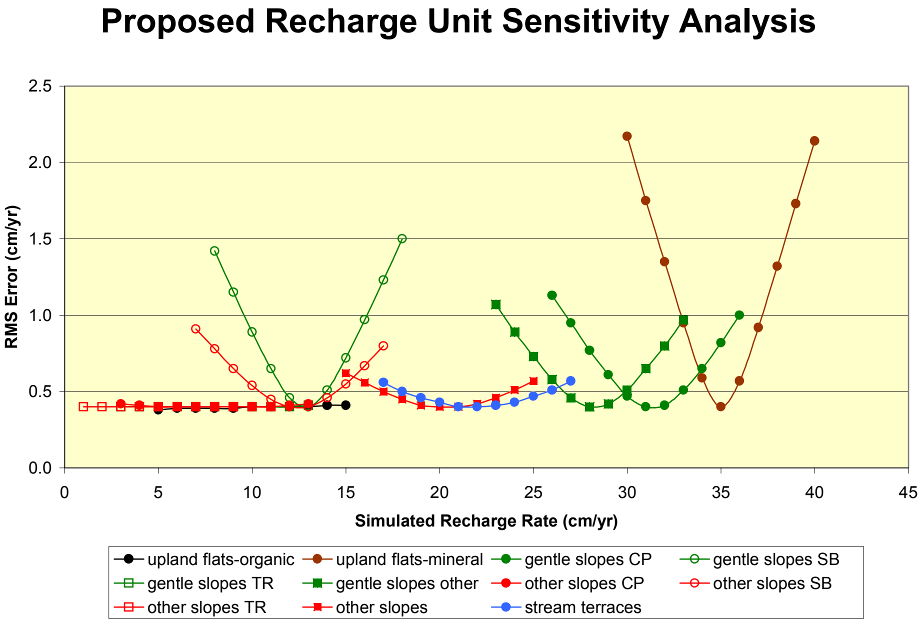


Figure 15. Recharge unit sensitivity analysis.

Table 3. Recharge Units, Landscape Units, and Final Recharge Rates

Recharge Units	*Recharge Rates*			*Landscape Units*
	cm/yr	*in/yr*	*gpd/mi^2*	
upland flats-organic	10	3.9	187,000	wet flats organic
upland flats-mineral	35	13.8	656,000	wet flats-ct mineral wet flats-ft mineral dry flats-ct CP dry flats-ft CP
gentle slopes CP	31	12.2	581,000	gentle slopes-ct CP gentle slopes-ft CP
gentle slopes SB	13	5.1	244,000	gentle slopes SB
gentle slopes TR	8	3.1	150,000	gentle slopes TR
gentle slopes other	28	11.0	524.000	gentle slopes other
other slopes CP	8	3.1	150,000	moderate slopes CP steep slopes CP
other slopes SB	12	4.7	225,000	moderate slopes SB steep slopes SB
other slopes TR	6	2.4	112,000	moderate slopes TR steep slopes TR
other slopes	20	7.9	374,000	moderate slopes other steep slopes other
stream terraces	22	8.7	412,000	stream terraces-ct stream terraces-ft
terraces organic	10	3.9	187,000	terraces organic
flood plains	0	0	0	flood plains
Estuarine Recharge Units				
barrier dunes	42	16.5	805,000	barrier dunes
back barriers	10	3.9	187,000	back barriers
beaches	0	0	0	beaches
marine terraces	10	3.9	187,000	marine terraces
marshes	0	0	0	marshes
Other Units				
urban land	6	2.4	112,000	urban land
water	0	0	0	water
undifferentiated	0	0	0	misc. units

SENSITIVITY ANALYSIS COMMENT

Several observations on our proposed modified landscape model can be made based on the sensitivity analysis illustrated in Figure 15 and the recharge units listed in Table 3. Of most significance, the model is calibrated based on a conceptual landscape setting of upland flats, valley slopes, and valley bottoms. Such a model is representative of the North Carolina Piedmont Province and Coastal Plain above 12 meters elevation (39 feet) mean sea level. The estuarine recharge units listed in Table 3 were estimated based on literature values and professional judgement, and are included to assist in complete river basin recharge estimation. The histogram shown in Figure 16 gives the relative aggregate percentage of each recharge unit used in the calibration. Four of these units: upland flats-organic, gentle slopes TR, other slopes CP, and other slopes TR, combined, represented only three percent of the calibrated area, and were insensitive to changes in the simulated recharge rates. In general, these units represent a minor percentage of the landscape setting, and we believe our recharge rate estimates are sufficient.

OTHER RECHARGE RATE COMMENT

Note that the recharge value for “other slopes CP” is significantly lower than most Piedmont rates in similar landscape settings. We believe this phenomenon is attributable to the nature of moderate slopes in the middle Coastal Plain. These slopes are mapped as narrow ribbons along major drainages (see cover illustration) and may reflect outcroppings or scarps of less permeable confining layers formed in coastal paleovalleys during ocean highstands. Other modeling we have done substantiates the low recharge rate assigned to this recharge unit. Note also that wet flats and dry flats, including both coarse and fine textured soils, were combined into a single upland flats-mineral recharge unit, based on the calibration results. We believe this result reflects two different phenomena, each contributing to the high recharge rate. Most of the upland wet flat areas are forested, creating extensive macropores for water to infiltrate into the subsurface, as discussed on page 5. Because the stream network has not advanced into these upland areas, much of the wet flat recharge is lost to evapotranspiration processes. Drainage ditches constructed in Coastal Plain dry flat areas, on the other hand, have allowed extensive farming in these areas, but much of the recharge to these dry flats percolates to the ditches, creating additional storage for infiltrating water. The distribution of recharge units shown in Figure 16 provides insight into the nature of the Piedmont/Coastal Plain landscape. Almost half the area receiving recharge in these 13 calibration drainages is composed of gently sloping landscape settings, and another third of the area is represented by mineral upland flats. However, the mineral flats accounted for 46% of the total recharge in these 13 drainages.

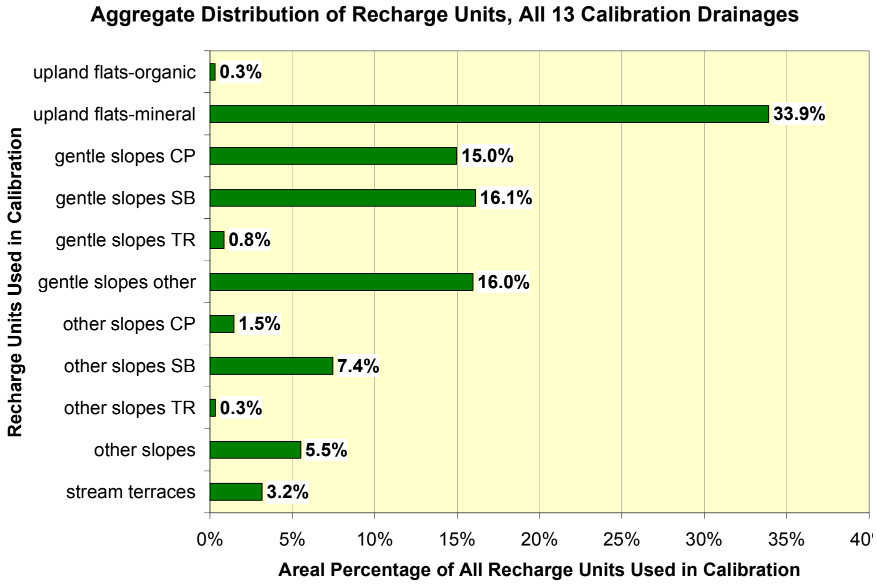


Figure 16. Distribution of recharge units in calibration drainages.

6.6 Other Simulation Models Investigated

DESCRIPTION OF MODELS

During the course of our research we investigated the ability of several available data sets to predict ground water recharge in the 13 calibration drainages. Each of these models investigated included some set of landscape units and weighted rainfall. We further subdivided the landscape units based on: mapped geology, soil permeability, or mineralogy. As discussed on page 22, Piedmont geologic regions used in our modeling were delineated based on the geologic parent material associated with each detailed soil mapping unit. We also modeled landscape units divided by geologic belt, and by the major metamorphic rock units of phyllites and argillites, based on the Geologic Map of North Carolina (Brown and Parker, 1985). We coupled the soil permeability model discussed on page 38 with the landscape model and also investigated soil permeability in terms of the classes used in the county soil reports: very rapid, rapid, moderately rapid, moderate, moderately slow, slow, and very slow. Finally, we divided the upland flat and valley slope landscape units by mineralogy using the following divisions: siliceous, mixed, kaolinitic, and montmorillonitic.

MODEL SIMULATIONS

For all of these alternative models, the RMS error in our objective function ranged between 1.5 and 2.5. None of the other models investigated performed as well as the modified landscape model.

6.7 Example of Modified Landscape Model Use

APPLICABILITY OF METHOD

Our ground water recharge mapping methodology can be employed at any scale using the modified landscape model, from an entire river basin to a small first order stream catchment. Analyses are performed using the GIS program ArcView (version 3.2) from Environmental Systems Research Institute (ESRI). Any GIS program that can read and manipulate ArcView shape files may be utilized. To illustrate the utility of this method, in this sub-section we develop recharge estimates, maps, and landscape analyses for a small 14-digit hydrologic unit sub-watershed in Wake County called Middle Creek south of Raleigh and east of Holly Springs. We selected this example because the sub-watershed spans three geologic regions and includes portions of the Coastal Plain. This Middle Creek hydrologic unit also represents a portion of the USGS gaged Middle Creek drainage area, shown as area number 10 in Figure 6 and Table 2 on page 31.

SOURCE OF DATA

Our method uses modified GIS digital soil coverages of the individual county soil surveys in ArcView 3.2 shapefile format (NC State Plane coordinate system, NAD 83), as explained on page 26. A complete set of individual county coverages will be available through the Groundwater Section by the end of 2002. Each county coverage contains the following fields or attributes for each mapped soil polygon (in addition to the standard ArcView fields):

Table 4. Fields Added to Digital County Soil Coverages

Field	*Description*
Musym	Soil mapping unit symbol
Landscape_	Landscape unit, shown in Table 3, see page 45
Recharge_u	Recharge unit, shown in Table 3, see page 45
Rain_in_yr	Polygon mean annual rainfall, see page 37
Recharge_c	Rainfall weighted recharge (cm/yr), see page 37
Recharge_g	Rainfall weighted recharge (gpd/mi^2)

SUB-WATERSHED DELINEATION

To create a shapefile of the Middle Creek hydrologic unit, we used the statewide hydrologic unit coverage available through the North Carolina Center for Geographic Information and Analysis (CGIA), selected the individual 14-digit unit, and created a new ArcView theme. We then used this theme and the ArcView GeoProcessing Wizard to clip a Middle Creek shapefile from our modified Wake County soils shapefile. In our version of ArcView we found that the GeoProcessing Wizard inaccurately calculated polygon areas in the clipped shapefile. To correct these area problems, we used a third party ArcView extension called XTools, available through ESRI, that calculated corrected areas for the clipped polygons and added the corrections to the shapefile (*.dbf) as a new field.

RECHARGE CALCULATIONS

To estimate recharge in the Middle Creek hydrologic unit, we applied the modified landscape model, using ArcView to aggregate and summarize individual fields by recharge unit. Specifically, we selected the Middle Creek theme, opened the theme table, selected the Recharge_u field, and used the summarize item listed under the Field menu. The corrected area field was summarized by summing values and the Recharge_c field was summarized by calculating the average value. Output from the created summary table is shown in Table 5.

Table 5. Example Recharge Estimation for Middle Creek Sub-Watershed, Wake County

*ArcView Summary Table (also *.dbf file)*				*Recharge Contribution*		
Recharge Unit	*Mean Weighted Rate (cm/yr)*	*Area (square meters)*	*Percent of Total Area*	*cm/yr*	*in/yr*	*gpd/mi^2*
upland flats-mineral	32.15	3,650,426	2.8	0.91	0.36	17,116
gentle slopes CP	28.46	25,631,962	19.9	5.68	2.23	106,386
gentle slopes SB	11.85	3,476,662	2.7	0.32	0.13	6,008
gentle slopes TR	7.24	2,707,125	2.1	0.15	0.06	2,858
gentle slopes other	25.55	35,373,449	27.5	7.03	2.77	131,807
other slopes CP	7.34	6,706,099	5.2	0.38	0.15	7,179
other slopes SB	10.95	7,303,909	5.7	0.62	0.24	11,664
other slopes TR	5.43	1,392,449	1.1	0.06	0.02	1,103
other slopes	18.26	38,740,051	30.1	5.50	2.17	103,165
stream terraces	20.10	3,545,055	2.8	0.55	0.22	10,392
flood plains	-	*ignore*				
undifferentiated	-	*ignore*				
water	-	*ignore*				
Totals:		128,527,187	100.0	21.22	8.35	~400,000

Note that areal measurements are in square meters, and that the model only considers recharge unit areas where ground water recharge actually occurs. Next we calculated the percent of total area for each recharge unit and multiplied this percentage by the mean weighted recharge weight for that unit (column 2) to obtain the recharge contribution from that recharge unit (column 5). Totaling the recharge unit contributions gives an estimate for ground water recharge occurring in the sub-watershed of 21.22 cm/yr. This value compares favorably with the baseflow estimate of 22.15 cm/yr for the larger gaged basin, which has a higher proportion of Coastal Plain soils. To convert from cm/yr to in/yr multiply cm/yr by 0.3937. Multiply in/yr by 47,610 to convert to gallons per day per square mile, and round the result.

LANDSCAPE ANALYSIS

Arcview can also be used to summarize landscape characteristics of the sub-watershed by summarizing on the Landscape_ field. The results of this type of analysis are presented in Table 6. Summary results are shown in units of acres for clarity of presentation.

Table 6. Example Landscape Analysis for Middle Creek Sub-Watershed, Wake County

Landscape Units	*Soil Texture and Geologic Regions*			*Landscape Units*		*Valley Model*	
	Area (m^2)	*acres*	*percent*	*acres*	*percent*	acres	*percent*
UPLAND FLATS						902	2.5
wet flats mineral				218	0.6		
coarse textured	89,080	22	0.1				
fine textured	792,170	196	0.5				
dry flats CP				684	1.9		
coarse textured	1,301,011	321	0.9				
fine textured	1,468,165	363	1.0				
VALLEY SLOPES						29,982	82.5
gentle slopes				16,803	45.7		
CP coarse textured	12,879,784	3,183	8.8				
CP fine textured	12,752,178	3,151	8.7				
SB Slate Belt	3,476,662	859	2.4				
TR Triassic Basin	2,707,125	669	1.8				
other	35,373,449	8,741	24.0				
moderate slopes				11,776	32.4		
CP Coastal Plain	6,706,099	1,657	4.6				
SB Slate Belt	6,640,752	1,641	4.5				
TR Triassic Basin	1,291,820	319	0.9				
other	33,017,218	8,159	22.4				
steep slopes				1,603	4.4		
SB Slate Belt	663,157	164	0.5				
TR Triassic Basin	100,629	25	0.1				
other	5,722,833	1,414	3.9				
VALLEY BOTTOMS						4,795	13.2
stream terraces				876	2.4		
fine textured	3,545,055	876	2.4				
flood plains	15,860,423	3,919	10.8				
Other Units						676	1.9
water	2,141,540	529	1.5	529	1.5		
misc. units	594,347	147	0.4	147	0.4		
Totals:	147,123,497	36,355	100.0	36,355	100.0	36,355	100.0

Based on the above table, it appears that Piedmont soils cover about three quarters of the Middle Creek sub-watershed, and that valley slopes are the predominant landform. Gentle slopes account for more than half of these slopes, while steep slopes represent less than 5 percent of the total area.

LANDSCAPE MAPPING

The Middle Creek shapefile we created can also be viewed in ArcView, as illustrated in Figure 17, using a legend created from the Landscape_ field. Figure 17 illustrates the Piedmont moderate to steep slopes in the north and west part of the sub-watershed, with Coastal Plain soils to the south. A few remnant dry flats in the upper reaches of a tributary to Middle Creek can also bee seen. The steeper slopes form along the sides of stream channels, while the gentle slopes form divides or interfluves between the streams. The large footprint of the Middle Creek stream terraces and flood plains running along the middle of the illustration is also readily visible. Sunset and Bass lakes, located east of the town of Holly Springs (not shown) are visible just left of center in Figure 17.

RECHARGE MAPPING

Figure 18 illustrates the ground water recharge map prepared for the Middle Creek sub-watershed. This map was created from the same coverage used to prepare Figure 17, but applying a different ArcView legend.

MAP INTERPRETATION

Figure 18 provides insight into the nature of ground water recharge in the Middle Creek sub-watershed. Prominent in the illustration are the brown-colored ground water discharge areas, or flood plains, along major stream channels. In our model flood plains were assigned a zero recharge value because they are primarily ground water discharge areas. The effects of underlying geology on ground water recharge can be seen in the upper left hand corner of Figure 18. The yellow-orange colored areas with less than 10 cm/yr recharge lie in the Triassic Basin. The adjacent light-green colored areas with 10-15 cm/yr recharge occur on Slate Belt soils. Some gently sloping Slate Belt soils can also be seen along Middle Creek and its tributaries to the east in Figure 18. The darker green areas primarily to the north of Middle Creek with 15-20 cm/yr recharge represent moderate to steeply sloping Raleigh Belt soils, which we have classified as “other slopes” in terms of recharge. The teal colored areas with 25-30 cm/yr recharge are primarily the gentle slopes of the Raleigh Belt and upper Coastal Plain that form the interfluves between streams. Because of rainfall weighting, both Coastal Plain and “other” gentle slopes fall in the same classification bin of 25-30 cm/yr recharge. The dark blue areas with 30-35 cm/yr recharge to the bottom are the Coastal Plain upland flats along the transition zone between the Piedmont and Coastal Plain provinces.

OTHER OBSERVATIONS

Figure 18 also illustrates two conditions that should be considered when interpreting these recharge maps. First, note that the teal-colored gentle slopes appear to abruptly end about two thirds of the way up the map. This phenomenon represents an artifact of the classification scheme used and rainfall weighting. These gentle slopes extend to the top of the map, but rainfall is less in the northern portion of the sub-watershed, placing recharge values in a lower classification bin. Also note the lower recharge values assigned to Coastal Plain moderate slopes in the lower part of the figure. Coastal Plain moderate slope recharge values were calibrated based primarily on middle Coastal Plain drainages. Nearer the Piedmont-Coastal Plain transition zone, these moderate slopes are less ribbon like (as discussed on page 46), and more similar to the “gentle slopes other” of the Piedmont. Delineation of such change exceeded our scope of work, but recharge rate changes might be appropriate on a project by project basis.

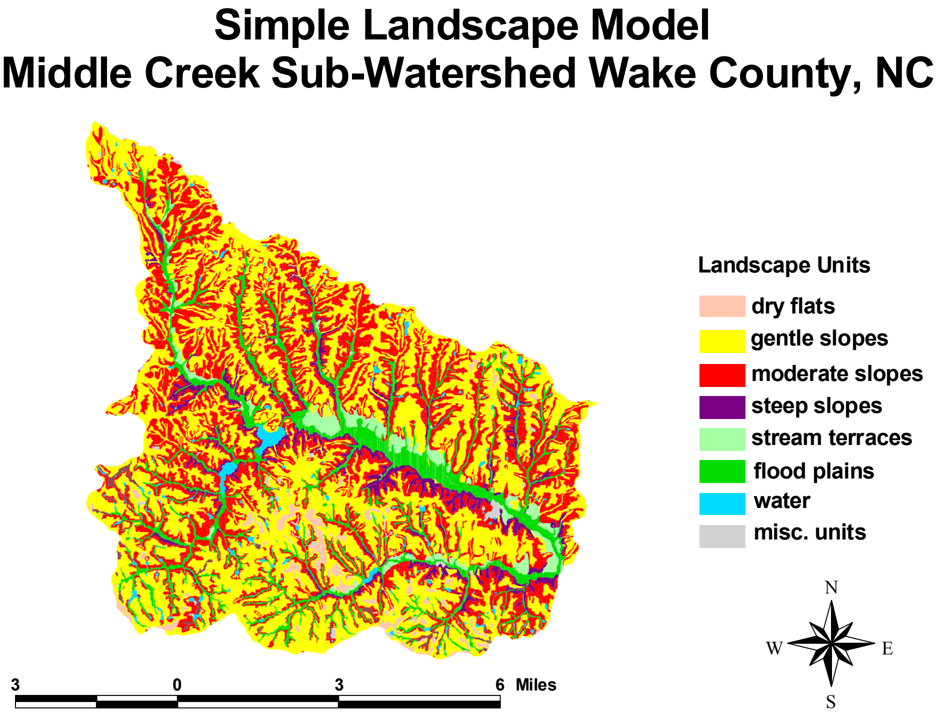


Figure 17. Middle Creek sub-watershed landscape model.

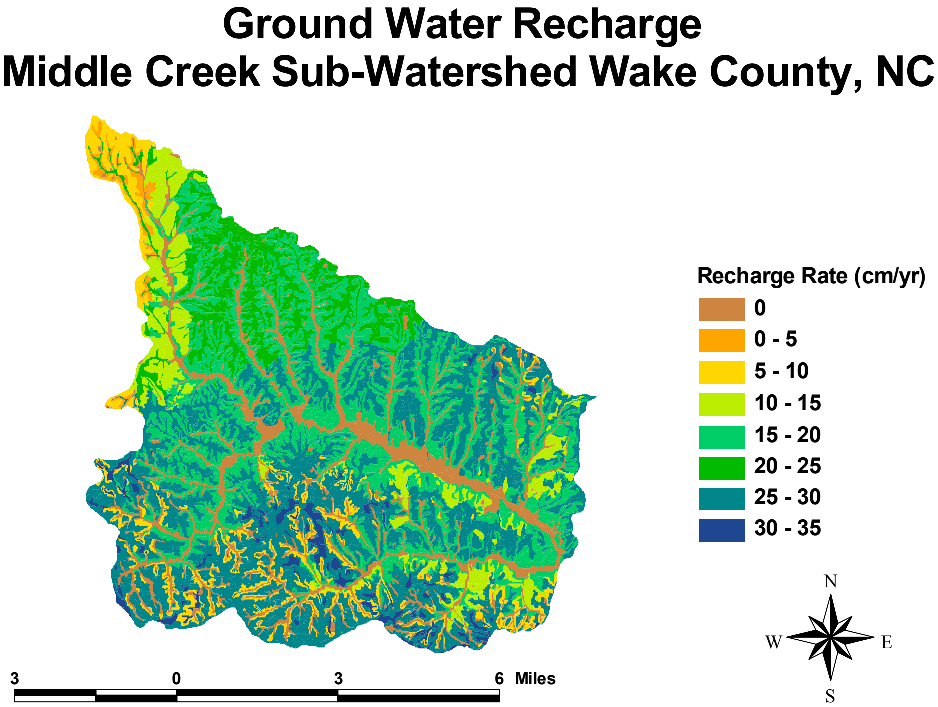


Figure 18. Middle Creek sub-watershed ground water recharge model.

SECTION 7

Summary, Applicability, and Limitations

OVERVIEW

This report presents a method for mapping average, annual ground water recharge in the Piedmont and Coastal Plain provinces of North Carolina. Section 7 briefly summarizes the report, by section, then discusses the applicability and limitations of the methodology developed.

7.1 Summary

1. HYDROGEOLOGIC CONCEPTS

Section 1 introduces the concepts of ground water recharge and the movement or flow of ground water from upland recharge areas to lower riverine areas of ground water discharge within a drainage basin. Several factors controlling the rate of ground water recharge are discussed, including depth to the water table, slope of the land surface, and infiltration capacity of the unsaturated soil profile. Various methods for estimating ground water recharge are also summarized. The hydrogeologic concepts presented in Section 1 form the basis for the mapping methodology we develop beginning in Section 4.

2. RELATED STUDIES

Section 2 reviews related ground water recharge studies in Virginia, New Jersey, and North Carolina. As Section 2 documents, stream hydrograph separation models are being used by several state and federal agencies to estimate ground water recharge and the ground water contribution to streamflow.

3. LANDSCAPE AND SOILS

Our recharge methodology focuses on the drainage basin, dividing the landscape into upland flats, valley slopes, and valley bottoms using detailed county soil mapping units. Section 3 reviews the classification schemes we use to divide the landscape and explains how soils are mapped in the field. By differentiating landscape settings, we provide a visual tool to enhance insight into the movement of water and transport of pollutants through the basin. Within the basin soils regulate the infiltration of water into the ground-water system and provide storage for water in the unsaturated zone above the water table.

4. MAPPING METHODOLOGY

Section 4 describes the methodology used to create the ground water recharge maps and explains how mapping problems were resolved. In this section we provide the detailed criteria used to combine soil mapping units into hydrogeologic areas having similar recharge characteristics, and describe the hydrologic setting in which each area is found. We also explain how mapping problems, such as stream-terrace delineation, soil mapping units occurring in multiple landscape settings, and edge matching problems between counties were resolved. Section 4 provides a self-contained description of how the ground-water recharge maps are created.

5. RECHARGE ESTIMATION

Section 5 documents our methodology to estimate ground water recharge. This methodology uses Monte Carlo simulation techniques to calibrate simulated ground water recharge estimates to calculated recharge in 13 gaged USGS drainage areas. In each gaged drainage, ground water discharge is calculated using the Rorabaugh-Daniel stream hydrograph separation method and equated with total recharge to the area. For each simulation, a set of decision rules is used to randomly select recharge values for the hydrogeologic areas found within the drainage. These estimates are weighted by local rainfall and aggregated to estimate a recharge value for the drainage. This simulated drainage value is subtracted from the calculated recharge value to estimate error. A root mean square (RMS) error objective function is then used to determine an error value for the simulation. The simulation objective is to minimize this aggregate RMS error. A sensitivity analysis determines the final estimated recharge values.

6. ALTERNATIVE MODELS

In Section 6 five simulation models to estimate ground water recharge are evaluated. These different models illustrate which variables most effectively simulate calculated recharge in the 13 gaged drainages. Evaluated models include: uniform recharge, weighted rainfall, soil permeability, and simple and modified landscape models. An example applying the modified landscape model is also presented.

7.2 Applicability

USES OF METHOD

We originally developed the recharge methodology presented in this report to estimate the ground-water contribution to streamflow at the sub-watershed level (explained in Appendix B) in North Carolina's Neuse and Tar-Pamlico river basins. The method, however, is applicable from first order catchments to entire river basins in the Piedmont and Coastal Plain provinces of North Carolina, and quite possibly in similar regions of the southeastern United States as well. The recharge maps created using these techniques offer a visual perspective of the basin landscape that differentiates upland recharge areas from discharge areas found in the valley bottoms along stream channels. Such visualization provides insight into the role geomorphic processes play in shaping the landscape and creating pathways for the movement of water.

7.3 Limitations

EFFECTIVENESS OF METHOD

Our techniques provide a consistent methodology for mapping ground water recharge in the Piedmont and Coastal Plain regions of North Carolina. Recharge rate estimates have been developed using accepted stream hydrograph separation techniques and the Rorabaugh Daniel model. Using the modified landscape model and Monte Carlo simulation calibrated to USGS gaged drainage areas, we obtained good recharge estimates that appeared to fit conditions in different drainage settings.

LIMITATIONS OF METHOD

These estimates of ground-water recharge and discharge, however, reflect average, annual estimates based on 20 years of streamflow records between 1967 to 1986. The estimates do not account for variations between years due to variable rainfall patterns, the inherent variability in individual storm events, nor do they differentiate subsurface interflow from ground water flow beneath the water table. The methodology reflects a regional, steady-state approach, averaging conditions over time and space. The techniques do not account for changes in land use, except where soils have been mapped as urban. Any site-specific implementation of these techniques should take local conditions into consideration, including vegetation and land use. Finally, these base-flow separation techniques are empirical tools lacking a firm physical basis, as Nathan and McMahon (1990) and Halford and Mayer (2000) succinctly document.

CONCLUSION

Despite these limitations, we believe our methodology is sufficient to solve the immediate problem facing North Carolina of estimating, on a regional scale, the ground-water contribution to stream flow in the State’s rivers and streams. The recharge estimates are reasonable and provide a consistent statewide methodology for average annual baseflow estimates in the in the Piedmont and Coastal Plain.

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APPENDIX A

Soil Characteristics Used to Map Recharge

INTRODUCTION

Appendix A provides a more detailed description of the different soil characteristics used in our recharge methodology. These characteristics include slope gradient, drainage class, and soil texture. Before defining these terms, however, it is important to note the differences between organic and inorganic soils.

ORGANIC AND INORGANIC SOILS

Two major types of soils occur worldwide; organic and inorganic. Organic soils are those soils that contain 12 to 18 percent organic carbon by weight, depending upon clay content, and are at least 16 inches or more in thickness. These are the peats, mucks, mulls, etc., formed under conditions where the rate of organic accumulation exceeds oxidation. With few exceptions, these soils occur in landscape positions where they remain saturated under anaerobic conditions for the majority of the year. All other soils are mineral soils.

SLOPE GRADIENT

The USDA Natural Resources Conservation Service (NRCS) classifies slopes based on the type of landscape in an area so that landscape units can be identified and mapped consistently. The term *slope gradient* is used to designate the predominate percent grades in the mapped unit. The NRCS recognizes two sets of slope classes, simple and complex slopes. A complex slope is one that is multidirectional and complicated by ridges and depressions within the delineation, as compared with a simple slope that has a relatively smooth grade. In terms of ground water recharge, as slopes become steeper, more water will tend to run across the surface down the slope, rather than infiltrating into the subsurface. Also, steeper slopes tend to be more highly eroded. Erosion removes the more porous surface layers of the soil that are better able to retain water. The NRCS uses the following slope classes (USDA, Soil Conservation Service 1983):

Table 7. Slope Classification Used by Natural Resources Conservation Service

Classes		*Slope Gradient*	
Simple Slopes	*Complex Slopes*	*Lower Limit (%)*	*Upper Limit (%)*
nearly level	nearly level	0	1–3
very gently sloping or gently sloping	gently undulating or undulating	1–3	5–8
moderately sloping or strongly sloping	gently rolling or rolling	4–8	8–16
moderately steep	hilly	10–16	18–30
steep	very hilly	20–30	30–60
very steep	very steep	45–65	–

DRAINAGE CLASS

Drainage class refers to the frequency and duration of periods of saturation or partial saturation during soil formation, as opposed to altered drainage, which is commonly the result of artificial drainage or irrigation but may be caused by the sudden deepening of channels or the blocking of drainage outlets. Seven classes of natural soil drainage are recognized (North Carolina Soils Staff 1994):

- *Excessively drained*. Water is removed from the soil very rapidly. The occurrence of free water commonly is very deep; annual duration is not specified. The soils are commonly very coarse textured or rocky. All are free of mottling related to wetness. The soil has very rapid permeability and the water table is greater than 5.0 feet below the soil surface. Low chroma colors, if present within 5.0 feet of the soil surface, are uncoated sand or are lithochromic.

- *Somewhat excessively drained*. Water is removed from the soil rapidly. Internal free water occurrence is commonly very deep; annual duration is not specified. The soils are commonly sandy and very pervious. All are free of mottling that is related to wetness. The soil has rapid permeability and the water table greater than 5.0 feet below the soil surface. Low chroma colors, if present within 5.0 feet of the soil surface, are uncoated sand or are lithochromic.

- *Well drained.* Water is removed from the soil readily, but not rapidly. Internal free water occurrence is deep or very deep; annual duration is not specified. Water is available to plants throughout the growing season in humid regions. Wetness does not inhibit growth or roots for significant periods. The soil surface and permeability is moderately rapid or slower. Low chroma colors, if present within 4.0 feet of the soil surface, are uncoated sand or are lithochromic. If an umbric horizon is present, it is due to cool temperature.

- *Moderately well drained.* Water is removed from the soil somewhat slowly during some periods of the year. Internal free water occurrence commonly is moderately deep and transitory through permanent. The soils are wet for only a short period of time within the rooting depth during the growing season, but long enough that most mesophytic crops are affected. They commonly have a slowly previous layer within 40 inches, periodically receive high rainfall, or both. The water table is 2.0 to 4.0 feet below the soil surface with any permeability. A few series overlap moderately well drained and somewhat poorly drained classes and list 1.5 to 2.5 feet depth for the water table in their range. If an umbric horizon is present, it is due to cool temperature.

- *Somewhat poorly drained.* Water is removed slowly so that the soil is wet at shallow depth for significant periods during the growing season. The occurrence of internal free water commonly in shallow and transitory or common. Wetness markedly restricts the growth of mesophytic crops, unless artificial drainage is provided. The soils commonly have one or more of the following: slowly previous layer, a high water table, additional water from seepage, or nearly continuous rainfall. The soil can have any permeability and the water table is 1.0 to 2.0 feet below the soil surface (usually 1.0 to 1.5). The soil always has a subhorizon with dominant chroma of 3 or more in the upper 2.5 feet, usually immediately below the epipedon.

- *Poorly drained.* Water is removed so slowly that the soil is wet at shallow depths periodically during the growing season or remains for long periods. The occurrence of internal free water is shallow or very shallow and common or persistent. Free water is commonly at or near the surface long enough during the growing season that most mesophytic crops can not be grown, unless the soil is artificially drained. The soil however is not continuously wet directly below the plow layer. Free water at shallow depth is usually present. This water table is commonly the result of a slowly pervious layer of seepage, or nearly continuous rainfall, or a combination of these. The soil can have any permeability and the water table is 0 to 1.0 foot below the surface. The soil has a dominant chroma of 2 or less throughout, unless color is from coated or uncoated fragments. If the soil has a umbric or mollic epipedon it is due to cool temperature.

- *Very poorly drained.* Water is removed from the soil so slowly that free water remains at or very near the ground surface during much of the growing season. The occurrence of internal free water is very shallow and persistent or permanent. Unless the soil is artificially drained, most mesophytic crops can not be grown. The soils are commonly level or depressed and frequently ponded. If rainfall is high or nearly continuous, slope gradients may be greater. The soil can have any permeability and the water table is 0 to 1.0 foot below the soil surface. The soil has a dominant chroma of 2 or less usually present. Very wet soils, such as in marshes, may not have an umbric or mollic epipedon.

SOIL TEXTURE

Soil texture measures the percentages of the inorganic soil particle sizes and directly influences the infiltration capacity of the soil. All other factors being equal, soils with finer textures tend to have less infiltration capacity than those with coarser textures. The term loam is used for soils with certain percentages of sand, silt, and clay particles, and has nothing to do with the organic content of the soil. Generally speaking, loam is a mixture of equal percentages of sand and silt, with slightly less clay. All textural subdivisions discussed in this report refer to the textural class of the profile control section. The specific control section varies between types of soils, but in general terms, it is the average texture of the entire soil profile. Soil taxonomy provides the textural description used in our methodology, not the texture of the surface horizon sometimes listed in county soil reports. For example, “Gritney fine sandy loam” is a textural description that refers to the surface horizon for one phase of all possible Gritney soil mapping units. The actual control section texture of all Gritney soils is defined by taxonomy as clayey. All soil series are defined by a single control section textural class. In some of our landscape unit classes, we differentiated coarse textured and fine textured soils. Soils where the texture of the control section was classed as loamy or coarser were grouped as coarse textured. If the texture was classed as fine loamy or finer, we grouped the soil as fine textured.

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APPENDIX B

River Basins, Subbasins, and Hydrologic Units

BACKGROUND

In our report the terms river basin, subbasin, watershed, sub-watershed, and hydrologic unit are frequently used. These terms have specific meanings when describing the stream network in North Carolina. Appendix B discusses each of these terms and explains the development of hydrologic unit codes in the State. As pertinent background, the New World Dictionary (Guralnik 1976) defines basin as all the land drained by a river and its branches. A catchment is defined as the area draining into a river, reservoir, etc.

STREAM CLASSIFICATIONS

As part of our mapping project, recharge estimates have been developed for individual stream segments within the Neuse and Tar-Pamlico river basins. In trying to identify representative stream segments, however, we encountered a stream classification problem involving differing federal and State methods for subdividing river basins. To help the reader understand the nature of this problem, we have outlined in the following paragraphs the different methods employed by federal and State agencies in classifying streams segments in North Carolina.

FEDERAL SYSTEM 8-DIGIT HYDROLOGIC UNIT

Development of the federal system for classifying stream segments has been succinctly summarized by Biggerstaff (USDA Natural Resources Conservation Service 1995) in the report, *North Carolina Cooperative Hydrologic Unit River Basin Study*:

> *Under the sponsorship of the Water Resources Council, a nationally uniform hydrologic unit system was developed in 1974 by the U. S. Geological Survey's Office of Water Data Coordination. This system divides the country into 21 regions, 222 sub-regions, 352 accounting units, and 2,149 cataloging units based on surface hydrologic features. A hierarchical code consisting of two digits for each of the above four levels combine to form an eight-digit hydrologic unit. The hydrologic unit system is used to identify any hydrologic area of interest. An eight-digit hydrologic unit generally covers 700 or more square miles.*

8-DIGIT EXAMPLE

The Neuse and Tar-Pamlico river basins can be used to illustrate this 8-digit classification system. As shown in Table 8, the headwater subbasins for the Tar-Pamlico, 03020101, and Neuse, 03020201, rivers can be identified using the 8-digit code.

Table 8. Example of 8-Digit Federal Hydrologic Unit Code

hydrologic code	*subdivision*	*specific name*
03	region	South Atlantic - Gulf region
03 02	subregion	Neuse - Pamlico River Basins
03 02 01	accounting unit	Tar, Pamlico, White Oak Rivers
03 02 01 01	cataloging unit	Upper Tar River subbasin
03 02 02	accounting unit	Neuse River, excluding sound
03 02 02 01	cataloging unit	Upper Neuse River subbasin

Note that both the Neuse and Tar-Pamlico basins are grouped into the same subregion, and are only differentiated at the accounting unit level. Using this system, four cataloging units, or subbasins, are identified for both the Neuse and Tar-Pamlico rivers. In addition, Pamlico Sound is designated 03020105, and Core Sound and the White Oak River below the Neuse basin are designated 03020106. These 8-digit codes were mapped by the U. S. Geological survey in 1974 (U. S. Geological Survey 1974).

FEDERAL SYSTEM
11-DIGIT HYDROLOGIC UNIT

In 1978 the USDA Soil Conservation Service (SCS) initiated a national program to further subdivide the 8-digit hydrologic unit codes into sub-watershed sized areas for use in water resource planning. These sub-watershed areas were nominally sized at 250,000 acres, or 390 square miles. An extension of three digits, designated a “sub-unit,” was added to the 8-digit codes forming an 11-digit hydrologic unit code (HUC) to designate sub-watersheds (USDA Natural Resources Conservation Service 1995). In our Tar-Pamlico study area there are 49 sub-watershed areas, and in the Neuse, 50 areas.

FEDERAL SYSTEM
14-DIGIT HYDROLOGIC UNIT

In the early 1990s the SCS, which has since been renamed the Natural Resources Conservation Service (NRCS), expanded the 11-digit hydrologic unit designation to 14 digits, by adding a 3-digit “reporting unit.” This expansion was necessitated by the need to more accurately target project activities and to account for the results of these activities. These 14-digit units ranged in size from approximately 4,000 acres (6 square miles) to 50,000 acres (78 square miles). Within North Carolina the State NRCS office coordinated the delineation of these 14-digit units with federal, State, and private agencies, attempting to reconcile the delineations with existing boundaries previously designated by other agencies, including terminating these units at USGS stream gaging stations, where practical. The NRCS report (USDA, NRCS 1995) delineates all the 14-digit hydrologic units in the State. A copy of the 14-digit hydrologic unit coverage for the entire State is available in digital format through the North Carolina Center for Geographic Information and Analysis (CGIA). Within the Tar-Pamlico river basin we identified 168 14-digit hydrologic units, and within the Neuse 200 units.

RECENT FEDERAL INITIATIVES

More recently the U. S. Geological Survey and member agencies of the Federal Geographic Data Committee (FGDC), Spatial Water Data Subcommittee have been coordinating and conducting a series of regional workshops to promote the development of a nationally consistent hydrologic unit coverage. Under this new standard 11 and 14-digit hydrologic units will be reduced to 10 and 12-digit hydrologic units. A draft report from this committee entitled, "Federal Standards for Delineation of Hydrologic Unit Boundaries," has been circulated among stakeholders.

3-CHARACTER MAP UNITS

With development of the 14-digit code, the NRCS had created a detailed system for classifying segments of the stream network in North Carolina. However, these 14 digit codes were difficult to represent on maps because of their length, and also, such units were cumbersome to discuss in conversation. As an alternative to 14-digit numbers, Biggerstaff, in his 1995 report, used 3-character codes to designate the 14-digit hydrologic units on North Carolina county maps. The 3-character code was comprised of an initial letter (A–Z), followed by a two digit code. The initial letters represented major streams in the State, or portions thereof, e.g., the upper Tar River is identified by the letter "E." The following two digits represent, approximately, upstream hydrologic units within the major stream, beginning at the mouth of the stream. In Biggerstaff's report these 3-character codes were called "CAMPS" numbers for a now defunct accounting system. We call the 3-character hydrologic unit attribute a "Map #."

EVOLVING STATE SYSTEM

The State of North Carolina has been involved in river basin planning since the 1920s. By the early 1970s a set of 17 river basins had evolved, designated simply as 01 to 16 by the N. C. Department of Natural and Economic Resources, with the Savannah basin designated 07A. At that time the Environmental Protection Agency recognized 13 basins in North Carolina, with the Neuse basin designated 03-04, and the Tar-Pamlico as 03-03. During the 1970s federal funding supported several river basin planning activities within the State, and North Carolina adopted the EPA river basin designations, but still recognized 17 river basins within the State. To this day the Division of Water Quality still uses these EPA codes.

COMPARING FEDERAL AND STATE SYSTEMS

The cooperative effort within North Carolina to develop 14-digit hydrologic unit codes attempted to reconcile differences between stream classifications among various federal and state agencies. At the 14-digit level this objective was accomplished. In other words, the integrity of each of the federal 14-digit hydrologic units is maintained within the state river basin classification system, i.e., each state category is composed of one or more 14-digit hydrologic units. This correspondence breaks down, however, at the 8-digit and 11-digit levels designating cataloging units and sub-watershed boundaries, especially near the coast. To illustrate, Table 9 compares the subbasin and 14-digit hydrologic unit designations used by the Division of Water Quality in the Tar-Pamlico basin, with hydrologic units shown as 3-character codes. Note the good correspondence between subbasins 03-03-01 and 03-03-02 and the hydrologic units. This correspondence begins to break down in the coastal subbasins at the bottom of the table.

Table 9. Tar-Pamlico DWQ Subbasins and Hydrologic Units

DWQ subbasin	*acres*	*sq. miles*	*hydrologic units (map #s)*
03-03-01	410,906	642.04	E27-E56
03-03-02	424,168	662.76	E01-E26
03-03-03	270,995	423.43	D14-D18, D20-D31
03-03-04	571,463	892.91	D32-D67
03-03-05	190,352	297.42	D06-D13, D19, D70
03-03-06	155,316	242.68	D01-D05
03-03-07	761,604	1,190.01	C55-C63, C65-C86, C97
03-03-08	780,703	1,219.85	C30, C35-C37, C40-C47
totals:	3,565,508	5,571.11	168 hydrologic units