Methods of Rating Unsaturated Zone and Watershed Characteristics of Public Water Supplies in North Carolina

By Jo Leslie Eimers, J. Curtis Weaver, Silvia Terziotti, and Robert W. Midgette

---

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 99–4283

Prepared in cooperation with the

Public Water Supply Section of the Division of Environmental Health,
North Carolina Department of Environment and Natural Resources

Raleigh, North Carolina
2000

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

For additional information write to:

District Chief
U.S. Geological Survey
3916 Sunset Ridge Road
Raleigh, NC 27607

Copies of this report can be purchased from:

U.S. Geological Survey
Information Services
Box 25286, Federal Center
Denver, CO 80225

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS, TEMPERATURE, VERTICAL DATUM, AND ACRONYMS

Multiply	by	To obtain
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
	Flow	
foot squared per day (ft^2/d)	0.0929	meter squared per day

Temperature: In this report, temperature is given in degrees Fahrenheit (°F), which can be converted to degrees Celsius (°C) by using the following equation:

$$°C = 5/9\ (°F - 32)$$

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929), a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Acronyms used in this report:

AMC	ARC/INFO macro language
BFI	base-flow index
DEM	Digital Elevation Model
DENR	Department of Environment and Natural Resources
DLG	digital line graph
EDC	EROS Data Center
GIS	Geographic Information System
HMK	harmonic mean hydraulic conductivity
LANDSAT	Land Remote Sensing Satellite
MLRC	Multi-Resolution Land Characteristics
MUIR	Map Unit Interpretation Record
NAWQA	National Water-Quality Assessment
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
NWI	National Wetlands Inventory
PRISM	Parameter-Elevation Regressions on Independent Slopes Model
PWSS	Public Water Supply Section
SCS	Soil Conservation Service
SDWA	Safe Drinking Water Act
SSURGO	Soil Survey Geographic data base
STATSGO	State Soil Geographic data base
SWAP	Source Water Assessment Program
TM	Thematic Mapper
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

Methods of Rating Unsaturated Zone and Watershed Characteristics of Public Water Supplies in North Carolina

By Jo Leslie Eimers, J. Curtis Weaver, Silvia Terziotti, and Robert W. Midgette

ABSTRACT

Overlay and index methods were derived for rating the unsaturated zone and watershed characteristics for use by the State of North Carolina in assessing more than 11,000 public water-supply wells and approximately 245 public surface-water intakes. The rating of the unsaturated zone and watershed characteristics represents a practical and effective means of assessing part of the inherent vulnerability of water supplies to potential contamination. Factors that influence the inherent vulnerability of the drinking water supply to potential contamination were selected and assigned ratings (on a scale of 1 to 10) to cover the possible range of values in North Carolina. These factors were assigned weights of 1, 2, or 3 to reflect their relative influence on the inherent vulnerability of the drinking water supply. The factor values were obtained from Geographic Information System data layers, and were transformed into grids having 60-meter by 60-meter cells, with each cell being assigned a value.

Identification of factors, the development of ratings for each, and assignment of weights were based on (1) a literature search, which included examination of potential factors and their effects on the drinking water; and (2) consultation with experts in the science and engineering of hydrology, geology, forestry, agriculture, and water management.

Factors selected for rating the inherent vulnerability of the unsaturated zone are vertical hydraulic conductance, land-surface slope, land cover, and land use. Vertical hydraulic conductance is a measure of the capacity of unsaturated material to transmit water. Land-surface slope influences whether precipitation runs off land surfaces or infiltrates into the subsurface. Land cover, the physical overlay of the land surface, influences the amount of precipitation that becomes overland flow or infiltrates into the subsurface. Land use describes activities that occur on the land surface and influence the potential generation of nonpoint-source contamination.

Factors selected for rating the watershed characteristics upstream from surface-water intakes are average annual precipitation, land-surface slope, land cover, land use, and ground-water contribution. The average annual precipitation represents the mass of water that becomes available for transport in a watershed. Land-surface slope, land cover, and land use have similar influences in watersheds as those identified for the unsaturated zone. Ground-water contribution represents the part of streamflow that is derived from ground-water discharge.

INTRODUCTION

The need for high-quality drinking water supplies in North Carolina has become more critical in recent years as population growth and economic development have become widespread. The Federal Safe Drinking Water Act (SDWA) Amendments of 1996 emphasize pollution prevention as an important strategy for the protection of ground-water and surface-water resources. This new focus in the SDWA promotes the prevention of drinking water contamination as a cost-effective means of ensuring reliable, long-term, and safe drinking water sources for public water-supply systems (North Carolina Department of Environment and Natural Resources, 1999a). Specifically, Section 1453 of the SDWA Amendments requires that States develop and implement a Source Water Assessment Program (SWAP) to delineate source water areas, inventory potential contaminants in these areas, and determine the susceptibility of each public water supply to contamination. Guidance in developing a SWAP plan is provided by the U.S. Environmental Protection Agency (USEPA; U.S. Environmental Protection Agency, 1997). North Carolina's source water protection strategy is to build upon existing programs and activities with a program that is non-regulatory, state implemented, and incentives driven, (North Carolina Department of Environment and Natural Resources, 1999a).

The agency charged with the task of susceptibility assessment in North Carolina is the Public Water Supply Section (PWSS) of the Department of Environment and Natural Resources. The U.S. Geological Survey (USGS) is directed under the Clean Water Action Plan, funded by Congress in 1999, to assist States with water-quality monitoring and susceptibility determinations.

In February 1999, the PWSS submitted a SWAP plan to the USEPA describing a method for assessing the susceptibility to contamination of more than 11,000 wells and approximately 245 surface-water intakes in North Carolina. To develop the method and procedures described in the SWAP plan, the PWSS convened a Technical and Citizens Advisory Committee. The committee reviewed draft proposals prepared by PWSS staff, discussed alternatives, and provided recommendations. This process resulted in the decision that the determination of overall susceptibility of each public ground-water supply well and surface-water intake should be based on two key components—a contaminant rating and an inherent vulnerability rating.

The contaminant rating is determined by the PWSS from an inventory of existing data bases of potential contaminant sources. Additional factors include the density of contaminant sources in the delineated area, proximity to the intake, and the relative risk of the contaminants to the public water supply.

The inherent vulnerability rating is a measure of the potential for contaminants within a delineated source area to reach the ground-water or surface-water supply. The inherent vulnerability of a ground-water source of public water supply is determined by combining an aquifer rating and an unsaturated zone rating (North Carolina Department of Environment and Natural Resources, 1999a). The inherent vulnerability of a surface-water source of public water supply is determined by combining a watershed classification, intake location, raw water quality (water plant data), North Carolina Division of Water Quality Use Support rating, and watershed characteristics rating (North Carolina Department of Environment and Natural Resources, 1999a). In cooperation with the PWSS, the USGS developed methods to rate unsaturated zones for public ground-water systems and watershed characteristics for public surface-water intakes. All other components of inherent vulnerability were compiled by the PWSS.

Developing methods for rating unsaturated zone and watershed characteristics required identification of factors affecting the transport of water through the unsaturated zone or watershed. These factors were used to construct the ratings by an overlay and index method (National Research Council, 1993). The specific unsaturated zone and watershed characteristics ratings used in this report are not necessarily transferable to other regions; however, the methods used to develop the ratings are transferable.

Purpose and Scope

The purpose of this report is to present methods to rate the unsaturated zone for public ground-water supplies and watershed characteristics for public surface-water supplies in North Carolina, and to show an example calculation for both unsaturated zone and watershed characteristics ratings. Factors contributing to the ratings of the unsaturated zone and watershed characteristics are presented, and limitations of this statewide overlay and index rating system are discussed.

For ground-water supplies, the selected contributing factors include vertical hydraulic conductance, land-surface slope, land cover, and land use. The selected factors contributing to watershed characteristics ratings are average annual precipitation, land-surface slope, land cover, land use, and ground-water contribution. Methods for determining unsaturated zone and watershed characteristics ratings are presented for an unnamed well and an unnamed surface-water intake.

Acknowledgments

The authors are grateful to colleagues in the Public Water Supply Section of the North Carolina Division of Environmental Health, Department of Environment and Natural Resources (DENR), for their assistance in this collaborative project—Elizabeth Morey, Hydrogeologist; Gale Johnson, Hydrogeologist; and Rajpreet Butalia, Geographic Information Systems Coordinator.

The authors also gratefully acknowledge the following scientists and engineers who provided additional technical review of this work:

- Richard Burns, Watershed and Forest Hydrologist, U.S. Forest Service, U.S. Department of Agriculture
- Ronald Coble, Professional Geologist (retired USGS)
- Ed Holland, Orange Water and Sewer Authority
- Beth McGee, Clean Water Management Trust Fund
- Ted Mew, Groundwater Section, Division of Water Quality, North Carolina DENR
- Joe Rudek, Environmental Defense Fund
- Henry Wade, Pesticides Section, North Carolina Department of Agriculture
- Steve Zoufaly, Division of Water Quality, North Carolina DENR

METHODS OF RATING UNSATURATED ZONE AND WATERSHED CHARACTERISTICS OF PUBLIC WATER SUPPLIES

Mechanisms of Inflow to Public Water Supplies

Precipitation recharges ground water by infiltrating the subsurface to reach the upper surface of the saturated zone, referred to as the water table (Winter and others, 1998). Vertical hydraulic conductance of the unsaturated zone is a quantitative measure of the ease of water movement through unsaturated materials. Precipitation also can travel overland to nearby surface water. Land-surface characteristics, such as land use, land cover, and slope, affect the amount of infiltration versus overland flow.

Tóth, (1963) characterized ground-water flow as local, intermediate, and regional. The local flow system recharges at interstream uplands and to adjacent lowlands or streams. Local flow systems are the most dynamic and shallowest flow systems and have the greatest interchange with surface water (Winter and others, 1998).

Local flow systems can be underlain by intermediate and regional flow systems. Intermediate ground-water flow is discharged from the ground-water system into nearby, larger streams, and regional ground-water flow is discharged from the ground-water system into distant streams.

Inflow to surface-water bodies includes both overland flow and discharge from the ground-water system. Precipitation flows through a thin unsaturated zone adjacent to streams and lakes, which causes the water table to rise quickly adjacent to the surface-water body (fig. 1; Winter and others, 1998). When the rate of precipitation exceeds the infiltration capacity of the subsurface, precipitation ponds at land surface or travels to streams as overland flow. The mechanisms for delivery of precipitation to the ground water and surface water are depicted in figure 1.

The procedures that are presented for rating unsaturated zone and watershed characteristics represent the potential for water, with or without contaminants, to (1) travel through the unsaturated zone to reach the water table in a ground-water supply source water assessment area, or (2) travel overland or through the shallow subsurface of a watershed to reach a surface-water supply intake. This study does not attempt to characterize how water transport processes might effect contaminants.

Method for Rating Vulnerability of a Water Supply

Although the vulnerability of drinking water supply is a concept and not a measurable property, inherent vulnerability can be inferred from surrogate information that is measurable (National Research Council, 1993). Methods for assessing vulnerability are of three types—overlay and index (such as those used in this report), process-based simulation models,

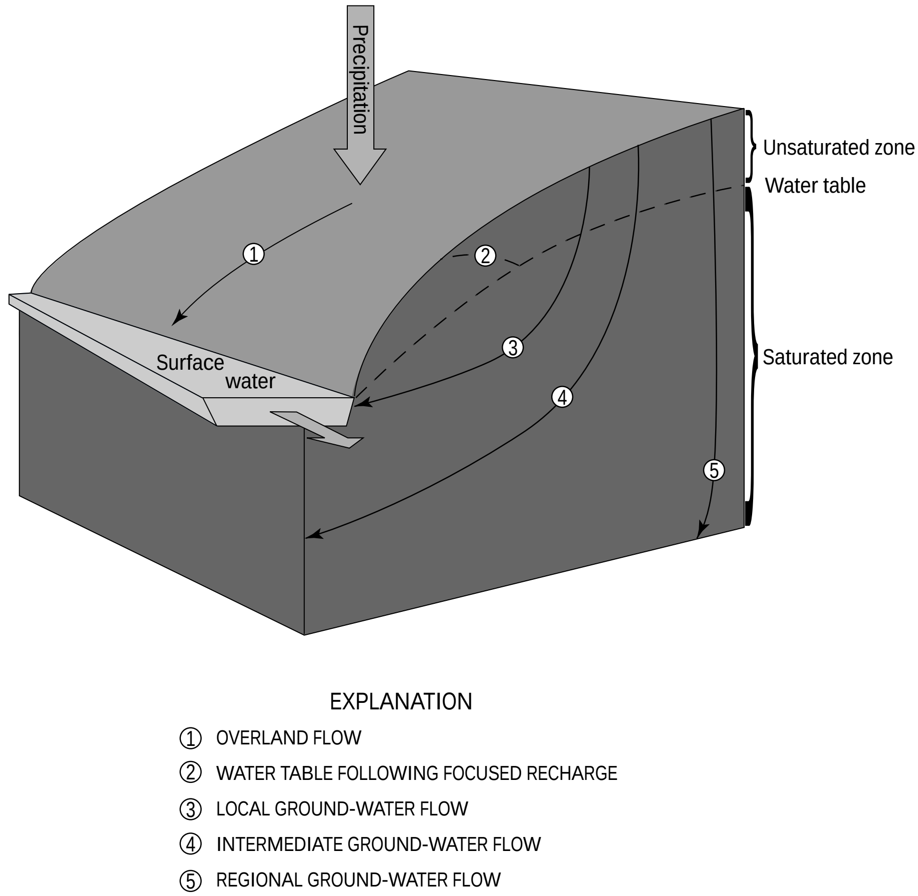

Figure 1. Mechanisms for delivery of precipitation to ground water and surface water (modified from Freeze and Cherry, 1979; Winter and others, 1998).

and statistical (National Research Council, 1993; Vrba and Zaporozec, 1994). Process-based simulation models require analytical or numerical solutions to equations that represent coupled processes governing contaminant transport. Statistical methods incorporate data on known areal contaminant distributions and characterize the contamination potential for specific geographic areas from which data were drawn.

The overlay and index method used in this report combines maps of various factors that influence inherent vulnerability. Each factor is categorized over the range of its possible values; these categories are then rated according to their relative influence on water-resource vulnerability. Statewide data were developed for each factor by using a Geographic Information System (GIS).

Because shallow ground-water vulnerability is strongly influenced by the spatial distribution of hydrogeologic and geographic features, mapping commonly is used to determine and display ground-water vulnerability around a well screen (Johnson and Van Driel, 1978; Aller and others, 1987; Whittemore and others, 1987; de Mulder and Hillen, 1990; Adams and Foster, 1992). Surface-water quality also is influenced by the spatial distribution of surficial features, and mapping hydrogeologic and geographic features is a tool used to determine surface-water vulnerability (Miller and Mattraw, 1982; McMahon and Lloyd, 1995; Nolan and Clark, 1997).

For this investigation, geologic, hydrologic, climatic, physiographic, and cultural factors were assigned weights that reflect their influence on water resources. Ratings and weights were assigned after review of pertinent literature and after seeking broad-based expert opinion. An initial estimate of ratings and weights was derived from literature and the expert opinions of the authors and other members of the PWSS. Eight scientists and engineers representing the

U.S. Forest Service, the Orange Water and Sewer Authority, the Clean Water Management Trust Fund, the Division of Water Quality of North Carolina DENR, the Environmental Defense Fund, and the Pesticides Section of the North Carolina Department of Agriculture reviewed these ratings and weights. The USGS and PWSS selected these individuals because of their expertise in the science and engineering of hydrology, geology, forestry, agriculture, and water management across the State of North Carolina. Six USGS reviewers with technical expertise in North Carolina hydrology examined the ratings and weights that characterize the influence of the factors on water-resource vulnerability.

Factors Used to Determine an Unsaturated Zone Rating

The unsaturated zone rating is based on a combination of factors that contribute to the likelihood that water, with or without contaminants, will reach the water table by following the path of aquifer recharge. The selected factors, which are represented by GIS spatial-data layers, include vertical conductance of the unsaturated zone, land-surface slope, land cover, and land use (table 1). The values of each of these four factors are categorized, and the categories are assigned a rating on a scale of 1 to 10. A rating of 1 reflects a low contribution to inherent vulnerability and 10 reflects a high contribution. For example, the rating for land-surface slope is low (1) in areas of high slope (greater than 50 percent slope) and high (10) in areas of low slope (less than 2 percent slope) because increased infiltration potential in flat terrain leads to an increased likelihood of ground-water contamination.

With the exception of land use, these factors influence the physical transport of water. The land-use factor is included as a measure of the potential for generating nonpoint-source contamination at land surface and is included to fulfill requirements for the SWAP plan to consider nonpoint-source contaminants (North Carolina Department of Environment and Natural Resources, 1999a). For the purpose of calculating the unsaturated zone rating, each of these four factors is weighted on the basis of the importance of the factor in determining vulnerability. Vertical hydraulic conductance and land use are weighted more heavily than are land-surface slope and land cover, because expert opinion determined that vertical hydraulic conductance and land use are more important influences on ground-water supplies than are land-surface slope and land cover.

Table 1. Factors that contribute to the unsaturated zone rating

Factor	Relevance of the factor	Weight
Vertical hydraulic conductance of the unsaturated zone	The harmonic mean of a series of layers of unsaturated material provides a single value for the capacity of the entire sequence of the unsaturated zone to transmit water, with or without contaminants, from the land surface to the water table.	3
Land-surface slope	The inclination, or change in elevation, of the land surface indicates the likelihood that precipitation will infiltrate or run off.	2
Land cover	The type of material covering the land surface influences the likelihood that precipitation will infiltrate or run off.	2
Land use	The type of land use influences the likelihood of potential nonpoint-source contamination.	3

Vertical Hydraulic Conductance of the Unsaturated Zone

In order to measure the capacity of the entire sequence of materials that overlie the saturated zone to transmit water, the thickness of the unsaturated zone and the hydraulic conductance of unsaturated material must be determined. At selected sites throughout the State, depth to the water table and hydraulic conductance of the unsaturated zone were estimated. As the methods of rating the unsaturated zone and watershed characteristics described in this report are implemented statewide, estimates of the depth to the water table and the hydraulic conductance of a variety of geologic materials will be needed.

For a given component of the series of materials composing the unsaturated zone, the vertical hydraulic conductance value, C, is calculated by using the following equation:

$$C = \frac{K_{unsat} \times A}{L} \quad (1)$$

where:

K_{unsat} = vertical hydraulic conductivity of the unsaturated zone,

A = cross-sectional area, and

L = length of vertical flow, or depth from land surface to the water table.

K_{unsat} is a function of moisture content, porosity, and other textural aspects of the material (O'Hara 1996). Saturated hydraulic conductivity, K_{sat}, is the upper bound of possible K_{unsat} values (Freeze and Cherry, 1979) and, as such, is used in this study as a conservative estimate of K_{unsat}. That is, vertical hydraulic conductance derived by substituting K_{sat} for K_{unsat} is C_{max}, the maximum possible vertical hydraulic conductance:

$$C_{max} = \frac{K_{sat} \times A}{L} \quad (2)$$

Because K_{unsat} is difficult to estimate, this substitution of K_{sat} for K_{unsat} is commonly made (O'Hara, 1996). In this report, C_{max} is referred to simply as C, and it can be inferred that K_{sat} has been substituted for K_{unsat} in the computation of C.

Hydraulic conductance over the entire thickness of the unsaturated zone, C, is calculated for layers in series:

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \quad (3)$$

where C_i represents the hydraulic conductance of each layer, i, of the unsaturated zone. Depending on depth to water in any given location, the Blue Ridge and Piedmont Provinces can include estimates of vertical conductance for layers of soil, saprolite, and(or) fractured rock. The Coastal Plain Province can include estimates of vertical conductance for layers of soil and(or) sedimentary formations. In other words, the determination of vertical hydraulic conductance is reduced to estimating the thickness and vertical K_{sat} of each component of the unsaturated zone.

Thickness and vertical K_{sat} estimates were obtained for soil from the Natural Resources Conservation Service (NRCS) Soil Survey Geographic data base (SSURGO), State Soil Geographic data base (STATSGO), and the associated Map Unit Interpretation Record data base (MUIR) (Soil Survey Division Staff, 1993; U.S. Department of Agriculture, 1994, 1995). Estimates of soil thickness and vertical K_{sat} are explained below.

Soil K_{sat} values are available statewide. Soil types, by county, are identified in the SSURGO data base (U.S. Department of Agriculture, 1995). The NRCS developed the SSURGO data base at a scale of 1:24,000, primarily for use in planning and managing farm and ranch, landowner/user, township, or county natural resources. At present, SSURGO data are available for 70 of 100 North Carolina counties (fig. 2).

Where SSURGO data are unavailable, STATSGO data are used. The STATSGO data base was developed at a scale of 1:250,000 for use in regional, multistate, State, multicounty, and river basin resource, planning, management, and monitoring (U.S. Department of Agriculture, 1994). STATSGO data are available for every part of North Carolina. STATSGO map units can have multiple soils, each with specific soil characteristics. The area-weighted mean was used to calculate values for each mapping unit.

In North Carolina, up to six layers of a soil type are identified in both SSURGO and STATSGO data. Soil K_{sat} and thickness are identified for each soil layer. Depths to the upper and lower soil-layer boundaries are recorded in inches and are stored as $deph_i$ and $depl_i$, respectively. The maximum and minimum values for the range in soil K_{sat}, expressed in inches per hour, are stored in the MUIR data base as $permh_i$ and $perml_i$, respectively.

K_{sat} is distributed lognormally (Freeze and Cherry, 1979). Therefore, a log transformation is used in the determination of mean saturated K_{sat} in soil layer i, μ_i (O'Hara, 1994):

$$\mu_i = 10^{\left[\frac{\log(permh_i) + \log(perml_i)}{2}\right]} \quad (4)$$

where:

μ_i = log mean saturated K_{sat}.

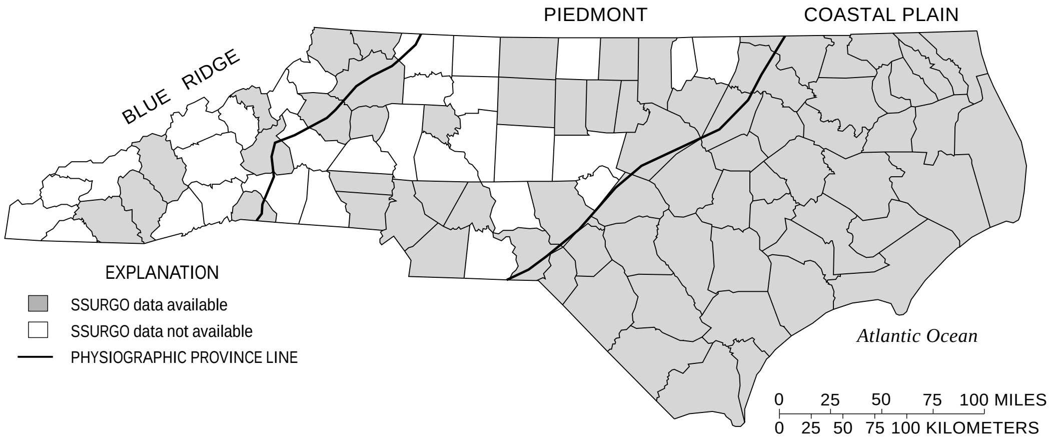

Figure 2. Physiographic provinces and availability of Soil Survey Geographic (SSURGO) data in North Carolina, August 1999.

To estimate the effective K_{sat} of a series of soil layers—μ_1, μ_2, μ_3, μ_4, μ_5, and μ_6—the harmonic mean described by Collins (1961), McDonald and Harbaugh (1988), and O'Hara (1996) is used. This harmonic mean K_{sat} (HMK) is defined as:

$$HMK = \frac{\sum_{i=1}^{i=6} |deph_i - depl_i|}{\sum_{i=1}^{i=6} \frac{|deph_i - depl_i|}{\mu_i}} \qquad (5)$$

The SSURGO spatial data include up to two soil types per map unit. The STATSGO spatial data include up to 21 soil types within each map unit. It is necessary to area-weight HMK within each map unit. The analytical technique detailed above was performed by using an ARC/INFO macro language (AML) program run in an ARC/INFO GIS environment (Environmental Systems Research Institute, Inc., 1994).

Vertical hydraulic conductance categories were divided into the same classes used in a previous study (O'Hara, 1996) and assigned ratings from 1 to 10 (table 2). Low ratings were assigned to the low conductance, and high ratings were assigned to the high conductance; areas characterized by low vertical hydraulic conductance contribute the least to the inherent vulnerability of ground-water supplies, and areas characterized by high vertical hydraulic conductance contribute the most to the inherent vulnerability of ground-water supplies.

Table 2. Vertical hydraulic conductance categories and ratings for the unsaturated zone (after O'Hara, 1996)

Vertical hydraulic conductance, in feet squared per day	Rating
Less than or equal to 500	1
Greater than 500 to less than or equal to 1,000	2
Greater than 1,000 to less than or equal to 2,000	3
Greater than 2,000 to less than or equal to 4,000	4
Greater than 4,000 to less than or equal to 8,000	5
Greater than 8,000 to less than or equal to 16,000	6
Greater than 16,000 to less than or equal to 32,000	7
Greater than 32,000 to less than or equal to 64,000	8
Greater than 64,000 to less than or equal to 128,000	9
Greater than 128,000	10

Land-Surface Slope

Land-surface slope influences the amount of precipitation that ponds on the land surface and infiltrates to contribute to ground water, or runs off the land surface as overland flow to surface water. When all other factors are the same, precipitation infiltrates into the subsurface in areas characterized by low slope; precipitation runs off land surface in areas characterized by high slope. The land-surface slope rating scheme was developed from literature about the effects of land-surface slope on surface water. The land-surface slope rating for surface water is the inverse of the rating used for ground water. The reader is referred to the section entitled "Factors Used to Determine a Watershed Characteristics Rating" for a more complete discussion of the derivation of this rating.

Demek and others (1972) suggested that slope categories should be based on slope frequency, but cautioned that categories may vary significantly from one region to another. No single slope-rating scheme is applicable in disparate geographic areas. In North Carolina, regional slopes range from relatively flat in the Coastal Plain Province to steep and highly variable in the Piedmont and Blue Ridge Provinces. However, local exceptions to these regional characterizations occur. For example, slopes in the Coastal Plain may be steep near streams, and in the Piedmont and Blue Ridge Provinces, slopes may be flat in flood plains, in valleys, and on hilltops. Analysis of a statewide GIS layer depicting land-surface slopes at a resolution of 60-meter grid cells indicates that nearly 57 percent of the State has slopes less than 2 percent (table 3). Slightly more than 85 percent of the State has slopes less than 10 percent.

Table 3. Land-surface slope categories and ratings for the unsaturated zone

[<, less than]

Land-surface slope, in percent	Area in North Carolina, in percent	Rating
Greater than 50 percent	<1	1
Greater than 20 to less than or equal to 50 percent	8	3
Greater than 10 to less than or equal to 20 percent	6	5
Greater than 5 to less than or equal to 10 percent	10	7
Greater than 2 to less than or equal to 5 percent	18	9
Less than or equal to 2 percent	57	10

Slopes were divided into classes and assigned ratings from 1 to 10 (table 3). Low ratings were assigned to high slopes, and high ratings were assigned to low slopes. Ground water is more vulnerable to contamination in areas where land-surface slope is low and infiltration is likely.

Land Cover

Land cover, which describes the physical overlay of the land surface, influences the amount of precipitation that infiltrates into the ground. Infiltration occurs where land cover is pervious. When precipitation falls directly onto the ground, the amount of infiltration depends on such factors as vegetative cover and soil compaction. Vegetation impedes runoff, increases temporary surface storage and, thus, increases infiltration of rainfall. Soil compaction promotes runoff and decreases infiltration.

Land-cover information was obtained from the USEPA and USGS Multi-Resolution Land Characteristics (MRLC) land-cover data base. This coverage was developed from remotely sensed data that were collected by using the Landsat Thematic Mapper (TM) sensor from 1990 through 1993, primarily during the spring seasons of 1991, 1992, and 1993 (Vogelmann and others, 1998). Data were stored at a 30-meter resolution.

Information was processed into nine general land-cover classes, which were further subdivided into 23 land-cover categories that were established for the eventual development of a consistent and generalized land-cover data base for all of the United States (Vogelmann and others, 1998). Within North Carolina, 15 land-cover categories from among six of the nine general classes of land cover are represented (table 4) and are used in the rating scheme developed for the land-cover factor.

Runoff coefficients (Viessmann and others, 1977; Chow and others, 1988; Lindeburg, 1992) and Soil Conservation Service (SCS) curve numbers (U.S. Department of the Interior, Bureau of Reclamation, 1973; Overton and Meadows, 1976; Lindeburg, 1992) were used as general guidelines in assigning ratings for land cover. The reader is referred to the discussion entitled "Factors Used to Determine a Watershed Characteristics Rating" for a more thorough discussion of surface-water studies that were used to make a preliminary estimate of land-cover ratings.

Land-cover categories are rated from 1 to 10 according to their contribution to the inherent vulnerability of ground-water supplies. Land covers that impede infiltration and contribute least to the inherent vulnerability of ground-water supplies are assigned a low rating. Land covers that permit infiltration and contribute the most to the inherent vulnerability of ground-water supplies are assigned a high rating. For example, where asphalt and structures dominate land cover, such as commercial/industrial areas, very little rainfall infiltrates into the subsurface; the land-cover rating for this category is 1. Where the land cover is forested, the surface is pervious and vegetation impedes runoff; the land-cover rating for this category is 10.

Table 4. Land-cover categories and ratings for the unsaturated zone, 1990–93

[<, less than]

Land-cover category	General description or example	Area in North Carolina, in percent	Rating
Commercial/ industrial	Land used for the manufacture of products or sale of goods. Includes all highly developed lands not classified as residential, most of which are commercial, industrial, or transportation.	1	1
Water	All areas of open water, generally with less than 25 percent vegetative cover.	9	2
Woody wetland	Areas of forested or shrubland vegetation where the soil or substrate is periodically saturated or covered with water.	11	2
Emergent wetland	Non-woody, vascular, perennial vegetation where the soil or substrate is periodically saturated or covered with water.	1	2
High-intensity residential	Residential development. Densely built urban centers, apartment complexes, and row houses. Vegetation occupies less than 20 percent of the landscape. Constructed materials account for 80 to 100 percent of the total area.	<1	2
Low-intensity residential	Residential development. Constructed materials account for 30 to 80 percent of the total area. Most commonly single-family housing areas, especially suburban neighborhoods.	2	4
Transitional	Areas dynamically changing from one land cover to another, often because of changes in land-use activities.	<1	5
Quarries/strip mines/ gravel pits	Areas of extractive mining activities with significant exposure of land surface.	<1	6
Row crops	Areas dominated by vegetation that is planted and(or) used for the production of crops, such as corn, soybeans, vegetables, tobacco, and cotton.	15	6
Barren land	Bare rock, sand, silt, gravel, or other earthen material with little or no vegetation regardless of its inherent ability to support life.	<1	7
Other grass	Vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes. Examples include parks, lawns, and golf courses.	<1	8
Hay/pasture	Areas dominated by vegetation, which is planted and(or) maintained for the production of food or feed. Grasses, legumes, or mixtures planted for livestock grazing.	6	8
Deciduous forest	Areas dominated by trees where 75 percent or more of the tree species shed foliage simultaneously.	24	10
Mixed forest	Areas dominated by trees where neither deciduous nor evergreen species represent more than 75 percent of the cover present.	10	10
Evergreen forest	Areas dominated by trees where 75 percent or more of the tree species retain their leaves all year. Canopy is never without green foliage.	19	10

Land Use

Land use describes activities that occur on the land surface. This factor represents the potential for generation of nonpoint-source contamination that might result from these activities. Land use is rated identically for the unsaturated zone and watershed characteristics (table 5). The reader is referred to the discussion entitled "Factors Used to Determine a Watershed Characteristics Rating" for a discussion relating land use to surface-water quality.

The effect of land use on ground-water quality has been the subject of many data-collection and interpretive investigations (Corwin and others, 1997). In 1984, the USGS began studies to evaluate quantitatively the effects of human activities, expressed as land use, on regional ground-water quality (Helsel and Ragone, 1984). One of these studies was performed on Long Island, New York. Recent work in this area (Eckhardt and Stackelberg, 1995) demonstrated that logistic regression equations based on explanatory variables of land use and population density characterize the probability of contaminants. The factors that most directly control the contaminant loadings at the water table, especially in unreactive surficial deposits, are the type, strength, and number of contaminant sources at land surface. Eckhardt and

Table 5. Land-use categories and ratings for the unsaturated zone and watershed characteristics, 1990–93

[<, less than]

Land-use category	General description or example	Area in North Carolina, in percent	Rating
Water	All areas of open water, generally with less than 25 percent vegetative cover.	9	1
Emergent wetland	Non-woody, vascular, perennial vegetation where the soil or substrate is periodically saturated or covered with water.	1	1
Woody wetland	Areas of forested or shrubland vegetation where the soil or substrate is periodically saturated or covered with water.	11	1
Barren land	Bare rock, sand, silt, gravel, or other earthen material with little or no vegetation regardless of its inherent ability to support life.	<1	2
Deciduous forest	Areas dominated by trees where 75 percent or more of the tree species shed foliage simultaneously.	24	3
Evergreen forest	Areas dominated by trees where 75 percent or more of the tree species retain their leaves all year. Canopy is never without green foliage.	19	3
Mixed forest	Areas dominated by trees where neither deciduous nor evergreen species represent more than 75 percent of the cover present.	10	3
Quarries/strip mines/ gravel pits	Areas of extractive mining activities with significant exposure of land surface.	<1	5
Hay/pasture	Areas dominated by vegetation, which is planted and(or) maintained for the production of food or feed. Grasses, legumes, or mixtures planted for livestock grazing.	6	5
Other grass	Vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes. Examples include parks, lawns, and golf courses.	<1	6
Transitional	Areas dynamically changing from one land cover to another, often because of changes in land-use activities.	<1	7
Row crops	Areas dominated by vegetation that is planted and(or) used for the production of crops, such as corn, soybeans, vegetables, tobacco, and cotton.	15	7
Low-intensity residential	Residential development. Constructed materials account for 30 to 80 percent of the total area. Most commonly single-family housing areas, especially suburban neighborhoods.	2	7
High-intensity residential	Residential development. Densely built urban centers, apartment complexes, and row houses. Vegetation occupies less than 20 percent of the landscape. Constructed materials account for 80 to 100 percent of the total area.	<1	8
Commercial/ industrial	Land used for the manufacture of products or sale of goods. Includes all highly developed lands not classified as residential, most of which are commercial, industrial, or transportation.	1	10

Stackelberg (1995) stated that characterization of contaminant sources can be statistically quantified through the surrogate variable, land use.

Also of note is a series of ground-water-quality studies in large river basins across the United States conducted by the USGS as part of the National Water-Quality Assessment (NAWQA) Program, which began in 1991. Investigations, such as Saad (1997), have focused on relating ground-water quality to land use and other factors.

The source of data for the land-use factor is identical to the source of data for land cover, both of which are derived from the same land-use and land-cover GIS layer (see Appendix). Although land-use and land-cover categories use the same data source and terminology, they are considered separate factors in the unsaturated zone ratings. The land-use factor measures the potential for generating nonpoint-source contamination at land surface; the land-cover factor influences the amount of precipitation that infiltrates the ground. These factors are treated separately to highlight the influence of nonpoint-source contaminants in the unsaturated zone rating.

Example of an Unsaturated Zone Rating

An unsaturated zone rating will be calculated for source water assessment areas around each public water-supply well in North Carolina. The PWSS will determine source water assessment areas by using a delineation method specified in the State's approved Wellhead Protection Program, where the area is a function of the amount of water pumped from the well and the approximate average rate of ground water recharged in the region (Heath, 1994; North Carolina Department of Environment, Health, and Natural Resources, 1995). The source water assessment area can be truncated by the presence of substantial surface-water bodies. In the method of determining unsaturated zone ratings, the source water assessment area is divided into discrete 60-meter by 60-meter cells (fig. 3). Only cells with more than 50 percent of their area in the source water assessment area are included in the calculation.

The four contributing factors—vertical hydraulic conductance, land-surface slope, land cover, and land use (table 1)—are assigned weights in the final calculation of the unsaturated zone rating. Weights are subjective measures (1, 2, or 3) that reflect the relative importance of factors that are used to determine ground-water vulnerability to contamination (table 1). The factor weights are multiplied by factor ratings and summed, resulting in an unsaturated zone rating that ranges from 10 to 100 for each cell (table 6). The unsaturated zone rating for a delineated source water assessment area is the average value over all the cells in the area; for the cells used in this example, the unsaturated zone rating is 57.8.

Factors Used to Determine a Watershed Characteristics Rating

The watershed characteristics rating is based on a combination of factors that contribute to the likelihood that water, with or without contaminants,

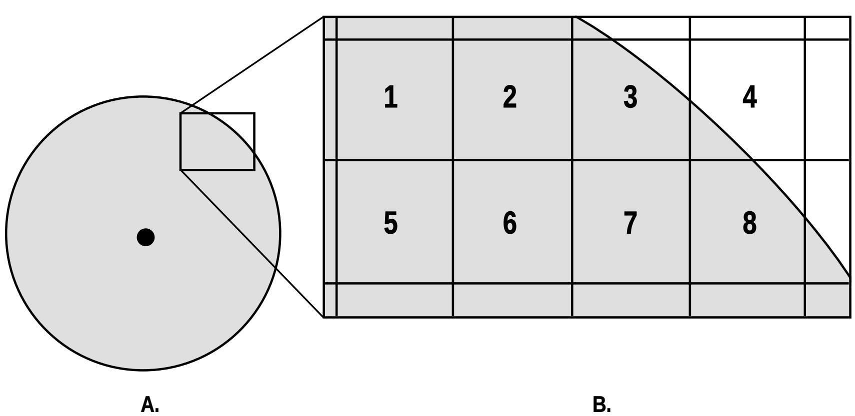

Figure 3. (A) An unnamed well encircled by source water assessment area and (B) a portion of the source water assessment area overlain by 60-meter by 60-meter cells to illustrate the calculation of the unsaturated zone rating. Only cells with more than 50 percent of their area in the source water assessment area are included in the calculation [in this example, cells 1, 2, 3, 5, 6, 7, 8].

Table 6. Example determination of an unsaturated zone rating for an unnamed water-supply well

[For each cell, the product of the factor weights and ratings are summed to determine the total rating for the cell. The overall rating is the average for all the cell ratings; possible values range from 10 to 100]

Cell number *i* (fig. 3)	Vertical hydraulic conductance [weight (w_1)=3]		Land-surface slope [weight (w_2)=2]		Land-cover and land-use category	Land cover [weight (w_3)=2]	Land use [weight (w_4)=3]	Grid cell rating
	In feet squared per day	Rating (r_1) (table 2)	In percent	Rating (r_2) (table 3)		Rating (r_3) (table 4)	Rating (r_4) (table 5)	$R_i = \sum_{i=1}^{4} (w_i \times r_i)$
1	2,500	4	3	9	Row crop	6	7	63
2	2,000	3	4	9	Hay/pasture	8	5	58
3	2,100	4	3	9	Low-intensity residential	4	7	59
5	1,300	3	4	9	Hay/pasture	8	5	58
6	1,200	3	6	7	Hay/pasture	8	5	54
7	1,000	2	1	10	Low-intensity residential	4	7	55
8	1,100	3	2	10	Low-intensity residential	4	7	58

Unsaturated zone rating for *n* (7) selected cells (fig. 3) $\dfrac{\sum_{i=1}^{7} R_i}{n} = \dfrac{405}{7} = 57.8$

will reach a public surface-water supply intake by following the path of overland flow or the path of shallow subsurface flow. The selected factors, which can be represented in the form of GIS spatial-data layers, include average annual precipitation, land-surface slope, land cover, land use, and ground-water contribution (table 7). The values of each of these five factors are categorized, and the categories are assigned a rating on a scale of 1 to 10. A rating of 1 reflects a low contribution to inherent vulnerability and 10 reflects a high contribution. For example, the rating for land-surface slope is low (1) in areas where the slope is low and high (10) in areas where the slope is steep. Runoff potential increases in steeper terrain, which leads to an increased likelihood of surface-water contamination.

With the exception of land use, these factors influence the physical transport of water. The land-use factor is included as a measure of the potential nonpoint-source of contamination caused by activities occurring at the land surface and is included to fulfill requirements of the SWAP plan to consider nonpoint-source contaminants (North Carolina Department of Environment and Natural Resources, 1999a). To determine the watershed characteristics rating, the five factors are weighted on the basis of importance of the factor relative to other factors in affecting public water-supply vulnerability. Ratings are computed for

Table 7. Factors that contribute to the watershed characteristics rating

Factor	Relevance of the factor	Weight
Average annual precipitation	The source of water that travels overland to streams or lakes.	3
Land-surface slope	The inclination, or change in elevation, of the land surface indicates the likelihood that precipitation will infiltrate or run off.	2
Land cover	The type of material covering the land surface influences the likelihood that precipitation will infiltrate or run off.	1
Land use	The type of land use influences the likelihood of potential nonpoint-source contamination.	3
Ground-water contribution	The portion of surface water derived from ground water.	1

delineated source water assessment areas upstream from each intake, which are portions of the basin defined in accordance with the State's Water Supply Watershed Protection program, (North Carolina Department of Environment and Natural Resources, 1999b, 1999c).

Average Annual Precipitation

Precipitation is the source of water transported overland to a stream or lake. In this study, two measures of precipitation were evaluated for use in the rating scheme—rainfall intensity and average annual precipitation. Rainfall intensity is a meaningful measure of precipitation because streamflows peak during intense rainfalls (Viessmann and others, 1977). Concerns about the quality of raw water at surface-water intakes commonly are related to intense rainfall occurring in 24 hours or less. In a statewide investigation of sediment characteristics of streams in North Carolina, Simmons (1993) reported that rainfall magnitude and intensity are the most important precipitation factors affecting sediment load. When substantial amounts of rain fall in relatively short periods of time, such as a few hours, large drops of water hitting the ground surface commonly will break down soil particles. These particles in turn may be transported via overland flow, especially after soil infiltration rates are exceeded. Selected chemical constituents, such as trace metals and some nutrients that attach to soil may, therefore, become subject to transport. Concerns related to the resolution and accuracy of available rainfall-intensity information, however, resulted in the selection of average annual precipitation as the measure of precipitation for the watershed characteristics rating scheme.

Several issues limit the use of available information for rainfall intensity in North Carolina. Current information on rainfall intensity, presented in the rainfall-frequency atlas for the United States (Hershfield, 1961), is based on 30 years of rainfall data collected through 1958. In North Carolina, approximately 110 rainfall-observation stations with data for 24-hour intervals were used to map the magnitudes and intensity of rainfall events. Since 1961, no update of the frequency data has been completed for North Carolina. Changes to rainfall-intensity maps are likely to occur as a result of additional data at many observation stations and improved statistical analysis methods developed since 1961 (Dr. Leslie Julian, Hydrometeorological Design Studies Center, National Oceanic and Atmospheric Administration, oral commun., April 28, 1999). Another limitation of rainfall intensity is the relatively coarse scale of the existing rainfall-frequency maps (approximately 1:10,000,000) as compared to the map scales of the other coverages (1:250,000) used in the watershed characteristics ratings. In the future, if updates are made to rainfall intensity maps, rainfall intensity data could be re-examined as a possible replacement for average annual precipitation. An appropriate choice would be the 24-hour, 25-year storm because of its common use in engineering design of hydraulic overflow-prevention structures. Selection of average annual precipitation for the watershed characteristics rating in North Carolina is consistent with its use in other States where annual or seasonal precipitation is included as a factor in the rating (California Department of Health Services, Division of Drinking Water and Environmental Management, January 1999; R.L. Joseph, U.S. Geological Survey, Water Resources Division, oral commun., March 8, 1999; Texas Natural Resource Conservation Commission, April 30, 1999).

In North Carolina, average annual precipitation varies from about 40 inches to more than 80 inches (table 8; fig. 4); however, two-thirds of the State receives between 40 and 50 inches of average annual rainfall. Most of the variation occurs in the Blue Ridge Mountains, with the highest and lowest average amounts occurring in this area. Giese and Mason (1993) reported that more of the precipitation that falls in the mountains is converted to streamflow than in the

Table 8. Average annual precipitation categories and ratings for watershed characteristics

[<, less than]

Average annual precipitation, in inches	Area in North Carolina, in percent	Rating
Less than or equal to 40	< 1	1
Greater than 40 to less than or equal to 45	20	2
Greater than 45 to less than or equal to 50	48	3
Greater than 50 to less than or equal to 55	23	4
Greater than 55 to less than or equal to 60	5	5
Greater than 60 to less than or equal to 65	2	6
Greater than 65 to less than or equal to 70	1	7
Greater than 70 to less than or equal to 75	< 1	8
Greater than 75 to less than or equal to 80	< 1	9
Greater than 80	1	10

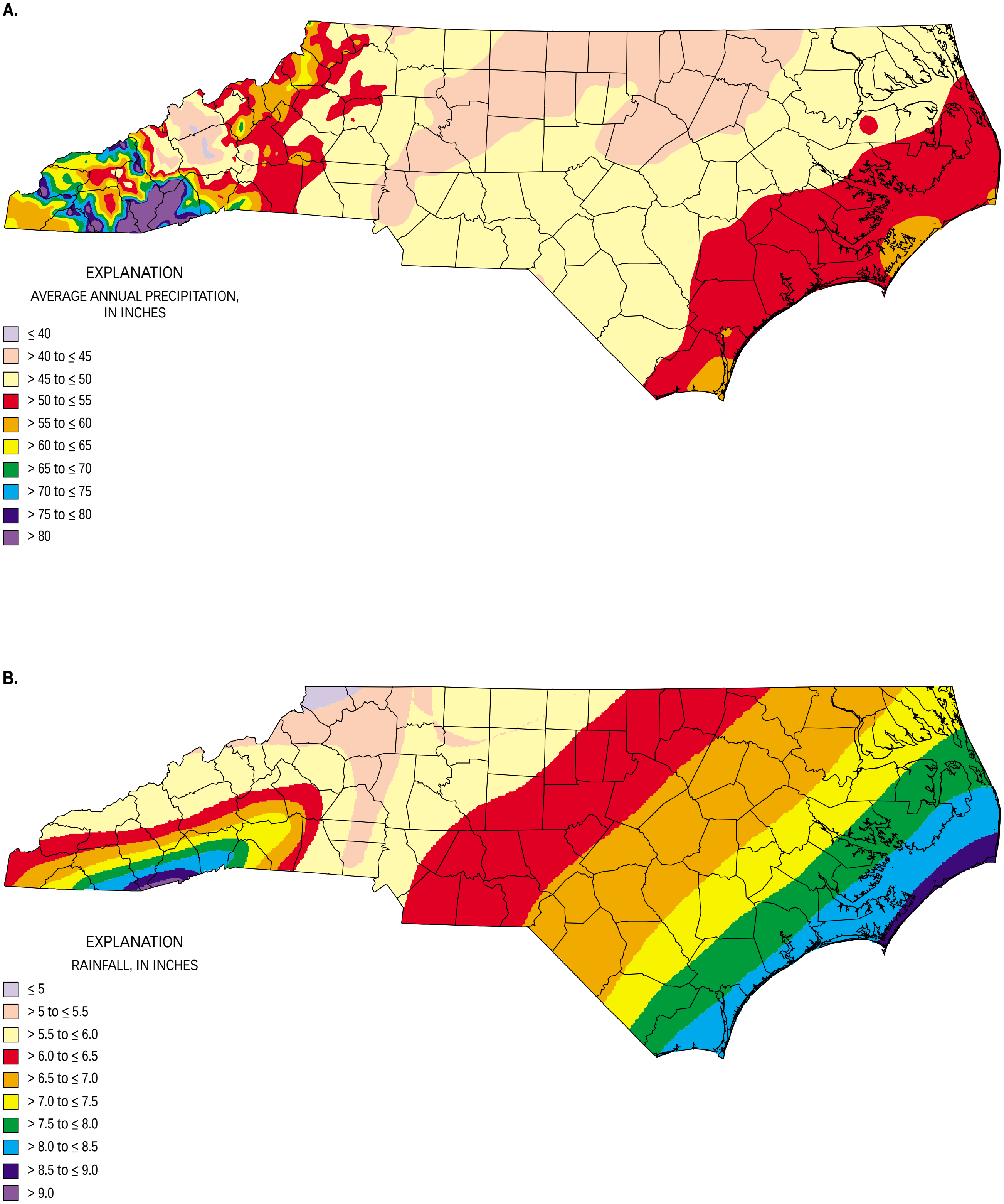

Figure 4. (A) Average annual precipitation and (B) a 24-hour, 25-year rainfall event in North Carolina.

Piedmont and Coastal Plain areas of the State. Among the factors likely to contribute to the occurrence of higher streamflow in the mountains are higher relief, cooler temperatures, and a shorter growing season (lower evapotranspiration). McMahon and Lloyd (1995) reported that evapotranspiration rates within the Albemarle-Pamlico drainage basin vary from about 30 inches in the Blue Ridge Province to about 36 inches in the Coastal Plain Province. These rates constitute approximately 55 and 70 percent, respectively, of the average annual precipitation in these areas.

Average annual precipitation is derived from the Parameter-Elevation Regressions on Independent Slopes Model (PRISM), which uses a regression model relating land-surface elevation to precipitation in order to interpolate between weather observation stations (Daly, 1996). The average annual precipitation values used in PRISM are based on data collected from 1961 to 1990 at about 140 observation stations in North Carolina.

Average annual precipitation was categorized in increments of 5 inches, from less than 40 inches to more than 80 inches (table 8). The areas of the State receiving between 40 and 50 inches of rainfall during the year have a precipitation rating of 2 or 3 (table 8; fig. 4). Average annual precipitation amounts exceeding 80 inches are rated 10 because very few water-supply systems have watersheds located solely in the highest elevations of North Carolina where rainfall exceeds this amount.

Land-Surface Slope

Land-surface slope influences the amount of precipitation that either runs off the land surface as overland flow and contributes to surface water or ponds on the land surface and contributes to ground water. The reader is referred to the previous section entitled "Factors Used to Determine an Unsaturated Zone Rating" for a more complete discussion of the derivation of this rating.

The relation between slope and the occurrence of overland flow is underscored by its effects on water quality in regionalization studies for predicting streamflow quantity and quality. Sauer and others (1983) used slope as one of the explanatory variables in regression models developed in a hydrologic investigation of urban runoff. Harned and others (1995) noted higher suspended-sediment concentrations in a river in the Piedmont than in the Coastal Plain, which generally has lower topographic relief and lower stream gradients than the Piedmont. Nutrient and trace metal constituents can attach to sediment particles; thus, steeper slopes result in higher vulnerability of surface-water supply intakes to contaminant transport (Simmons, 1993). Giese and Mason (1993) report that among the factors likely to contribute to the occurrence of higher streamflow in the mountains is the existence of steep slopes that result in more rapid runoff. Chow and others (1988) report that the percentage of rainfall that is translated into overland flow to the streams is based on a combination of factors, including land-surface slope.

Slopes were divided into six categories and assigned ratings from 1 to 10 (table 9). These are the same categories used in unsaturated zone ratings (table 2), but rating values are reversed. Low ratings are assigned to the low slopes, and high ratings are assigned to the high slopes. Surface-water supplies are more vulnerable to contamination in areas where land-surface slopes are high.

Table 9. Land-surface slope categories and ratings for watershed characteristics

[<, less than]

Land-surface (basin) slope, in percent	Area in North Carolina, in percent	Rating
Less than or equal to 2 percent	57	1
Greater than 2 to less than or equal to 5 percent	18	3
Greater than 5 to less than or equal to 10 percent	10	5
Greater than 10 to less than or equal to 20 percent	6	7
Greater than 20 to less than or equal to 50 percent	8	9
Greater than 50 percent	< 1	10

Land Cover

Land cover, which describes the physical overlay of the land surface, influences the amount of precipitation that runs off. Runoff predominates where land cover is impervious. For developed areas where asphalt and structures dominate the surface, most of the rainfall runs off as overland flow. Where rain falls directly onto the ground, the level of infiltration depends, in part, on the soil characteristics and vegetative cover. The reader is referred to the previous section entitled "Factors Used to Determine a Watershed Characteristics Rating" for more discussion of the land-cover factor.

Simmons (1993) discussed the effects of vegetative cover as an important factor in erosion, sediment disintegration, and transport by overland flow or wind. Vegetative cover impedes erosion in a number of ways—by reducing splash erosion, increasing evapotranspiration, reducing runoff potential, and increasing infiltration as precipitation falls on and is held by decayed matter. Simmons (1993) cited average annual erosion rates from the U.S. Department of Agriculture (1977) for rural areas—0.1 ton per acre from forests, 1.3 tons per acre from grassland pastures, and 7.5 tons per acre from croplands. Disturbing cropland areas and clearing vegetative cover results not only in more soil material available for transport, but less impedance to overland flow.

Peak flow, or maximum discharge, also may be used as a measure of the degree of infiltration potential provided by a particular land cover. Hydraulic equations used in the prediction of peak flows commonly include a variable that represents the land cover in the basin upstream from the structure.

The Rational Method equation for estimating peak discharge includes a variable referred to as the runoff coefficient. Chow and others (1988) reported that the runoff coefficient implies a fixed ratio of the peak discharge rate to the rainfall rate in the basin. The percentage of rainfall that is translated into overland flow to the streams, however, is based on a combination of factors, including percentage of imperviousness, ponding characteristics, and soil condition. Tables of runoff characteristics used with the Rational Method commonly are found in applied hydrology, hydraulic, and civil engineering manuals (Viessmann and others, 1977; Chow and others, 1988; Lindeburg, 1992).

Predicting peak flows by using methods developed by the U.S. Department of Agriculture SCS (now the Natural Resources Conservation Service) relies on a runoff variable known as a curve number, which is based on land cover and other factors (U.S. Department of the Interior, Bureau of Reclamation, 1973; Overton and Meadows, 1976; Lindeburg, 1992). Overton and Meadows (1976) developed a comprehensive table of curve numbers with respect to land-cover categories.

As with the land-cover ratings for the unsaturated zone, ratings were assigned to the land-cover categories by using information about the runoff coefficients and SCS curve numbers as general guidelines. High ratings are associated with land cover that presents low impedance to overland flow (table 10).

Land Use

Land use describes activities that occur on the land surface. This factor represents the potential for generation of nonpoint-source contamination that might result from these activities. Land use is rated identically for watershed characteristics and the unsaturated zone (table 5). The reader is referred to the previous section entitled "Factors Used to Determine an Unsaturated Zone Rating" for a discussion relating land use to ground-water quality.

The effect of land use on surface-water quality has been the subject of many data-collection and interpretive investigations. Of note is a series of surface-water-quality studies in large river basins across the United States conducted by the USGS as part of the NAWQA Program. Mueller and others (1995) developed nationwide comparisons of findings from individual NAWQA river basins. In general, nutrient concentrations downstream from agricultural areas were higher than concentrations downstream from undeveloped areas. In the water-quality investigation of the Albemarle-Pamlico drainage basin located in North Carolina and Virginia, Harned and others (1995) noted that the highest nitrogen and phosphorus concentrations were observed in more developed basins and areas having a large percentage of agricultural and farm-animal operations.

In the Albemarle-Pamlico drainage basin, McMahon and Lloyd (1995) confirmed that agricultural and developed areas tend to have the greatest negative effect on water quality. These land uses generally introduce high quantities of nutrients, sediments, and other chemical constituents into the hydrologic system. Within agricultural areas, the effects on water quality vary, depending on the use of lands for crop production or livestock grazing. McMahon and Lloyd (1995) also noted that while runoff from forested areas may be expected to have the least impact on water quality, runoff from lands used for silviculture (tree production) could contain pesticides used for weed and insect control. However, McMahon and Lloyd (1995) also noted that wetlands can act as natural water-treatment systems because the slower water velocities allow suspended sediments and adsorbed chemical constituents to settle out.

Omernik (1977) reported some general relations between land use and nitrogen and phosphorus loads in surface water. Using land-use categories expressed as a function of percentage forest, cleared, agriculture, and urban uses, basins with high percentages of urban and

Table 10. Land-cover categories and ratings for watershed characteristics, 1990–93

[<, less than]

Land-cover category	General description or example	Area in North Carolina, in percent	Rating
Deciduous forest	Areas dominated by trees where 75 percent or more of the tree species shed foliage simultaneously.	24	1
Evergreen forest	Areas dominated by trees where 75 percent or more of the tree species retain their leaves all year. Canopy is never without green foliage.	19	1
Mixed forest	Areas dominated by trees where neither deciduous nor evergreen species represent more than 75 percent of the cover present.	10	1
Water	All areas of open water, generally with less than 25 percent vegetative cover.	9	3
Emergent wetland	Non-woody, vascular, perennial vegetation where the soil or substrate is periodically saturated or covered with water.	1	3
Woody wetland	Areas of forested or shrubland vegetation where the soil or substrate is periodically saturated or covered with water.	11	3
Hay/pasture	Areas dominated by vegetation, which is planted and(or) maintained for the production of food or feed. Grasses, legumes, or mixtures planted for livestock grazing.	6	3
Other grass	Vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes. Examples include parks, lawns, and golf courses.	< 1	4
Barren land	Bare rock, sand, silt, gravel, or other earthen material with little or no vegetation regardless of its inherent ability to support life.	< 1	5
Transitional	Areas dynamically changing from one land cover to another, often because of changes in land-use activities.	< 1	5
Quarries/strip mines/ gravel pits	Areas of extractive mining activities with significant exposure of land surface.	< 1	5
Row crops	Areas dominated by vegetation that is planted and(or) used for the production of crops, such as corn, soybeans, vegetables, tobacco, and cotton.	15	6
Low-intensity residential	Residential development. Constructed materials account for 30 to 80 percent of the total area. Most commonly single-family housing areas, especially suburban neighborhoods.	2	7
High-intensity residential	Residential development. Densely built urban centers, apartment complexes, and row houses. Vegetation occupies less than 20 percent of the landscape. Constructed materials account for 80 to 100 percent of the total area.	< 1	8
Commercial/ industrial	Land used for the manufacture of products or sale of goods. Includes all highly developed lands not classified as residential, most of which are commercial, industrial, or transportation.	1	10

agricultural land uses produced higher loadings of total nitrogen. Surface waters draining entirely agricultural or urban areas had a nearly tenfold increase in nitrogen concentration compared to forested drainage basins. Similar trends for total phosphorus were observed; however, the differences in concentration between urban/agricultural basins and forested basins were not as pronounced.

The source of data for the land-use factor is identical to the source of data for land cover, and both are derived from the same land-use and land-cover GIS layer (see Appendix). Although land-use and land-cover categories use the same data source and terminology, they are considered separate factors in the watershed characteristics ratings. The land-use factor measures the potential for generating nonpoint-source contamination at land surface; the land-cover factor influences the amount of precipitation that runs off as overland flow. These factors are treated separately to highlight the influence of nonpoint-source contaminants in the watershed characteristics rating.

Ground-Water Contribution

Surface water and ground water are parts of one system. In North Carolina, streamflows are, in part, derived from underlying aquifers, particularly aquifers where the upper boundary is the water table (fig. 1). The effect of ground-water contribution to surface water is included in the assessment of watershed characteristics to address the influence that ground water has on surface-water quantity and quality. In this study, ground-water contribution is derived from the unsaturated zone rating described in the previous section entitled "Example of an Unsaturated Zone Rating."

The portion of streamflow derived from ground water is known as base flow, which is affected by a number of factors. Sear and others (1999) reported that whereas base flow to a stream depends on the nature of the soils and lithology in the upstream catchment, recharge is controlled by precipitation, evaporation, and temperature.

To obtain a general snapshot of ground-water contribution in streams across the State, streamflow records at more than 200 active and discontinued gaging stations across North Carolina were used to determine the base-flow index (BFI) for each site by using available period of record (through the 1997 water year for active sites). The BFI is the ratio of the mean annual ground-water discharge (base flow) to the mean total annual streamflow (Wahl and Wahl, 1988; Nathan and McMahon, 1990; Rutledge and Mesko, 1996). BFI values across the State ranged from about 13 to nearly 73 percent (mean of about 49 percent) of the total annual streamflow.

Base flow generally composes more of the total streamflow in the Coastal Plain Province than in the Piedmont Province. The lower base flow in the Piedmont reflects the fact that Piedmont topography has higher relief than Coastal Plain topography, and that Piedmont formations are, on the whole, less transmissive than Coastal Plain formations. In the Coastal Plain Province, BFI values ranged from about 29 to 71 percent of the total streamflow with a mean of 48 percent. Wilder and others (1978) assessed the water resources for northeastern North Carolina and noted that the ground-water contribution accounted for about two-thirds of the total streamflow in that region. Bales and Pope (1996) reported that base flow at a gaging station on the Waccamaw River averaged 53 percent of the total annual streamflow from 1940 to 1994. Base flow averaged nearly 71 percent at a site on the nearby Lumber River (Bales and Pope, 1996).

The BFI values for sites in the Piedmont Province ranged from about 13 to 68 percent of total annual streamflow with a mean of 37 percent. In the Blue Ridge Province, BFI values ranged from 30 to 73 percent of the total annual streamflow with a mean of 62 percent. The relatively high mean is consistent with previous regional assessments, which indicated higher levels of base flow in the Blue Ridge Province compared to the Piedmont Province (Giese and Mason, 1993; Rutledge and Mesko, 1996). Factors influencing the higher levels of base flow include higher precipitation amounts and greater topographic relief, lower evapotranspiration, shorter growing seasons as well as shallow soils and fractured bedrock, which can serve as conduits for the subsurface flow to streams.

The inclusion of a ground-water contribution factor in this study addresses the influence that ground water has on surface waters. The method previously described for determining unsaturated zone ratings is applied to an area 1,000 feet on either side of streams within the delineated basins. Unsaturated zone ratings can range from 10 to 100. Ground-water contribution ratings for the cells in these areas are calculated exactly as for unsaturated zone ratings, then divided by 10 to scale the values in the range from 1 to 10, like other factors used in other watershed characteristics ratings.

The use of a 1,000-foot buffer is consistent with the buffer being used by the PWSS to inventory and rate point-source discharges near streams (North Carolina Department of Environment and Natural Resources, 1999a). By restricting ground-water contribution to an area of about 1,000 feet on either side of streams, the ground-water contribution factor emphasizes focused recharge (a local water table rise caused by stormflow) and local ground-water flow, the most dynamic and shallowest flow system that has the greatest interchange with surface water (Winter and others, 1998).

In this study, ground-water contribution originating outside of this buffer is not considered, although sub-surface flow does occur over much longer distances. Beyond the 1,000 feet from surface-water bodies, the rating for ground-water contribution is zero.

Example of a Watershed Characteristics Rating

For a given watershed, ratings for each of the five factors (precipitation, slope, land cover, land use, and ground-water contribution) are multiplied by respective factor weights, and summed to create a unique rating for each grid cell. Weights (1, 2, or 3) are subjective measures that reflect the relative importance of factors used to determine ground-water vulnerability to contamination (table 7). The overall rating for the watershed is determined by averaging the ratings for the grid cells. The range of possible ratings is 10 to 100.

An example watershed characteristics rating is presented. Ratings are computed for delineated source water assessment areas upstream from each intake, which are portions of the basin defined in accordance with the State's Water Supply Watershed Protection program (North Carolina Department of Environment and Natural Resources, 1999b, 1999c). The watershed has grid cells (60 meters by 60 meters) throughout the basin (fig. 5). Only cells with more than 50 percent of their area contained within the watershed are included in the calculation. Ratings for all grid cells were calculated (table 11) and averaged to produce the overall watershed characteristics rating (47.9 for the cells used in this example).

LIMITATIONS

The overlay and index methods of unsaturated zone and watershed characteristics ratings that were used here are broad-brush-stroke methods that assess an aspect of inherent vulnerability on the basis of expert opinion. Given that the task of susceptibility assessments is to rate hundreds of surface-water intakes and thousands of wells, the statewide approach is a practical and effective step. These methods of rating the unsaturated zone and watershed characteristics have limitations, which include the following:

- The data used to represent land use and land cover have limitations. The land-use and land-cover data base was gathered during 1990–93; in some areas, land use and land cover have changed since the early 1990's. Substantial development has occurred in North Carolina around urban centers. Furthermore, the land-use and land-cover data

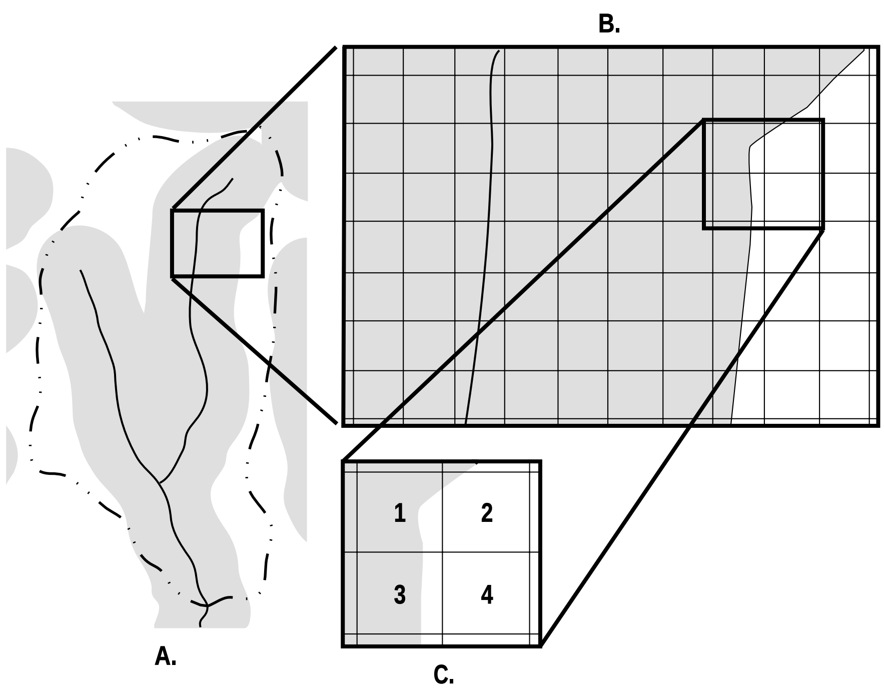

Figure 5. (A) An unnamed watershed upstream from a surface-water supply intake showing basin outline, stream network, and 1,000-foot buffered area around streams; inset (B) 60-meter by 60-meter cells overlaid on a portion of the watershed; and inset (C) a subset of four cells used to illustrate the calculation of a watershed characteristics rating.

Table 11. Example determination of a watershed characteristics rating for part of an unnamed watershed upstream from a water-supply intake

Cell number *i* (fig. 5)	Precipitation [weight (w_1)=3]		Land-surface slope [weight (w_2)=2]		Land-cover and land-use category	Land cover [weight (w_3)=1]	Land use [weight (w_4)=3]	Ground-water contribution [weight (w_5)=1]		Grid cell rating
	In inches	Rating (r_3) (table 8)	In percent	Rating (r_2) (table 9)		Rating (r_3) (table 10)	Rating (r_3) (table 5)	Unsaturated zone rating value	Rating (r_3)	$R_i = \sum_{i=1}^{5} (w_i \times r_i)$
1	56	5	52	10	Forest	1	3	46	4.6	49.6
2	56	5	47	9	Forest	1	3	0	0	43.0
3	56	5	48	9	Forest	1	3	50	5.0	48.0
4	56	5	45	9	Hay/pasture	3	5	0	0	51.0

Watershed characteristics rating for *n* (4) selected cells (fig. 5) $\dfrac{\sum_{i=1}^{4} R_i}{n} = \dfrac{191.6}{4} = 47.9$

tend to underestimate the extent of urban centers, possibly assigning heavily wooded urban land as forested land. The land-use and land-cover data base relied upon the National Wetlands Inventory (NWI) to identify wetland areas. The 1:24,000 NWI maps are inconsistent across quadrangle boundaries because of differing dates of mapping and technician error. The land-use and land-cover data in North Carolina are limited to 15 categories. It is not possible to extract categories that have been grouped together. The data do not distinguish orchards or Christmas tree farms, but lump silviculture in with forests or row crops. Also, the data do not distinguish quarries from strip mines, or bare rock from sand.

- The data used to calculate vertical hydraulic conductance have limitations. The primary layer for this factor was soils data. The soil data are from two data bases with quite different scales (1:24,000 and 1:250,000). The differences between STATSGO and SSURGO data are noteworthy; SSURGO data are much more detailed and informative. Additionally, some soil types were not assigned permeability and thickness values; these soils are assigned the permeability and thickness values derived from STATSGO data (see Appendix). In all cases, unsaturated hydraulic conductivity of the unsaturated zone is replaced by saturated hydraulic conductivity, which means that estimated vertical hydraulic conductance is always the maximum estimated value. Another limitation of the vertical hydraulic conductance layer is that statewide estimates of depth to water are not available, neither are statewide estimates available for vertical hydraulic conductance of geologic units underlying soil.

- The primary limitation of the land-surface slope factor was introduced in the development of the source —the digital elevation model. To develop a continuous elevation surface, a connected stream and river network was created in North Carolina. The centerline of water bodies was used to create the stream network. This created a surface representative of stream channels beneath reservoirs or lakes, thus assigning higher slopes within lakes and reservoirs than now exist. For the final statewide slope computation, elevation data that incorporate existing water-body outlines should be used.

- The ground-water contribution factor to watershed characteristics rating has limitations. First, it is not just the 1,000-foot buffered area that contributes to surface-water bodies, but rather the entire interstream area. Second, the method used to identify the ground-water contribution area is flawed. Buffered areas from all surface-water

- bodies are used in calculations, even if the surface-water body is located in an adjacent watershed.

Other contributing factors may be important in determining inherent vulnerability to specific contaminants. Organic content of soil may have been used to predict areas through which certain contaminants, such as pesticides, would not likely be transported but rather bound to the soil. Organic content was not selected because vulnerability assessments in this study are not specific to particular contaminants. Vegetative cover, which also might have been used to predict areas through which some contaminants would not likely be transported but rather bound to plants, and which also would influence overland flow, was not selected for lack of a map showing average annual vegetative cover. Also not considered is the effect of airborne contaminants, notably nitrogen, from livestock and fertilizer that are generated outside the watershed or source water assessment area (Rudek, 1997). Anthropogenic effects also can be a substantial source of airborne nitrogen. This factor was not selected because insufficient statewide ambient air-quality monitoring data are available to evaluate this potential source of contamination.

- Other data may have been used to represent the contributing factors. Storm intensity would have been selected in place of average annual precipitation had more recent, finer-scale data been available.
- The methods derived for rating unsaturated zone and watershed characteristics use 60-meter by 60-meter cells. However, the data used to represent the factors would support a finer grid of 30-meter by 30-meter cells.
- The assigned rates and weights were determined by expert opinion and selected to reflect contributions to water-supply vulnerability. A statistical analysis of the factors and ambient water-quality data could be performed in the future to determine if assigned weights and rates could be improved.

The strength of the overlay and index method is its appeal to common sense. The weakness is that consensus among experts does not imply veracity; the hypothesis that selected factors influence water quality was not tested empirically. Several studies to determine statistical relations between contributing factors and specific ground-water-quality parameters have been performed (Grady, 1994; Eckhardt and Stackelberg, 1995; Rupert, 1998, 1999; Eric Vowinkel, USGS, oral commun., February 5, 1999; Mike Sweat, USGS, oral commun., August 3, 1999). It would be a meaningful contribution to investigate the statistical relation between contributing factors and particular water contaminants in North Carolina. The greatest expense of such a study would be gathering sufficient water-quality data through a monitoring program; the benefit would be increased capability to protect source waters.

SUMMARY

The Source Water Assessment Program (SWAP), established by the SDWA Amendments of 1996, is designed to promote pollution prevention as a cost-effective means of providing reliable, long-term, safe drinking water sources for public water-supply systems. In North Carolina, the lead agency responsible for developing and implementing this pollution prevention program is the Public Water Supply Section (PWSS). To assist the PWSS in its efforts to rate the inherent vulnerability of more than 11,000 public water-supply wells and approximately 245 public surface-water intakes, the USGS developed methods to rate the unsaturated zone around public ground-water supplies and watershed characteristics of public surface-water intakes.

The PWSS will complete the inherent vulnerability analysis by further considering aquifer characteristics and watershed classification, intake location, and raw-water quality. Additionally, the PWSS will consider known point sources of contamination to describe the susceptibility of public water supplies to contamination.

Overlay and index methods were applied by the USGS to rate unsaturated zone and watershed characteristics. Factors were selected that influence the inherent vulnerability of drinking water sources. The distribution of values for each factor was classified over the possible range of values in North Carolina. Categories were rated on a scale of 1 to 10, where 1 indicates a minimal influence on the inherent vulnerability of a water supply, and 10 indicates a maximal influence on inherent vulnerability. The GIS data layers were divided into 60-meter by 60-meter cells, with one class of each contributing factor assigned to each cell.

Each factor was weighted in terms of its influence on the inherent vulnerability. Factor weights sum to 10. Multiplying the rates and weights and summing for each factor produces an index of the inherent vulnerability of the unsaturated zone and watershed characteristics for each cell. Inherent vulnerability values for all cells in the delineated source water protection areas are averaged to yield a single index characterizing the ground- or surface-water supply.

Selection of factors and subsequent assignment of final rates and weights for every category of contributing factors was based initially on a literature search. The literature search was followed by consultation with experts in hydrology, geology, forestry, agriculture, and water management.

Factors contributing to the inherent vulnerability of the unsaturated zone are the vertical hydraulic conductance, land-surface slope, land cover, and land use. Factors contributing to the inherent vulnerability of the watershed are the average annual precipitation, land-surface slope, land cover, land use, and ground-water contribution. These factors influence the physical transport of water, with or without contaminants. In addition to influencing water transport, land use effects the likelihood for generation of nonpoint-source contamination.

Vertical hydraulic conductance measures the capacity of the entire sequence of unsaturated material to transmit water. In the western and central parts of North Carolina, the unsaturated zone can be soil, saprolite, and(or) fractured rock. In the eastern part of North Carolina, the unsaturated zone can be soil, sedimentary rock, or unconsolidated sediments. Estimates of vertical hydraulic conductivity and thickness of these unsaturated zone components are used to derive the vertical hydraulic conductance. Soil data are from one of two data bases—SSURGO or STATSGO. Up to six soil layers may exist in any location; harmonic mean hydraulic conductivity for these six layers is the central value of hydraulic conductivity for all six layers combined. Vertical hydraulic conductivity of saprolite, fractured rock, sedimentary rock, and unconsolidated sediments are estimated from literature.

Land-surface slope influences whether precipitation runs off the land surface or infiltrates into the subsurface. Regional slopes range from relatively flat in the Coastal Plain Province to steep, highly variable slopes in the Blue Ridge and Piedmont Provinces. Locally, slopes in the Coastal Plain can be steep near streams. About 85 percent of the State is characterized by slopes less than 10 percent; about 57 percent of the State is characterized by slopes less than 2 percent.

Land cover, the physical overlay of the land surface, influences the amount of precipitation that infiltrates into the ground or runs off as overland flow. The more impervious the surface, the more precipitation runs off; the more pervious the surface, the more precipitation infiltrates into the subsurface. Commercial/industrial land cover has the least amount of pervious surface; forests have the most amount of pervious surface.

Land use describes activities that occur on the land surface and influence the potential generation of nonpoint-source contamination. Agricultural and developed areas (commercial/industrial and high-intensity residential areas) tend to have the greatest contribution of nutrients, sediment, and other chemical constituents. Forested areas are rated as having minimal impact on water quality, except where the land is used for silviculture and pesticide use can be high. Wetlands and barren lands also are rated low in terms of adverse impact on water quality.

Ground-water contribution represents the part of streamflow that is derived from ground-water discharge. In this study, ground-water contribution is a factor in areas within about 1,000 feet of streams. By restricting ground-water contribution to an area of about 1,000 feet on either side of streams, ground-water contribution emphasizes focused recharge and local ground-water flow. In this scenario, ground-water contribution is not considered to have originated outside of this buffer, though much of the flow in a stream experiencing low-flow conditions will have originated in these interstream areas. Base flow was assessed at 61 streams throughout North Carolina. Base flow ranges from about 29 to 71 percent in the Coastal Plain Province, from about 13 to 68 percent in the Piedmont Province, and from about 30 to 73 percent in the Blue Ridge Province.

The overlay and index methods described in this report are based on expert opinion concerning the relative importance of selected factors on source water quality, not on scientific experimentation. The relative rating of unsaturated zone and watershed characteristics is a practical and effective method for assessing one aspect of the inherent vulnerability of water supplies to contamination.

REFERENCES

Adams, B., and Foster, S.D., 1992, Land-surface zoning for groundwater protection: Journal of the Institution of Water and Environmental Management, v. 6, p. 312–320.

Aller, L., Bennet, T., Lehr, J.H., Petty, R.J., and Hackett, G., 1987, DRASTIC—A standardized system for evaluating ground water pollution potential using hydrogeologic settings: U.S. Environmental Protection Agency, EPA/600/2-87-036, 455 p.

Bales, J. D., and Pope, B.F., 1996, Streamflow characteristics of the Waccamaw River at Freeland, North Carolina, 1940–94: U.S. Geological Survey Water-Resources Investigations Report 96-4093, 35 p.

Bara, T.J., comp., ed., 1994, Multi-resolution land characteristics consortium—documentation notebook, [Environmental Monitoring and Assessment Program-Landscape Characterization, Contract 68-DO-0106]: Research Triangle Park, N.C., ManTech Environmental Technology, Inc. [variously paged].

Buol, S.W., and Weed, S.B., 1991, Saprolite-soil transformations in the Piedmont and Mountains of North Carolina: Geoderma, v. 51, p. 15–28.

California Department of Health Services, Division of Drinking Water and Environmental Management, January 1999, Appendix C, Physical barrier effectiveness checklist—Surface water source: accessed May 10, 1999, at URL http://www.dhs.ca.gov/ps/ddwem/dswapdoc/appc.

Chow, V.T., Maidment, D.R., and Mays, L.W., 1988, Applied hydrology: New York, McGraw-Hill Book Co., 572 p.

Collins, R.E., 1961, Flow of fluids through porous materials: New York, Reinhold Publishing Corp., 270 p.

Corwin, D.L., Vaughn, P.J., and Loague, K., 1997, Modeling nonpoint source pollutants in the vadose zone with GIS: Environmental Science and Technology, v. 31, no. 8, p. 2157–2174.

Daly, Christopher, 1996, Overview of the PRISM model, PRISM Climate Mapping Program: accessed March 18, 1999, at URL http://www.ocs.orst.edu/prism/prism_new.html.

Daly, Christopher, Neilson, R.P., and Phillips, D.L., 1994, A statistical-topographic model for mapping climatological precipitation over mountainous terrain: Journal of Applied Meteorology, v. 33, p. 40–158.

Daly, Christopher, Taylor, G.H., and Gibson, W.P., 1997, The PRISM approach to mapping precipitation and temperature, *in* Reprints, 10th Conference on Applied Climatology, Reno, Nev., American Meteorological Society, p. 10–12.

Daniel, C.C., III, 1989, Statistical analysis relating well yield to construction practices and siting of wells in the Piedmont and Blue Ridge Provinces of North Carolina: U.S. Geological Survey Water-Supply Paper 2341-A, 27 p.

Daniel, C.C., III, Smith, D.G., and Eimers, J.L., 1997, Hydrogeology and simulation of ground-water flow in the thick regolith-fractured crystalline rock aquifer system of Indian Creek Basin, North Carolina: U.S. Geological Survey Water-Supply Paper 2341-C, 137 p.

Demek, J., Embleton, C., Gellert, J.F., and Verstappen, H.T., eds., 1972, Manual of detailed geomorphological mapping: Prague, Academia, Publishing House of the Czechoslovak Academy of Sciences, 343 p.

de Mulder, E.F.J., and Hillen, R., 1990, Preparation and application of engineering and environmental geological maps in the Netherlands: Engineering Geology, v. 29, no. 4, p. 279–290.

Eckhardt, D.A., and Stackelberg, P.E., 1995, Relation of ground-water quality to land use on Long Island, New York: Ground Water, v. 33, no. 6, p. 1019–1033.

Environmental Systems Research Institute, Inc., 1994, Cell-based modeling with GRID 7.0.2—Hydrologic and distance modeling tools, ARC/INFO On-line manuals: Redlands, Calif.

Fels, J.E., and Matson, K.C., 1996, A cognitively-based approach for hydrogeomorphic land classification using digital terrain models, *in* Proceedings of the Third International Conference on Integrating GIS and Environmental Modeling, Santa Barbara, Calif., National Center for Geographic Information and Analysis, 11 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, N.J., Prentice-Hall, Inc., 604 p.

Giese, G.L., Eimers, J.L., and Coble, R.W., 1997, Simulation of ground-water flow in the Coastal Plain aquifer system of North Carolina: U.S. Geological Survey Professional Paper 1404-M, 142 p.

Giese, G.L., and Mason, R.R., Jr., 1993, Low-flow characteristics of streams in North Carolina: U.S. Geological Survey Water-Supply Paper 2403, 29 p.

Grady, S.J., 1994, Effects of land use on quality of water in stratified-drift aquifers in Connecticut: U. S. Geological Survey Water-Supply Paper 2381, 56 p.

Graham, R.C., and Buol, S.W., 1990, Soil-geomorphic relations on the Blue Ridge Front, II. Soil characteristics and pedogenesis: Soil Science Society of America Journal, v. 54, p. 1367–1377.

Graham, R.C., Daniels, R.B., and Buol, S.W., 1990, Soil-geomorphic relations on the Blue Ridge Front, I. Regolith types and slope processes: Soil Science Society of America Journal, v. 54, p. 1362–1366.

Harned, D.A., McMahon, Gerard, Spruill, T.B., and Woodside, M.D., 1995, Water-quality assessment of the Albemarle-Pamlico drainage basin, North Carolina and Virginia—Characterization of suspended sediment, nutrients, and pesticides: U.S. Geological Survey Open-File Report 95-191, 131 p.

Heath, R.C., 1994, Ground water recharge in North Carolina: North Carolina Department of Environmental Management, Groundwater Section, informal report, 52 p.

Helsel, D.R., and Ragone, S.E., 1984, Evaluation of regional ground-water quality in relation to land use, U. S. Geological Survey toxic waste—ground-water contamination program: U.S. Geological Survey Water-Resources Investigations Report 84-4217, 33 p.

Hershfield, D.M., 1961, Rainfall frequency atlas of the United States for durations from 30 minutes to 24 hours and return periods from 1 to 100 years: U.S. Department of Commerce, Weather Bureau Technical Paper 40, 115 p.

Howe, S.S., and Breton, P.L., 1998, Water resources data for North Carolina, water year 1997, v. 2, Ground-water records: U.S. Geological Survey Water-Data Report NC-97-2, 251 p.

Jenson, S.K., and Domingue, J.O., 1988, Software tools to extract topographic structure from digital elevation data for geographic information system analysis: Photogrammetric Engineering and Remote Sensing, v. 54, no. 11, p. 1593–1600.

Johnson, R.H., and Van Driel, J.N., 1978, Susceptibility of Coastal Plain aquifers to contamination, Fairfax County, Virginia, A computer composite map: U.S. Geological Survey Open-File Map 78-265, 1 sheet.

Lindeburg, M.R., 1992, Civil engineering reference manual (6th ed.): Belmont, Calif., Professional Publications, approx. 690 p.

Matson, K.C., and Fels, J.E., 1996, Approaches to automated water table mapping, *in* Proceeding of the Third International Conference on Integrating GIS and Environmental Modeling, Santa Barbara, Calif.: National Center for Geographic Information and Analysis, 12 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A Modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, chap. A1, book 6, [variously paged].

McMahon, Gerard, and Lloyd, O.B., Jr., 1995, Water-quality assessment of the Albemarle-Pamlico drainage basin, North Carolina and Virginia—Environmental setting and water-quality issues: U.S. Geological Survey Open-File Report 95-136, 72 p.

Mew, H.E., Jr., Medina, M.A., Jr., Heath, R.C., and Jacobs, T.L., 1994, Suitability of the normal data distribution to model water-table fluctuations, 1. Model development: Hydrological Science and Technology, v. 10, no. 1–4, p. 90–109.

Mew, H.E., Jr., Medina, M.A., Jr., Jacobs, T.L., and Heath, R.C., 1995, Suitability of the normal data distribution to model water-table fluctuations, 1. Parameter distribution: Hydrological Science and Technology, v. 11, no. 1–4, p. 83–103.

Miller, R.A., and Mattraw, H.C., Jr., 1982, Storm water runoff quality from three land-use areas in South Florida: Water Resources Bulletin, v. 18, no. 3, p. 513–519.

Mueller, D.K., Hamilton, P.A., Helsel, D.A., Hitt, K.J., and Ruddy, B.C., 1995, Nutrients in ground water and surface water of the United States—An analysis of data through 1992: U.S. Geological Survey Water-Resources Investigations Report 95-4031, 74 p.

Nathan, R.J., and McMahon, T.A., 1990, Evaluation of automated techniques for base flow and recession analysis: Water Resources Research, v. 26, no. 7, p. 1465–1473.

National Research Council, 1993, Ground water vulnerability assessment—Predicting relative contamination potential under conditions of uncertainty: National Academy Press, Committee on Techniques for Assessing Ground Water Vulnerability, 204 p.

Nolan, B.T., and Clark, M.L., 1997, Selenium in irrigated agricultural areas of the western United States: Journal of Environmental Quality, v. 26, no. 3, p. 849–857.

North Carolina Department of Environment, Health, and Natural Resources, 1995, The North Carolina wellhead protection guidebook, Protecting local underground water supplies: Raleigh, North Carolina Department of Environment, Health, and Natural Resources, Division of Environmental Management, Groundwater Section, 249 p.

North Carolina Department of Environment and Natural Resources, 1999a, North Carolina source water assessment program plan: Raleigh, North Carolina Department of Environment and Natural Resources, Division of Environmental Health, Public Water Supply Section, [variously paged].

———1999b, Procedures for assignment of water quality standards: North Carolina Administrative Code Section 15A NCAC 2B.0100. Amended, effective April 1, 1999.

———1999c, Classification and water quality standards applicable to surface water and wetlands of North Carolina: North Carolina Administrative Code Section 15A NCAC 2B.0200. Amended, effective April 1, 1999.

O'Hara, C.G., 1994, Permeability of soils in Mississippi: U.S. Geological Survey Water-Resources Investigations Report 94-4088, 1 sheet.

———1996, Susceptibility of ground water to surface and shallow sources of contamination in Mississippi: U.S. Geological Survey Hydrologic Investigations Atlas HA-739, 4 sheets.

Omernik, J.M., 1977, Nonpoint source-stream nutrient level relationships—A nationwide study, *in* Cooke, G.D., Welch, E.B., Peterson, S.A., and Newroth, P.R., 1986, Lake and reservoir restoration: Boston, Mass., Butterworth Publishers, 392 p.

Overton, D.E., and Meadows, M.E., 1976, Stormwater modeling: New York, Academic Press, 358 p.

Plaster, R.W., and Sherwood, W.C., 1971, Bedrock weathering and residual soil formation in central Virginia: Geological Society of America Bulletin, v. 82, p. 2813–2826.

Rudek, Joseph, 1997, Atmospheric nitrogen deposition and ecosystem health in North Carolina, A public perspective: North Carolina Environmental Defense Fund, 14 p.

Rupert, M.J., 1998, Probability of detecting atrazine/desethyl-atrazine and elevated concentrations of nitrate (NO2 + NO3 - N) in ground water in the Idaho part of the upper Snake River basin: U.S. Geological Survey Water-Resources Investigations Report 98-4203, 32 p.

———1999, Improvements to the DRASTIC ground-water vulnerability mapping method: U.S. Geological Survey Fact Sheet FS-066-99, 6 p.

Rutledge, A.T., and Mesko, T.O., 1996, Estimated hydrologic characteristics of shallow aquifer systems in the Valley and Ridge, the Blue Ridge, and the Piedmont physiographic provinces based on analysis of streamflow recession and base flow: U.S. Geological Survey Professional Paper 1422-B, 58 p.

Saad, D.A., 1997, Effects of land use and geohydrology on the quality of shallow ground water in two agricultural areas in the western Lake Michigan drainages, Wisconsin: U.S. Geological Survey Water-Resources Investigations Report 96-4292, 69 p.

Sauer, V.B., Thomas, W.O., Jr., Stricker, V.A., and Wilson, K.V., 1983, Flood characteristics of urban watersheds in the United States: U.S. Geological Survey Water-Supply Paper 2207, 63 p.

Sear, D.A., Armitage, P.D., and Dawson, F.H., 1999, Groundwater dominated rivers: Hydrological Processes, v. 13, p. 255–276.

Simmons, C.E., 1993, Sediment characteristics of North Carolina streams, 1970–79: U.S. Geological Survey Water-Supply Paper 2364, 84 p.

Soil Survey Division Staff, 1993, Soil survey manual: U.S. Department of Agriculture Handbook No.18, October 1993, 437 p.

Texas Natural Resource Conservation Commission, April 30, 1999, Source water assessment and protection program: accessed July 27, 1999, at URL http://www.tnrcc.state.tx.us/water/wu/swap/index.html.

Tóth, J., 1963, A theoretical analysis of groundwater flow in small drainage basins: Journal of Geophysical Research, v. 68, no. 16, August 15, 1963, p. 4795–4812.

U.S. Department of Agriculture, 1977, Erosion and sediment inventory for North Carolina: Soil Conservation Service, Special Report, August 1977, 11 p.

———1994, State soil geographic (STATSGO) data base, Data use information: U.S Department of Agriculture, Natural Resources Conservation Service, Miscellaneous Publication 1492, December 1994.

———1995, Soil survey geographic (SSURGO) data base: U.S Department of Agriculture, Natural Resources Conservation Service, Miscellaneous Publication 1527, January 1995.

U.S. Department of the Interior, Bureau of Reclamation, 1973, Design of small dams: Water Resources Technical Publication, 816 p.

U.S. Environmental Protection Agency, 1997, State source water assessment and protection programs guidance, Final guidance: EPA 816-R-97-009, [variously paged].

Vepraskas, M.J., Guertal, W.R., Kleiss, H.J., and Amoozegar, A., 1996, Porosity factors that control the hydraulic conductivity of soil-saprolite transitional zones: Soil Science Society of America Journal, v. 60, p. 192–199.

Vepraskas, M.J., Hoover, M.T., and Buoma, J., 1991, Sampling strategies for assessing hydraulic conductivity and water-conducting voids in saprolite: Soil Science Society of America Journal, v. 55, p. 165–170.

Viessmann, Warren, Jr., Knapp, J.W., Lewis, G.L., and Harbaugh T.E., 1977, Introduction to hydrology (2d ed.): New York, Harper and Row, 704 p.

Vogelmann, J.E., Sohl, T.L., Campbell, P.V., and Shaw, D.M., 1998, Regional land cover characterization using Landsat Thematic data and ancillary data sources: Environmental Monitoring and Assessment, v. 51, p. 415–428.

Vrba, Jaroslav, and Zaporozec, Alexander, eds., 1994, Guidebook on mapping groundwater vulnerability: Verlag Heinz Heise, International Association of Hydrogeologists, v. 16, International contributions to hydrogeology, 131 p.

Wahl, K.L., and Wahl, T.L., 1988, Effects of regional ground-water level declines on streamflow in the Oklahoma Panhandle, *in* Proceedings of Symposium on Water-Use Data for Water Resources Management, American Water Resources Association, Tucson, Ariz., August 1988, p. 239–249.

Whittemore, D.O., Merchant, J.W., Whistler, J., McElwee, C.E., and Woods, J.J., 1987, Ground water protection planning using the ERDAS geographic information system, Automation of DRASTIC and time-related capture zones, *in* Proceedings of the NWWA FOCUS conference on Midwestern Ground Water Issues: Dublin, Ohio, National Water Well Association, p. 359–374.

Wilder, H.B., Robison, T.M., and Lindskov, K.L., 1978, Water resources of northeast North Carolina: U.S. Geological Survey Water-Resources Investigations Report 77-81, 113 p.

Winter, T.C., Harvey, J.W., Franke, O.L., and Alley, W.M., 1998, Ground water and surface water, A single resource: U.S. Geological Survey Circular 1139, 79 p.

APPENDIX

DOCUMENTATION ON GEOGRAPHIC INFORMATION SYSTEM (GIS) DATA SOURCES

Land Use and Land Cover

The source data for both the land-use and land-cover components is the Multi-Resolution Land Characteristics (MRLC) data set. The MRLC data set is a product of the MRLC Consortium which consists of the Ecological Monitoring and Assessment Program of the U.S. Environmental Protection Agency (USEPA), U.S. Forest Service Remote Sensing Application Center, Gap Analysis Program of the U.S. Geological Survey (USGS) Biological Resources Division, Coastal Change Analysis Program of the National Oceanic and Atmospheric Administration (NOAA), and the National Water-Quality Assessment (NAWQA) Program and EROS Data Center (EDC) of the USGS. The mechanisms for collaboration were formalized with the signing of a Memorandum of Understanding in 1995.

The main objective of the MRLC consortium was to generate a generalized and consistent (seamless) land-cover data layer for the entire conterminous United States (Bara, 1994). The North Carolina portion of the data set was created as part of the land-cover mapping activities for Federal Region IV (the States of Kentucky, Tennessee, Mississippi, Alabama, North Carolina, South Carolina, Georgia, and Florida). The development of the Region IV data set was initiated during the spring of 1997, and a first draft product was completed during summer 1997. This data set was developed by personnel at the EDC, Sioux Falls, S.D.

The primary source of data for the MRLC data set was leaves-off (primarily spring) Landsat Thematic Mapper (TM) data, acquired during 1990–93, primarily during the spring seasons of 1991, 1992, and 1993 (Vogelmann and others, 1998). Additionally, leaves-on (summer) TM data sets were acquired and referenced. In total, 24 TM scenes were analyzed. These data sets were referenced to Albers Conical Equal Area coordinates, but projected to the North Carolina State Plane coordinate system for this project.

The general procedure used for processing the MRLC data set was to (1) mosaic multiple leaves-off TM scenes and classify them by using an unsupervised classification algorithm, (2) interpret and label classes into land-cover categories by using aerial photographs as reference data, (3) resolve confused classes by using the appropriate ancillary data source(s), and (4) incorporate land-cover information from leaves-on TM data, National Wetlands Inventory (NWI) data, and other data sources to refine and augment the "basic" classification developed above. More detailed information about the background and production process of the MRLC data sets can be obtained at the USEPA web site http://www.epa.gov/mrlc.

To test the methods, the MRLC data set was resampled from a 30-meter by 30-meter grid to a 60-meter by 60-meter grid, shifted, and snapped to match the lower-left corner of the other contributing-factor data sets. Since the MRLC is categorical data, a nearest neighbor algorithm was used to maintain the classification scheme. This resampling technique assigns a value to each cell in the coarser data set that is the value of the cell in the original source closest to the center of the larger cell. Resampling by using the nearest neighbor algorithm from a 30-meter by 30-meter to a 60-meter by 60-meter grid implies that the value from only 1 cell out of each 4-cell neighborhood will be represented in the output data set. However, the overall representation of land-cover and land-use classes is the same—the percentage of area within each land-use and land-cover class is the same statewide for the 30-meter by 30-meter and 60-meter by 60-meter data sets.

When rating methods are applied statewide, cell size will be retained at 30 meters by 30 meters. A 1999 release of the MRLC land-use and land-cover data (still the 1990–93 data, but with better distinctions among some categories) should be used.

Elevation and Slope

The source of the elevation data set used to derive the slope components is a Digital Elevation Model (DEM) developed by the USGS and North Carolina State University. The ARC/INFO version 7.1.1 TOPOGRID command was used to process the elevation surface model. TOPOGRID incorporates the software package, developed by Michael Hutchinson at Australian National University, known as "ANUDEM" (abbreviated form of Australian National University Digital Elevation Model) to produce the DEM. Four types of input data were used for the production of the DEM—hypsography (land-surface elevation) contour lines, hypsography points, hydrography, and shoreline. Following ANUDEM processing, a "fill" procedure (Jenson and Domingue, 1988) was used to remove remaining depressions. Each of the pre-processing steps is described briefly below.

Hypsography pre-processing:

The USGS 1:100,000-scale digital line graph (DLG) hypsography files were downloaded from the USGS GeoData web site (http://edcwww.cr.usgs.gov/doc/edchome/ndcdb/ndcdb.html). The DLG files were converted into a point GIS layer and a contour line GIS layer. Only the elevation and depression contours were used.

Hydrography pre-processing:

The 1:100,000-scale hydrography data are an early release of the River-Reach File (RF-3) distributed by the USEPA. Cataloging units that include any part of North Carolina were processed. Several changes were made in the RF-3 data set before its use in TOPOGRID. First, many small water bodies and streams that were not connected to the main stream network were eliminated. Larger unconnected streams were retained. Second, centerlines were generated for all large lakes, wide streams, and other water bodies. The polygons forming the water bodies were removed. Because the stream centerlines were used in the creation of the DEM rather than water-body polygons, the DEM is not flat in the areas covered by water. Third, TOPOGRID requires that all streams point downstream, so all lines pointing upstream were flipped. Finally, the RF-3 data were incomplete in several places. Large parts of several rivers and lakes were missing. Corrections were made by using data extracted from the USGS 1:100,000-scale hydrography DLG.

Shoreline pre-processing:

The shoreline of North Carolina at 1:24,000 scale was combined with the shoreline of adjacent states at 1:70,000 scale. The shoreline data were processed into a GIS data layer that defined water and land. The shoreline arc also was entered as a contour elevation with a zero-meters elevation value. Shoreline areas were examined to verify that no overlap of contour lines with shorelines occurred.

Once the entered data sets were finalized, the data were processed through the TOPOGRID function in half-degree by 1-degree geographic blocks. A 6-kilometer area of overlap was included around each block to minimize edge effects. The blocks were then mosaiced together to create a seamless DEM for the State. The final resolution of the DEM tested in several areas of the State is 60-meter by 60-meter cells, stored as a floating-point, raster grid. A percentage slope data layer was derived by using the SLOPE function in ARC/INFO GRID module.

When rating methods are applied statewide, GIS grid-cell size will be reduced to 30 meters by 30 meters. Improved slope data (based on 1:24,000 DEM data base) will be used.

Soils

Two sources of soil data were used for this report—county level and state level. Soil types by county were identified in the SSURGO data base of the Natural Resources Conservation Service (NRCS). The NRCS developed the SSURGO data base at a scale of 1:24,000, primarily for use in the natural-resource planning and management of farms and ranches, townships, or counties and by landowners/users. At the time of this report, county-level data have been processed for Alamance, Beaufort, Brunswick, Cabarrus, Currituck, Durham, Edgecombe, Granville, Guilford, Halifax, Hyde, Mecklenburg, Nash, Orange, and Stanly Counties in North Carolina.

Where county-level soil information was not available, the STATSGO data base for North Carolina was used. STATSGO is a digital, general-soils association map developed by the NRCS. It consists of a broad inventory of soil and non-soil areas that occur in a repeatable pattern on the landscape and that can be cartographically shown at the scale mapped. The soil maps for STATSGO are compiled by generalizing more detailed soil survey maps. Where more detailed soil survey maps are not available, data on geology, topography, vegetation, and climate are assembled, together with Land Remote Sensing Satellite (LANDSAT) images. Soils of like areas are studied, and the probable classification and extent of the soils are determined. STATSGO maps are at the 1:250,000 scale and are designed primarily for regional, multicounty, river basin, State, and multistate resource planning, management, and monitoring.

To test the rating methods, the STATSGO and SSURGO soil layers were compiled into one layer with a cell size of 60 meters by 60 meters. The SSURGO data were superimposed on the STATSGO data so that the best available data are always used. When rating methods are applied statewide, a cell size of 30 meters by 30 meters will be used.

Information about soil permeability and thickness was obtained from the Map Unit Interpretation Record (MUIR) attribute data base that is linked to the SSURGO soil-unit delineation and the STATSGO mapping unit. MUIR contains information about soils and individual layers within soils. Some problems were encountered with the attribute data for the SSURGO data. Certain soil series were not assigned permeability or thickness values, including dams, gullied lands, pits, mines, quarries, stony lands, udorthents, urban lands, dunes, and water. For statewide evaluation, missing values should be assigned the STATSGO value for the area.

ARC/INFO programs were written to process the MUIR data to extract thickness and permeability by layer for each soil unit. For SSURGO and STATSGO data, the weighted average by percentage of each soil component was applied to each mapping unit for thickness and harmonic mean permeability. The body of the report defines the equations used to calculate the harmonic mean permeability values.

More information on STATSGO, SSURGO, and the MUIR data bases can be obtained from the U.S. Department of Agriculture, NRCS, National Soil Survey Center, National Soil Data Access Facility web site, http://www.statlab.iastate.edu/soils/nsdaf/index.html.

Precipitation

The mean monthly precipitation estimates were generated by the Parameter-Elevation Regressions on Independent Slopes Model (PRISM) (Daly and others, 1994, 1997). PRISM is an analytical tool that uses point data, a DEM, and other spatial data sets to generate estimates of monthly, yearly, and event-based climatic parameters, such as precipitation, temperature, snowfall, degree days, and dew point. PRISM-derived data sets have been used in applications of climatology, hydrology, natural resources, global climate change, land use, planning, relocation, education, and geography. PRISM is uniquely designed to map climate in the most difficult situations, including high mountains, rain shadows, temperature inversions, coastal regions, and other complex climatic regimes.

PRISM uses a DEM to estimate the elevations of precipitation stations at the proper orographic scale, and uses the DEM and a windowing technique to group stations onto individual topographic facets. For each DEM grid cell, PRISM develops a weighted precipitation/elevation (P/E) regression function from nearby stations, and predicts precipitation at the cell's DEM elevation with this function. In the regression, greater weight is given to stations with location, elevation, and topographic positioning similar to that of the grid cell. Whenever possible, PRISM calculates a prediction interval for the estimate, which is an approximation of the uncertainty involved. By relying on many localized, facet-specific P/E relations rather than a single domain-wide relation, PRISM continually adjusts its frame of reference to accommodate local and regional changes in orographic regime with minimal loss of predictive capability.

Data entry into the national model consisted of 1961–90 mean monthly precipitation data from more than 8,000 NOAA cooperative sites, snow telemetry (SNOTEL) sites, and selected State network stations. Data-sparse areas were supplemented by a total of about 500 short-term stations. A station was included in this data set if it had at least 20 years of valid data, regardless of its period of record. PRISM software was used to minimize "seams" along State and regional boundaries. The North Carolina portion of the data set is distributed separately.

The DEM data for the model are 1:250,000-scale, distributed by the USGS. These data and their associated metadata are available from the USGS web site http://edcwww.cr.usgs.gov/doc/edchome/ndcdb/ndcdb.html.

Summing 12 monthly maps for the country created the national mean annual precipitation maps. The annual maps underwent extensive peer review by many State climatologists and other experts. This is part of a national effort by the NRCS and Oregon State University to develop state-of-the-art precipitation maps for each State in the United States.

Precipitation estimated for each grid cell is an average over the entire area of that cell; thus, point precipitation can be estimated at a spatial precision no better than half the resolution of a cell. For example, the precipitation data were distributed at a resolution of approximately 4 kilometers (km). Therefore, point precipitation can be estimated at a spatial precision no better than 2 km. However, the overall distribution of precipitation features is thought to be accurate. For further information, the online PRISM homepage can be accessed at the Oregon State University's "Climate Mapping with PRISM" web site—http://www.ocs.orst.edu/prism/prism_new.html.

Ground-Water Contribution

The ground-water contribution component was derived from applying the unsaturated zone ratings within a 305-meter area around all streams identified in the early release of the RF-3 distributed by the USEPA.

First, 305-meter polygons were drawn around all streams by using the ARC/INFO "BUFFER" command. The streams were processed within 8-digit hydrologic cataloging unit areas. Occasionally, the buffered areas extended over the ridgelines defined by the cataloging units. The areas that extended over the cataloging unit boundaries were removed.

Next, the buffered streams were adjusted to include water bodies that overlapped the buffered stream areas. This ensured that the middle of lakes wider than 305 meters were included in the analysis of ground-water contribution.

Finally, the unsaturated-zone component of inherent vulnerability was applied to the buffered zones within the six pilot sites by using overlay analysis. A raster layer with 60-meter by 60-meter cells was created for testing the rating methods in several areas of the State; however, 30-meter by 30-meter cells will be used when the method is applied statewide.

USGS
science for a changing world

ERRATA

Please attach to the PDF version of USGS WRIR 99-4283

"Methods of rating unsaturated zone and watershed characteristics of public water supplies in North Carolina," by J.L. Eimers, J.C. Weaver, Silvia Terziotti, and R.W. Midgette

1. **Page IV, Acronyms used in this report**—The acronym for ARC/INFO macro language was incorrectly listed as AMC; the correct acronym is **AML**. The acronym for Multi-Resolution Land Characteristics was incorrectly listed as MLRC; the correct acronym is **MRLC**.

2. **Page 20, Table 11**—The column subheadings under "Precipitation," "Land use," and "Ground-water contribution," were incorrectly shown as "Rating (r_3)"; the subheadings should read as circled below:

Table 11. Example determination of a watershed characteristics rating for part of an unnamed watershed upstream from a water-supply intake

Cell number *i* (fig. 5)	Precipitation [weight (w_1)=3]		Land-surface slope [weight (w_2)=2]		Land-cover and land-use category	Land cover [weight (w_3)=1]	Land use [weight (w_4)=3]	Ground-water contribution [weight (w_5)=1]		Grid cell rating
	In inches	Rating (r_1) (table 8)	In percent	Rating (r_2) (table 9)		Rating (r_3) (table 10)	Rating (r_4) (table 5)	Unsaturated zone rating value	Rating (r_5)	$R_i = \sum_{i=1}^{5} (w_i \times r_i)$
1	56	5	52	10	Forest	1	3	46	4.6	49.6
2	56	5	47	9	Forest	1	3	0	0	43.0
3	56	5	48	9	Forest	1	3	50	5.0	48.0
4	56	5	45	9	Hay/pasture	3	5	0	0	51.0

Watershed characteristics rating for *n* (4) selected cells (fig. 5)

$$\frac{\sum_{i=1}^{4} R_i}{n} = \frac{191.6}{4} = 47.9$$

3. **Page 23, References**—The URL for California Department of Health Services, Division of Drinking Water and Environmental Management, was incorrectly shown as http://www.dhs.ca.gov/ps/ddwem/dswapdoc/appc. The correct URL is:

http://www.dhs.ca.gov/ps/ddwem/dwsap/dwsapdoc/appc.htm.