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

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Overlay and index methods were developed by the U.S. Geological Survey and North Carolina Public Water Supply Section to rate the unsaturated zone and watershed characteristics for use in assessing more than 11,000 public water-supply wells and approximately 245 public surface-water intakes statewide for vulnerability to contamination. Factors selected for rating the vulnerability of the unsaturated zone to surface contamination were vertical series hydraulic conductance, land-surface slope, land cover, and land use. Factors selected for rating vulnerability of watersheds to surface contamination were average annual precipitation, land-surface slope, land cover, land use, and ground-water contribution. Selection of factors, development of ratings, and assignment of weights were based on literature and consultations with experts in hydrology, geology, forestry, agriculture, and water management.

Rating factors were assigned values from 1 to 10, covering the possible range of values of a given factor in North Carolina. Factors were weighted 1, 2, or 3 to reflect their relative influence on the vulnerability of the water supply. Factor values were put into geographic information system layers, which were grids having 30-meter by 30-meter cells.

The weakness of these rating methods is that consensus among experts does not imply veracity. An investigation of the statistical relations between contributing factors and particular water contaminants in North Carolina would, by confirming these methods, contribute to public water-supply protection efforts in North Carolina. Efforts to increase the accuracy of source water assessment area delineations for public water-supply wells also would contribute to public water-supply protection efforts in North Carolina.

## INTRODUCTION

The need for high-quality drinking water supplies in North Carolina has become 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). North Carolina is implementing a Source Water Assessment Program (SWAP) to delineate source water areas, inventory potential contaminants, and determine the susceptibility of each public water supply to contamination.

In North Carolina, the determination of overall susceptibility of each public ground-water supply and surface-water intake is based on two key components—a contaminant rating and an inherent vulnerability rating. The contaminant rating is determined by the State's Public Water Supply Section (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 contaminant risk 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 water supply. The inherent vulnerability of a ground-water source 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 is determined by combining watershed classification, intake location, raw-water quality, the State water quality use support rating, and watershed characteristics rating (North Carolina Department of Environment and Natural Resources, 1999a). In cooperation with the PWSS, the U.S. Geological Survey (USGS) developed methods to rate unsaturated zones for public ground-water systems and watershed characteristics for public surface-water intakes (Eimers and others, 2000). 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 developed in this investigation are not necessarily transferable to other regions; however, the methods that were used to develop the ratings are transferable.

### Purpose and Scope

Methods are presented to rate the unsaturated zone for public ground-water supplies and watershed characteristics for public surface-water supplies in North Carolina.  For ground-water supplies, the factors that were used to rate the unsaturated zone include vertical hydraulic conductance, land-surface slope, land cover, and land use. The factors contributing to watershed characteristics ratings are average annual precipitation, land-surface slope, land cover, land use, and ground-water contribution. Pilot study results are presented, and some limitations of North Carolina's public water supply susceptibility assessments are discussed.

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

The vulnerability of drinking water supplies is not a measurable property; however, inherent vulnerability can be inferred from surrogate information that is measurable (National Research Council, 1993). For this investigation, geologic, hydrologic, climatic, physiographic, and cultural factors were assigned weights that reflect their influence on water resources.  Initial estimates of the relative importance of each factor (its weight) and the degree of influence of that factor (ratings) were 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 County

Water and Sewer Authority, the North Carolina Clean Water Management Trust Fund, the North Carolina Division of Water Quality, 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 based on their expertise in hydrology, geology, forestry, agriculture, and water management in North Carolina. Finally, 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, reaches the water table by following the path of aquifer recharge. The selected factors, which are represented by GIS spatial-data layers, include vertical hydraulic conductance of the unsaturated zone, land-surface slope, land cover, and land use. These four factors are, to some extent, correlated. For example, an area characterized by steep slopes will not be characterized by land uses such as crop land.

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 potential for 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 calculating the unsaturated zone rating, each of these four factors is weighted on the basis of the importance of the factor in determining vulnerability. The sum of all unsaturated zone factor weights is 10. Expert opinion determined that vertical hydraulic conductance and land use (each weighted 3) are more important influences on ground-water supplies than are land-surface slope and land cover (each weighted 2).

### 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 outlined here for rating the unsaturated zone and watershed characteristics are implemented statewide, estimates of the depth to the water table and the hydraulic conductance of a variety of geologic formations will be needed.

Hydraulic conductance of the unsaturated zone is calculated for layers in series. Depending on depth to water, particular locations in the Blue Ridge and Piedmont Provinces may incorporate estimates of vertical conductance for layers of soil, saprolite, and(or) fractured rock. Locations in the Coastal Plain Province may require estimates of vertical conductance for layers of soil and(or) sedimentary formations. The determination of vertical hydraulic conductance is reduced to estimating the thickness and vertical hydraulic conductivity of each component of the unsaturated zone. Unsaturated hydraulic conductivity is a function of moisture content, porosity and other textural aspects of the material. Saturated hydraulic conductivity is the upper bound of possible unsaturated hydraulic conductivity (Freeze and Cherry, 1979) and, as such, is used in this study as a conservative estimate of unsaturated hydraulic conductivity.

Thickness and vertical hydraulic conductivity 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) (U.S. Department of Agriculture, 1994, 1995).

Developed at a scale of 1:24,000, SSURGO data are available for 70 of 100 North Carolina counties. STATSGO data are available for all of North Carolina at a scale of 1:250,000, and are used where SSURGO data are unavailable. STATSGO map units can include up to 26 distinct soils, each with specific soil characteristics (U.S. Department of Agriculture, 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. Low ratings were assigned to the low conductance, and high ratings were assigned to the high conductance. Areas characterized by low vertical hydraulic conductance (such as areas dominated by clayey soils) contribute the least to the inherent vulnerability of ground-water supplies, and areas characterized by high vertical hydraulic conductance (such as areas dominated by sandy soils) contribute the most to the inherent vulnerability of ground-water supplies.

### 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 tends to infiltrate into the subsurface in areas characterized by low slope; precipitation tends to run off land surface in areas characterized by high slope.

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. Nearly 57 percent of the State has slopes of less than 2 percent. Slightly more than 85 percent of the State has slopes of less than 10 percent.

Slopes were divided into classes and assigned ratings from 1 to 10. 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 influences the amount of precipitation that infiltrates into the ground. Infiltration occurs where land cover is pervious. Where precipitation falls directly onto the ground, the amount of infiltration depends on such factors as vegetative cover and soil compaction. Vegetation impedes runoff and increases temporary surface storage; in these ways, vegetation contributes to increased infiltration. During the growing season, evapotranspiration reduces the amount of water that infiltrates beyond the root zone. Soil compaction promotes runoff and decreases infiltration.

Land-cover information was obtained from the 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 (Vogelmann and others, 1998). Data were stored at a 30-meter resolution.

Runoff coefficients (Viessmann and others, 1977; Chow and others, 1988; Lindeburg, 1992) and Soil Conservation Service (SCS) curve numbers (U.S. Bureau of Reclamation, 1973; Overton and Meadows, 1976; Lindeburg, 1992) were used as general guidelines in assigning ratings for land cover.

Land-cover categories were rated from 1 to 10 according to their contribution to the inherent vulnerability of ground-water supplies (table 1). Land covers that impede infiltration and contribute least to the inherent vulnerability of ground-water supplies were assigned a low rating. Land covers that permit infiltration and contribute the most to the inherent vulnerability of ground-water supplies were 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.

### 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 was rated identically for the unsaturated zone and watershed characteristics (table 2).

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 quantify the effects of human activities, expressed as land use, on regional ground-water quality (Helsel and Ragone, 1984). One of these studies, performed on Long Island, New York (Eckhardt and Stackelberg, 1995), demonstrated that logistic regression equations based on explanatory variables including land use characterize the probability of contaminants. The factors that most directly control 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 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 that for land cover. Both are derived from the same GIS layer. 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 determines source-water assessment areas by using a delineation method specified in the State's approved Wellhead Protection Program, where the assessment area is a function of the amount of water pumped from the well and the approximate average rate of ground water recharge in the region (Heath, 1994; North Carolina Department of Environment, Health, and Natural Resources, 1995). For all public water-supply wells in North Carolina, susceptibility determinations are performed on a source-water assessment area centered around the wellhead. This circular area can be truncated by the presence of substantial surface-water bodies.

To determine unsaturated zone ratings, the source-water assessment area was divided into discrete 30-meter by 30-meter cells. Only cells with more than 50 percent of their area in the source-water assessment area were included in the calculation.

The four contributing factors were assigned weights in the final calculation of the unsaturated zone rating—3 for vertical hydraulic conductance, 2 for land-surface slope, 2 for land cover, and 3 for land use. Weights are subjective measures that reflect the relative importance of factors that are used to determine ground-water vulnerability to contamination. The factor weights are multiplied by ratings and summed, resulting in an unsaturated zone rating that ranges from 10 to 100 for each cell. 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 (fig. 1; table 3), 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, reaches 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. With the exception of land use, these factors influence the physical transport of water. The values of these factors were categorized, and the categories were 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.

The land-use factor is included as a measure of the potential nonpoint-source contamination caused by activities occurring at the land surface and is included to fulfill requirements of the SWAP plan to consider nonpoint sources (North Carolina Department of Environment and Natural Resources, 1999a). To determine the watershed characteristics rating, the five factors were weighted on the basis of importance relative to other factors in affecting public water-supply vulnerability— 3 for average annual precipitation, 2 for land-surface slope, 1 for land cover, 3 for land use, and 1 for ground-water contribution. The sum of all watershed characteristics factor weights is 10. Ratings were 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).

### Average annual precipitation

Precipitation is the source of water transported overland to a stream or lake. Eimers and others (2000) discuss the limitations of rainfall intensity data and the selection of average annual precipitation as the measure of precipitation in this investigation. In North Carolina, average annual precipitation varies from about 40 inches to more than 80 inches; 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.

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. Precipitation amounts between 40 and 50 inches during the year were rated 2 or 3. Average annual precipitation amounts exceeding 80 inches were rated 10.

### 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 relation between slope and the occurrence of overland flow is underscored by slope’s 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. Not only is sediment a concern, but 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) reported that steep slopes contribute to the occurrence of higher streamflow in the mountains. Chow and others (1988) reported that the percentage of rainfall that is translated into overland flow to the streams is based on various factors, including land-surface slope.

Slopes were divided into six categories and assigned ratings from 1 to 10. These are the same categories used in unsaturated zone ratings, 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.

### 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.

Simmons (1993) discussed the effects of vegetative cover in erosion, sediment disintegration, and transport by overland flow or wind. Vegetative cover impedes erosion by reducing splash, increasing evapotranspiration, reducing runoff potential, and increasing infiltration as precipitation falls on and is held by decayed matter. The U.S. Department of Agriculture (1977) cites average annual erosion rates 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 for land cover in the basin.

The Rational Method equation for estimating peak discharge includes a 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 Soil Conservation Service (SCS; currently called 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. 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 4).

### Land use

Land use describes activities that occur on the land surface. This factor represents the potential for generation of nonpoint-source contamination that can result from these activities. Land use is rated identically for watershed characteristics and the unsaturated zone (table 2). 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 investigations. Of note is a series of studies in large river basins across the United States conducted 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 developed basins and areas having a large percentage of agricultural and livestock 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) noted that although runoff from forested areas may be expected to have the least impact on water quality, runoff from lands used for silviculture can contain pesticides. McMahon and Lloyd (1995) also noted that wetlands can act as natural water-treatment systems because the slower water velocities allow suspended sediments and their adsorbed chemical constituents to settle out.

Omernik (1977) reported some general relations between land use and nitrogen and phosphorus loads in surface water. Basins with high percentages of urban and 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.

#### Ground-water contribution

Surface and ground water are parts of one hydrologic system. In North Carolina, streamflows are, in part, derived from underlying and adjacent aquifers, particularly shallow aquifers. 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 was derived from the unsaturated zone rating described in the previous section entitled "Example of an Unsaturated Zone Rating." Unsaturated zone ratings were computed for 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 in these areas were calculated by dividing the unsaturated zone ratings by 10 to scale the values to a range from 1 to 10.

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 was 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. 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 (fig 2; table 5). 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 (30 meters by 30 meters) throughout the basin. 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 and averaged to produce the overall watershed characteristics rating (47.9 for the cells used in this example; fig 2; table 5).

## LIMITATIONS

The overlay and index methods of unsaturated zone and watershed characteristics ratings that were used here are generalized methods that assess an aspect of inherent vulnerability on the basis of expert opinion. Hundreds of surface-water intakes and thousands of wells are rated uniformly and quickly. These ratings can be modified as updated data about the factors become available. These methods of rating the unsaturated zone and watershed characteristics have many limitations, which include the following:

- 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. These ratings can be updated when more recent land-use and land-cover data become available.
- The differences between STATSGO and SSURGO soils data are noteworthy; SSURGO data are much more detailed and informative. Vertical hydraulic conductance can be recalculated as more SSURGO data become available.

In North Carolina, susceptibility determinations for public ground-water supplies are performed on a circular source-water assessment area centered around the wellhead. This area is delineated by PWSS using a 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 recharge in the region. In reality, the source of water contributing to a well can be derived from an irregularly shaped area some distance from the wellhead. Factors that influence the shape and location of a well's source-water contributing area include heterogeneity of hydrogeologic units and topographic setting. A more accurate determination of the source-water assessment area of wells would improve source-water protection for large public ground-water supplies.

Finally, the strength of the overlay and index method is its statewide approach and its reliance on several factors thought to be important to ground-water and surface-water vulnerability from surface and near-surface contaminants. 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, U.S. Geological Survey, oral commun., February 5, 1999; Mike Sweat, U.S. Geological Survey, oral commun., August 3, 1999). A valuable contribution to North Carolina's source-water protection could be to investigate the statistical relation between contributing factors and the occurrence of particular waterborne contaminants in North Carolina.

## SUMMARY

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 developed by the USGS to rate unsaturated zone and watershed characteristics. Factors were selected that influence the inherent vulnerability of drinking water sources. Factors contributing to the inherent vulnerability of the unsaturated zone are vertical hydraulic conductance, land-surface slope, land cover, and land use. Factors contributing to the inherent vulnerability of the watershed are 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.

Each factor was weighted in terms of its influence on a public water supply's inherent vulnerability. Multiplying the rates and weights and summing for each factor produced 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 assessment areas were 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 on literature and consultations with experts in hydrology, geology, forestry, agriculture, and water management.

The overlay and index methods described in this report were 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 quick method for uniformly assessing one aspect of the inherent vulnerability of water supplies to contamination. Two facets of the susceptibility assessments currently used by North Carolina are suggested for further investigation: (1) accuracy of source-water assessment area delineations for public water-supply wells can be improved; and, (2) consensus among experts does not imply veracity; therefore statistical analysis of particular contaminants can be used to refine factor weights and ratings.

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**Table 1. 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 |

**Table 2. 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 | 10 | 3 |

| Land-use category | General description or example | Area in North Carolina, in percent | Rating |
|---|---|---|---|
| | represent more than 75 percent of the cover present. | | |
| 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 |

**Table 3. 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. 1) | 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 ($r_1$) | In percent | Rating ($r_2$) | | Rating ($r_3$) (table 1) | Rating ($r_4$) (table 2) | $R_i = \overset{4}{\underset{i=1}{?}} ( w_i \times r_i )$ |
| 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. 1)

$$\frac{\sum_{i=1}^{7} R_i}{n} = \frac{405}{7} = 57.8$$

**Table 4. 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 |

**Table 5. Example determination of a watershed characteristics rating for part of an unnamed watershed upstream from a water-supply intake**

| Cell number *i* (fig. 2) | 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 ($r_1$) | In percent | Rating ($r_2$) | | Rating ($r_3$) (table 4) | Rating ($r_4$) (table 2) | Unsaturated zone rating value | Rating ($r_5$) | $R_i = \sum_{i=1}^{5} (w_i \times r_i)$ |
| 1 | 6 | 5 | 52 | 10 | Forest | 1 | 3 | 46 | 4.6 | 49.6 |
| 2 | 6 | 5 | 47 | 9 | Forest | 1 | 3 | 0 | 0 | 43.0 |
| 3 | 6 | 5 | 48 | 9 | Forest | 1 | 3 | 50 | 5.0 | 48.0 |
| 4 | 6 | 5 | 45 | 9 | Hay/pasture | 3 | 5 | 0 | 0 | 51.0 |

Watershed characteristics rating for *n* (4) selected cells (fig. 2)

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

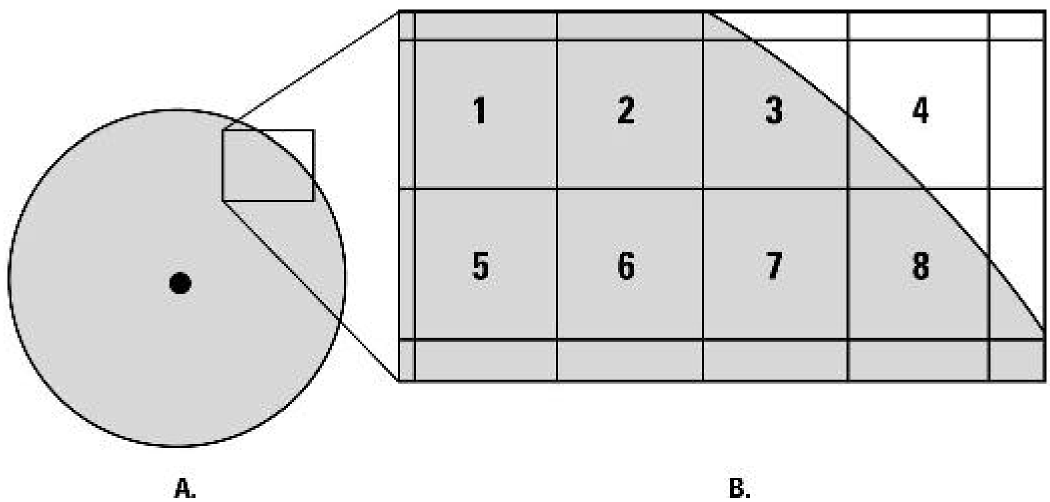


**Figure 1.** (A) An unnamed well encircled by source-water assessment area and inset (B) a portion of the source water assessment area overlain by 30-meter by 30-meter cells to illustrate the calculation of the unsaturated zone rating. Only cells with more than 50 percent of their area in the source-water assessment area are included in the calculation [In this example, cells 1, 2, 3, 5, 6, 7, 8].

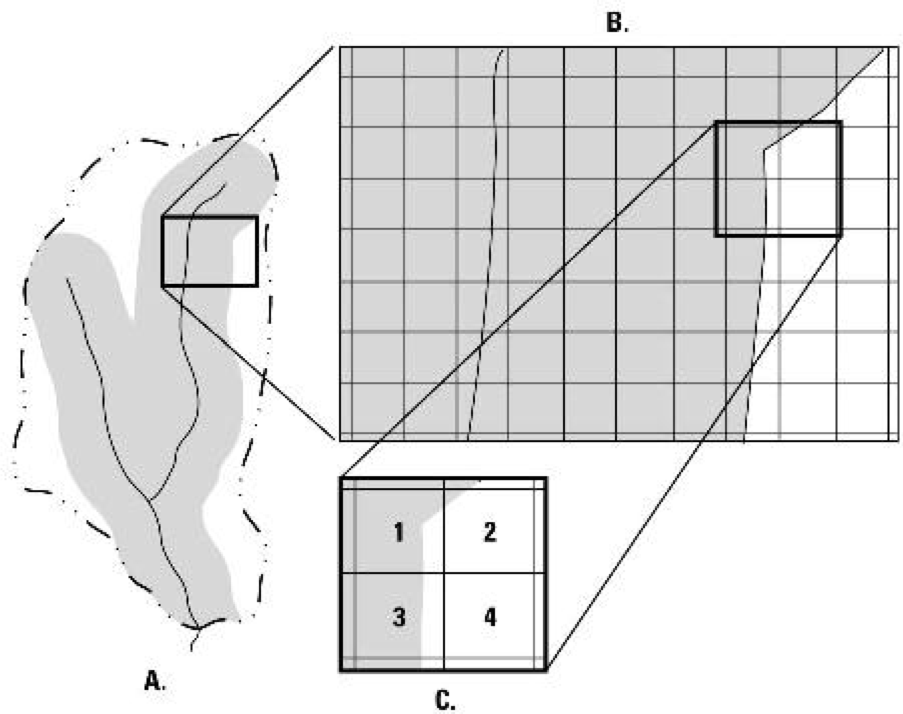


**Figure 2.** (A) An unnamed watershed upstream from a surface-water supply intake showing basin outline, stream network, and 1,000-foot buffered area around streams; inset (B) 30-meter by 30-meter cells overlaid on a portion of the watershed; and inset (C) a subset of four cells used to illustrate the calculation of watershed characteristics rating.