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EFFECT OF FORESTED WETLANDS ON NITRATE CONCENTRATIONS IN GROUND WATER AND SURFACE WATER ON THE DELMARVA PENINSULA

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Abstract: The Delmarva Peninsula is an extensively farmed region in which nitrate from commercial fertilizers and poultry has entered the ground water and streams. The peninsula contains forested wetlands in a variety of settings, and their size and location are a result of the surrounding hydrologic and soil conditions. Three regions, here referred to as hydrogeomorphic regions, were selected for study. Each region has characteristic geologic and geomorphic features, soils, drainage patterns, and distribution of farmland, forests, and forested wetlands. In all three regions, forested wetlands generally occupy poorly drained areas whereas farmlands generally occupy well-drained areas. The three hydrogeomorphic regions studied are the well-drained uplands, the poorly drained uplands, and the surficial-confined region. The well-drained uplands have the largest amount of farmland and the smallest amount of forested wetlands of the three regions; here the forested wetlands are generally restricted to narrow riparian zones. The poorly drained uplands contain forested wetlands in headwater depressions and riparian zones that are interspersed among well-drained farmlands. The surficial-confined region has the smallest amount of farmland and largest amount of forested wetlands of the three regions studied. Wetlands in this region occupy the same topographic settings as in the poorly drained uplands. Much of the farmland in the surficial-confined region was previously wetland. Nitrate concentrations in ground water and surface water on the peninsula range widely, and their distribution reflects (1) the interspersion of forests among farmland, (2) hydrogeologic conditions, (3) types of soils, and (4) the ground-water hydrology of forested wetlands. The well-drained uplands had higher median nitrate concentrations in ground water than the poorly drained uplands or the surficial-confined region. The highest nitrate concentrations were in oxic parts of the aquifer, which are beneath well-drained soils that are farmed, and the lowest were in anoxic parts of the aquifer, which are beneath poorly drained soils overlain by forested wetlands. The effect of forested wetlands on water quality depends on the hydrogeologic conditions, extent of farming, and type of soils. The three regions contain differing combinations of these factors and thus are useful for isolating the effects of forested wetlands on water quality.

Key Words: water quality, forested wetlands, hydrology.

INTRODUCTION

The Delmarva Peninsula (Figure 1) is on the northern Atlantic Coastal Plain and includes most of Delaware and the eastern shores of Maryland and Virginia. The peninsula covers about 16,000 km^2 (square kilometers) and is underlain by a series of sandy sediments that form a surficial aquifer that is discontinuous in some areas. The aquifer is 0- to 50-m (meters) thick over the entire peninsula but is 10- to 20-m thick in most areas. It is recharged primarily by rainfall. Nitrate from commercial fertilizers and poultry has entered the ground water and streams throughout most of the region.

In 1986, the National Water Quality Assessment Program of the U.S. Geological Survey (USGS) began a 6-year study to investigate regional- and local-scale water quality on the Delmarva Peninsula. The peninsula was divided into seven hydrogeomorphic regions (Figure 2) that represent distinct combinations of geologic and geomorphic features, drainage patterns, soil types, and land cover. The size, density, and distribution of forested wetlands differ among the hydrogeomorphic regions, and each hydrogeomorphic region contains characteristic patterns of ground-water flow and ground-water quality. Thus, the three regions provide a basis for comparison of the effect of forested wetlands on ground- and surface-water quality. This paper describes the three largest hydrogeomorphic regions, which together constitute about 68 percent of the peninsula, and compares the relation between ground-water nitrate concentrations and the distribution of forested wetlands.

FORESTED WETLANDS

The Delmarva Peninsula is nearly 40 percent forested, and most of the forests are in areas where the water table is at or just below land surface for most of the year. These areas, known as forested wetlands, occupy a variety of topographic settings on the peninsula, and their size and location are a result of hydrologic and soil conditions.

Characteristics and Distribution

Forested wetlands are of two types: (1) closed depressions that are frequently ponded and thus function as ground-water recharge or discharge areas, depending on the season (Phillips and Shedlock 1993), and (2) nontidal and tidal riparian zones, which are generally discharge areas. Throughout the peninsula, ground-water flow paths and chemical quality are related to the extent of farmland and forested wetlands and their location with respect to one another. Whereas most of the farmlands are in well-drained areas and are associated with oxic ground-water conditions, the forested wetlands occupy poorly drained areas and are associated with anoxic ground-water conditions.

Hydrogeomorphic Regions

The peninsula was delineated into seven areas, herein referred to as hydrogeomorphic regions, and the three largest regions were selected for study. Each region has characteristic geologic and geomorphic features, soils, drainage patterns, and distribution of farmland, forests, and forested wetlands. The delineation was based on a qualitative analysis of such factors as topography, geology, soils, and land cover. The boundaries were based on a comparison of topographic maps (USGS 7.5-minute, 1:24,000 scale), geologic maps (Owens and Denny 1978, 1979a, 1979b, 1984, 1986), maps of poorly drained soils (Simmons and Carpenter 1978, Carpenter 1983), and land-use maps (USGS 1979a, 1979b, 1979c, 1980a, 1980b, 1980c).

The extent of forested wetlands in each hydrogeomorphic region was estimated from (1) the ratio of poorly drained soils area to total area, (2) ratio of forest area to farmland, and (3) the degree of stream incision into the aquifer. (Poorly drained soils are defined by the Maryland Department of State Planning (1973) as soils that are wet for prolonged periods. They generally include soils less than 1 m above the water table throughout much of the spring and thus generally coincide with wetlands.) The extent of poorly drained soils in each hydrogeomorphic region was estimated from data on soil characteristics from a set of 78 drainage basins than cover about a third of the peninsula (D.H. Carpenter, U.S. Geological Survey, writt. comm., 1991). The percentage of each region that is occupied by poorly drained soils was calculated from an area-weighted average of the ratio of poorly drained soils to basin area for the basins within each of the hydrogeomorphic regions.

The Delmarva Peninsula consists of two regional geomorphic settings—the central uplands and the coastal lowlands (Figure 2). The central uplands, a 15- to 80-km-(kilometer) wide zone along the central part of the peninsula, encompasses four of the seven hydrogeomorphic regions—the well-drained uplands, the poorly drained uplands, the surficial-confined region, and the inner coastal plain (Figures 2 and 3). The central uplands range from 9 to 24 m above sea level, and the surficial aquifer consists of moderately permeable sand and gravel of mostly fluvial origin and ranges in thickness from 8 to more than 30 m (Owens and Denny 1979a; Figure 3).

The coastal lowlands flanks the central uplands and encompasses the remaining three regions—the fine-grained lowlands, the poorly drained lowlands, and the

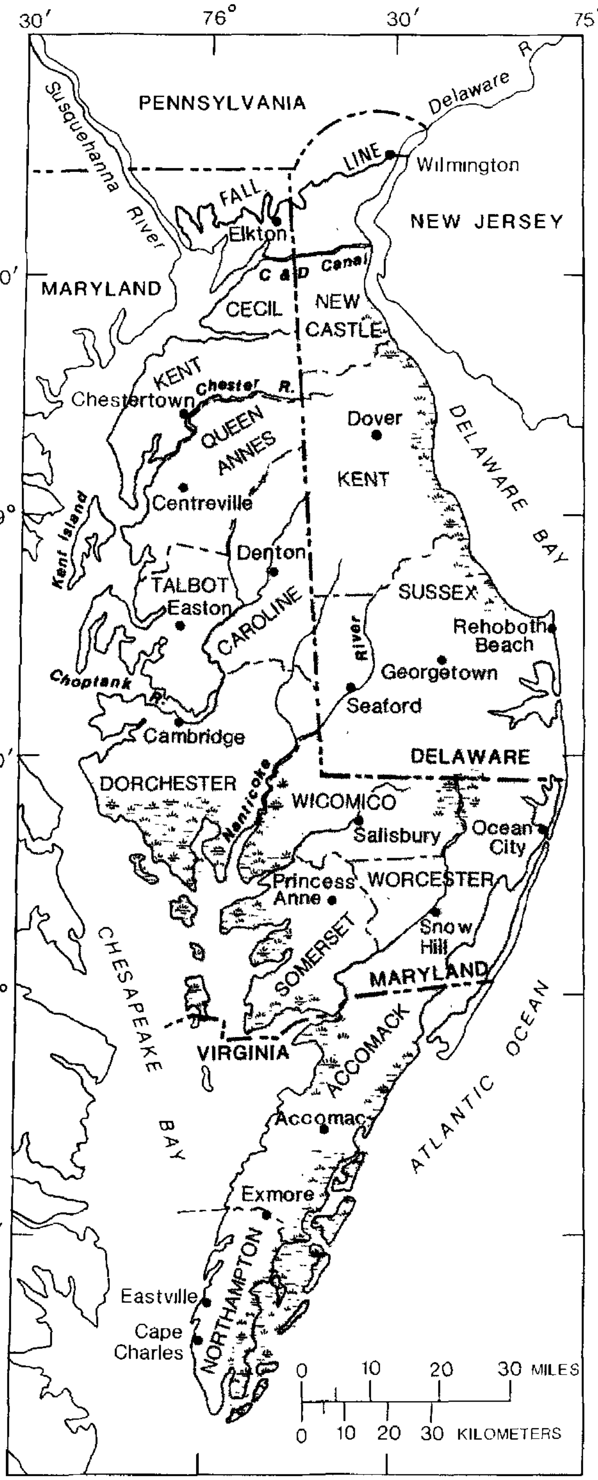

Figure 1. Location of Delmarva Peninsula. Study area includes entire area shaded in figure.

coastal wetland and beach region (Figure 3). The coastal lowlands range from 0 to 8 m above sea level, and the surficial aquifer consists of poorly permeable sediments of predominantly estuarine and marginal marine origin and generally is less than 5-m thick (Owens

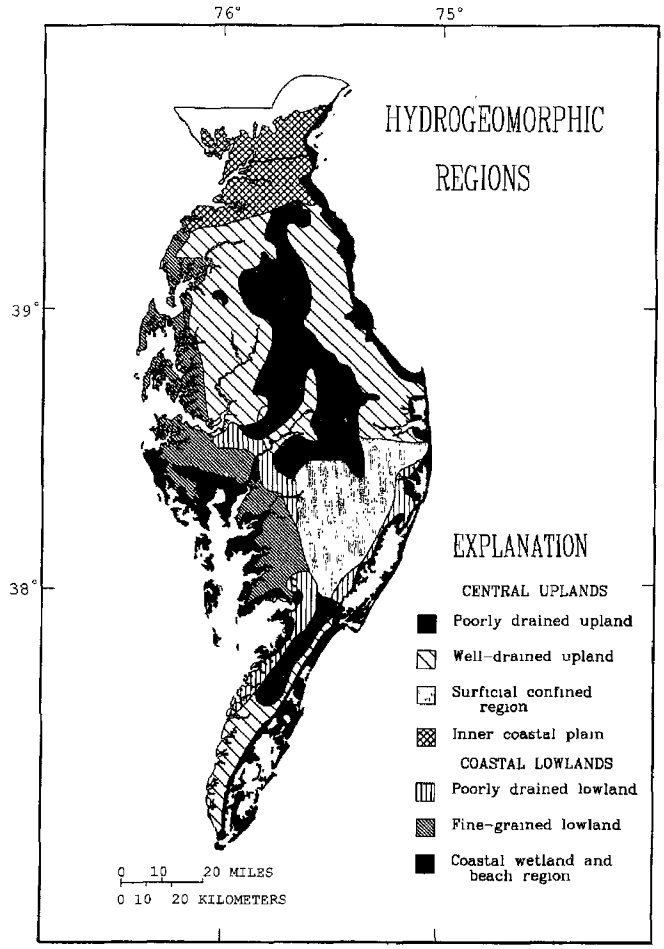

Figure 2. Hydrogeomorphic regions of the Delmarva Peninsula.

and Denny 1979a). Hydrogeomorphic regions in the coastal lowlands are not discussed further because they are smaller than regions in the central uplands and have less farmland.

The three hydrogeomorphic regions that were selected for study are the well-drained uplands, the poorly drained uplands, and the surficial-confined region. Characteristics of each are described in the following paragraphs.

Well-Drained Uplands. The well-drained uplands region, adjacent to the western and eastern flanks of the poorly drained uplands (Figure 2, 3), occupies the part of the central upland that is dominated by tidal parts of major rivers. Nontidal streams in this region are mostly short, steep tributaries that drain the narrow interfluves between tidal rivers. Local relief exceeds 10 m in places. Depth to the water table is generally more than 3 m and is as much as 10 m locally.

As a result of the high relief and good drainage, this region has the smallest amount of forested wetlands and the smallest ratio of poorly drained soils area to

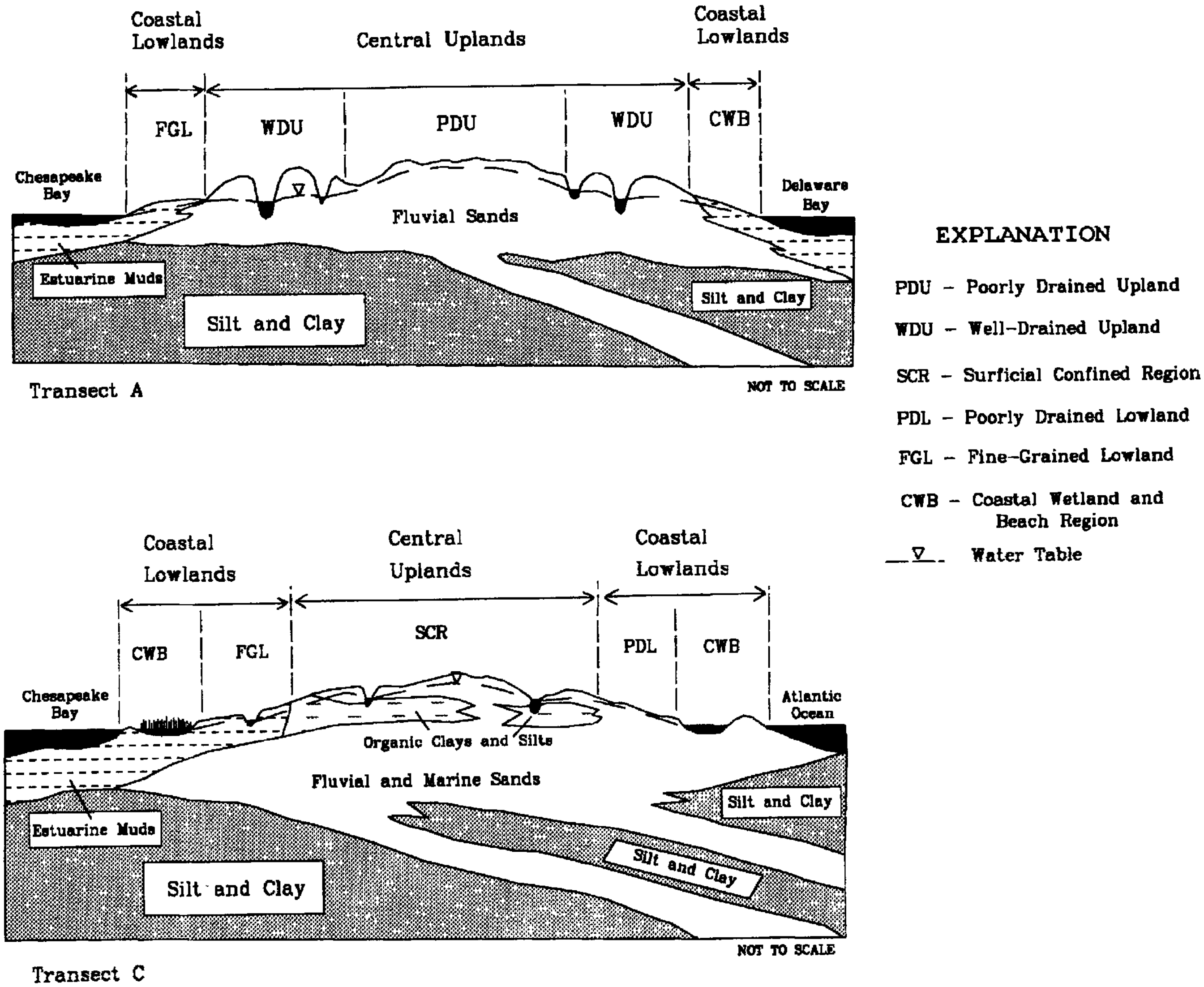

Figure 3. General topographic and hydrogeologic features of the Delmarva Peninsula. The upper cross section corresponds to transect A shown in Figure 4b, and the lower transect corresponds to transect C shown in Figure 4b. (Modified from Koterba *et al.* 1991, Figure 3.)

total area (0.20) of the three hydrogeomorphic regions studied (Table 1). Because well-drained soils are more suitable than poorly drained soils for farming, it also has the smallest ratio of forest to farmland (0.38) of the three regions (Table 1). Forests and poorly drained soils in this region are generally restricted to riparian zones; thus, virtually all forested wetlands are limited to these areas and typically form long, linear patches flanked by farmed areas.

Poorly Drained Uplands. The poorly drained uplands region lies along the nontidal headwaters of streams draining westward to the Chesapeake Bay and eastward to Delaware Bay and the Atlantic Ocean (Figures 2, 3). The region is dominated by ridge and swale topography; local relief is generally 4 m or less. Because the streams are mainly at the headwaters of rivers, they are mostly small and not deeply incised into the surficial aquifer.

This region contains a larger amount of forested wetlands than the well-drained uplands because it has a larger ratio of poorly drained soils to total area (0.56; see Table 1). Because the poorly drained soils generally consist of sandy loams and are permeable (U.S. Department of Agriculture 1966, 1970, 1974), the soil-drainage characteristics are more the result of low topographic gradients than low permeability. Demicco (1982) observed that poorly drained soils in the central part of the peninsula are commonly forested, whereas well-drained soils generally occupy ridges that contain farmland and are interspersed among the forested areas. Hence, the ratio of forest area to farmland (0.75)

Table 1. Landscape characteristics and median nitrate concentrations for the three major hydrogeomorphic regions.

Hydrogeomorphic Region	Ratio of Poorly Drained Soils to Total Area	Ratio of Woodland to Agricultural Land Cover	Median Ground-water Nitrate Concentration (milligrams per liter as nitrogen)*
Well-drained uplands	0.20	0.38	8.9
Poorly drained uplands	0.56	0.75	4.4
Surficial confined region	0.83	1.23	0.4**

* Data from Shedlock et al. 1993.
** Although median nitrate concentrations reported by Shedlock et al. for the surficial confined region include samples collected from the poorly drained lowlands and fine grained lowlands hydrogeomorphic regions, most of the samples were collected from the surficial confined region.

is higher than that for well-drained uplands (0.38) and reflects the wider distribution of poorly drained soils (Table 1).

The presence of forested wetlands in a wider variety of topographic settings in the poorly drained uplands than in the well-drained uplands is a result of the lower relief. Forested wetlands in the poorly drained uplands are found in riparian zones and topographic depressions in stream headwaters; these forested depressions are commonly adjacent to well-drained ridges. The dispersion of forested wetlands among farmland is characteristic of the poorly drained uplands region.

Surficial-Confined Region. The surficial-confined region lies in the south-central part of the peninsula and, in most respects, is similar to the poorly drained uplands region (Figures 2, 3). Topography is relatively flat (relief generally less than 3 m); therefore, the streams are not well incised into the aquifer, and the depth to water is generally less than 2 m. As a result, poorly drained soils dominate the region.

The surficial-confined region has the largest amount of forested wetlands of the three regions studied because it has extensive poorly drained soils, a large amount of forest, and low relief. It also has the highest ratio of poorly drained soils area to total area (0.83) of the three regions (Table 1) and the highest ratio of forest area to farmland (1.23) (Shedlock *et al.* 1993). Much of the farmland in this region occupies poorly drained soils and has been ditched to improve drainage.

Forested wetlands in the surficial-confined region occupy a variety of settings as a result of the topography. Drainage divides commonly are dominated by large tracts of flat, forested areas containing wetlands interspersed among farm tracts. Soils in these flat areas tend to be mucky. The riparian zones also contain forested wetlands.

The surficial aquifer in this region is stratigraphically more complex than elsewhere. Here it contains three distinct geologic units (Owens and Denny 1978, 1979b, 1984, 1986). The upper unit contains a 3- to 5-m-thick sequence of sand and peat layers, and in areas where the sand forms dunes, the unit exceeds 10 m in thickness. The upper unit contains a water table but is too thin to serve as a water-supply source. Beneath the upper unit is a 3- to 10-m-thick layer of silt, clay, and sand that confines the lower unit. The lower unit is 30-m-thick or greater. In some locations the middle unit is sandy or absent; here the lower and upper units function as a single aquifer.

NITRATE CONCENTRATIONS AND WATER CHEMISTRY

About 50 percent of the Delmarva Peninsula is farmland. The high permeability of the sandy, well-drained soils in the farmed areas can lead to widespread leaching of agricultural chemicals to the water table, especially nitrate (Denver 1989). This section describes the regional and local distribution of nitrate in ground water throughout the peninsula in relation to ground-water flow patterns and redox conditions. The discussion of regional nitrate distribution is based on (1) an analysis of published data (Hamilton *et al.* 1991) and (2) results from the USGS water-sampling network (Shedlock *et al.* 1993) (Figure 4a). The discussion of local patterns of nitrate concentration is based on results from three watersheds—Locust Grove, Vandyke, and Willards (Figure 4b); each represents the three major hydrogeomorphic region that surrounds it.

Regional and Local Well Networks

The regional well network (Figure 4a, 4b) consists of 193 wells sampled before 1987 by the USGS and 103 wells sampled as part of the USGS Delmarva project during 1987–90. The network sampled by the USGS Delmarva project includes wells distributed in an areal network and along five regional transects (Figure 4a and 4b). The regional well network taps several depths within the surficial aquifer, and the locations represent all types of land cover. The network design and strategy are discussed by Shedlock *et al.* (1993).

Water samples were collected from wells and adjacent surface-water bodies in all three watersheds. The wells were installed at differing depths along local

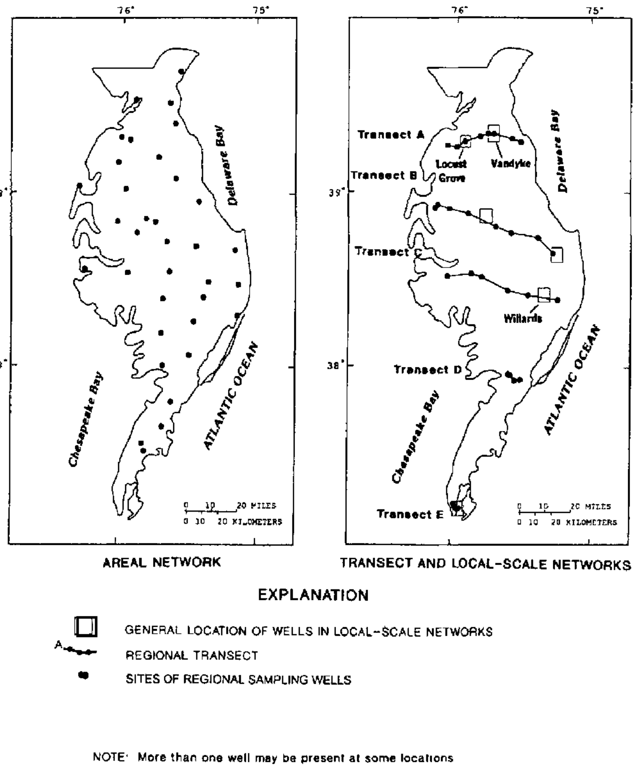

Figure 4. a) Regional and b) local networks (previously installed wells not shown). (Modified from Shedlock *et al.* 1993, Figures 23–24.)

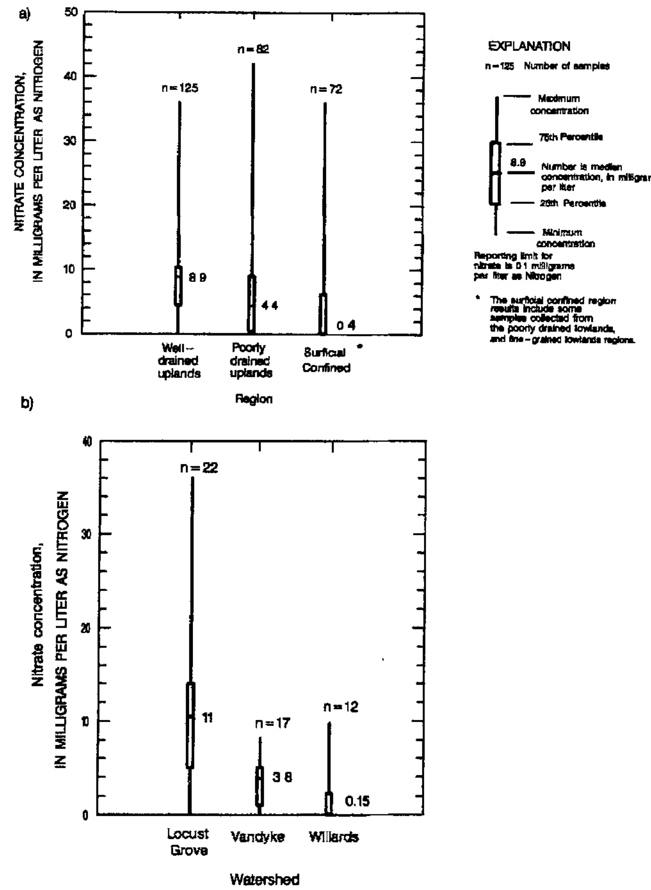

Figure 5. a) Nitrate concentrations in the three major hydrogeomorphic regions and b) Nitrate concentrations in the three local-scale networks (location shown in Figure 4b).

ground-water flowpaths to relate ground-water quality to ground-water flow and landscape characteristics. The direction of flow in each network was determined from water-level data. The percentage of total area occupied by poorly drained soils in each watershed was calculated from county-scale maps given in Simmons and Carpenter (1978) and Carpenter (1983). The ratio of forest area to farmland is based on 1:24,000-scale USGS topographic maps.

Regional Distribution of Nitrate

Water quality in the surficial aquifer reflects the overlying land use and soil characteristics. Within each hydrogeomorphic region, the degree of forest dispersion among agricultural areas determines the overall effect of agricultural chemicals on ground-water quality.

Water that recharges the aquifer through poorly drained soils, which are generally in forested areas, typically contains only ions that are derived from atmospheric precipitation and dissolution, and is mainly the calcium or sodium bicarbonate type. The median specific conductance is low—less than 60 μS/cm (micro-Siemens per centimeter) (Hamilton *et al.* 1993). Dissolved oxygen is generally absent; thus, the water is anoxic. Under anoxic conditions, reduced nitrogen species are stable, and nitrate can potentially be lost through denitrification (Korom 1992).

Water recharging the aquifer through well-drained soils, most of which are in farmed areas, contains variable concentrations of chemicals leached from fertilizer, manure, and lime, in addition to those from atmospheric precipitation and mineral dissolution. The water beneath farmed areas generally contains higher concentrations of calcium, magnesium, and nitrate than water from forested areas. The median specific conductance of ground water in farmed areas is 186 μS/cm (three times the specific conductance in poorly drained areas), and the presence of dissolved oxygen results in oxic (aerobic) conditions in which nitrate is stable and denitrification cannot occur (Korom 1992).

Differences in nitrate conditions among the three hydrogeomorphic regions studied are depicted in box plots in Figure 5a and summarized in Table 1. The median nitrate concentrations differ statistically among the regions. The well-drained uplands region has the highest median nitrate concentration (8.9 mg/l as N (milligrams per liter as nitrogen)), which can be attributed to the large amount of farmland and small amount of poorly drained soils in the region. The poorly drained uplands have a median nitrate concentration of 4.4 mg/L as N (less than half the median for the well-drained uplands). This reflects the smaller amount of farmland and the larger amount of poorly drained soils. The surficial-confined region had the lowest median nitrate concentration (0.4 mg/L as N); again the result of the small amount of farmland and large amount of poorly drained soils.

Nitrate concentrations vary widely within each hydrogeomorphic region (Figure 5a) because each region contains well-drained farmed areas (with oxic ground-water conditions) as well as forested wetlands (with anoxic ground-water conditions). Hence, the range of nitrate concentration within each region is related to the ratio of forest to farmland and the ratio of poorly drained soils area to total area (Table 1, Figure 5a).

Local Distribution of Nitrate

The following discussion is based on results from the three watersheds mentioned previously (Figure 4b). The soils, land cover, and degree of forested wetland interspersion among farmed areas in each watershed reflect the general characteristics of the respective hydrogeomorphic region. Because the watershed-scale networks were designed to focus on farmed areas (Shedlock *et al.* 1993), the ratio of forest area to farmland and the ratio of well-drained soil area to total area of each watershed are higher than in the surrounding region (Table 2).

Well-Drained Uplands (Locust Grove Watershed). This 5-km² watershed is dominated by an agricultural upland; forested wetlands are restricted to riparian zones. This watershed has the lowest ratio of forest to farmland (0.05) and the lowest ratio of poorly drained soils area to total area (0.05) of the three watersheds. The surficial aquifer consists primarily of sand and is 7- to 20-m thick. Ground-water flowpaths are longer than 300 m, originate in the agricultural uplands, and discharge to the stream that drains the watershed.

Nitrate concentrations in ground-water samples from Locust Grove range from less than 0.1 to more than 30 mg/L as N (Figure 5b). The median concentration of nitrate, 11 mg/L as N, is the highest of the three watersheds (Table 2). The highest concentrations were in samples from the farmed uplands, and the lowest were in samples from downgradient areas. All samples from Locust Grove were oxic, and the entire flow system has been affected by agriculture, as evidenced by the elevated nitrate concentrations.

The forested wetland in the riparian zone next to the stream that drains this watershed has little mitigating effect on nitrate concentrations of ground-water discharging to the stream because most of the ground

Table 2. Landscape characteristics and median nitrate concentrations of the three watersheds (locations are shown in Figure 2b).

Watershed	Hydrogeomorphic Region	Ratio of Poorly Drained Soils Area to Total Area	Ratio of Forest to Farmland	Median Ground-water Nitrate Concentration (in milligrams per liter as nitrogen)
Locust Grove	Well-drained uplands	0.05	0.05	11
Vandyke	Poorly drained uplands	0.25	0.15	3.8
Willards	Surficial confined region	0.95	0.84	0.15

water flows beneath the anoxic sediments of the riparian zone and discharges directly through the streambed (Bohlke *et al.* 1992). As a result, base-flow nitrate concentrations in this stream commonly exceed 9 mg/L as N.

Poorly Drained Uplands (Vandyke Watershed). This 0.2-km² watershed consists of a wooded depression with poorly drained soils and an ephemeral pond surrounded by agricultural uplands with generally well-drained soils. The ratio of forested area to farmland is 0.15, and the ratio of poorly drained soil area to total area is 0.25 (Table 2). The surficial aquifer is thin (10- to 13-m thick), and ground-water flow paths are short—less than 300 m. When the poorly drained soils of the depression are saturated, or when the depression contains ponded water, a water-table mound forms beneath the depression, and the depression becomes a recharge area for the surficial aquifer (Denver, in press).

Nitrate concentrations in ground water range from less than 0.1 to 8.2 mg/L as N; the median is 3.8 mg/L as N (Figure 5b; Shedlock *et al.* 1993). Water chemistry in the aquifer reflects the source of recharge: water infiltrating through the well-drained soil in the uplands is oxic, and water entering through the poorly drained soils in the depression is anoxic. Oxic water in the uplands contains higher nitrate concentrations than anoxic water near the depression (more than .4 mg/L as N and less than 0.1 mg/L as N, respectively) and becomes mixed with and diluted by the anoxic water as it nears the depression. Nitrate concentrations in the ephemeral pond also are generally less than 0.1 mg/L (Denver in press), as in the anoxic ground water surrounding the depression.

Surficial-Confined Region (Willards Watershed). This 15-km^2 watershed consists of a flat, sandy plain with low dune ridges (Shedlock *et al.* 1993). The plain is dominated by poorly drained soils, and the dunes are well drained; both contain forest and farmland. Forested wetlands are found on the flat plains as well as in riparian zones. Much of the farmland in this watershed is in poorly drained areas that have been ditched to improve drainage; therefore, most of the watershed was probably forested wetland before it was converted to farmland. This watershed has the highest ratio of forest area to farmland of the three watersheds (0.84) and the highest ratio of poorly drained soils to total area (0.95). The surficial aquifer contains a 3- to 8-m-thick sandy upper part that is generally separated from the 30-m thick sandy lower part by a confining layer of mostly clay and silt. In some locations, the clay and silt layer is absent, and the upper and lower parts act as a single unit.

Ground-water flow paths in the upper part of the aquifer are shorter than those in the lower part. Those in the upper part are generally less than 500-m long and originate in the flat interfluves or dunes between ditches and small streams and discharge to those ditches or streams. Those in the lower part are generally more than 500-m long; they originate as much as 5 km west of the watershed and discharge to large streams and rivers.

Nitrate concentrations in ground-water samples range from less than 0.1 to 9.8 mg/L as N (Figure 5b; Shedlock *et al.* 1993) and have the lowest median (0.15 mg/L as N) of the three watersheds. Water chemistry in both the upper and lower units reflects the redox conditions; highest nitrate concentration are in the upper part, in which the water is generally oxic beneath well-drained farmland and anoxic beneath forested wetlands and poorly drained farmland. The lowest nitrate concentrations, generally less than 0.1 mg/L as N, are in the lower part of the aquifer, where anoxic conditions generally prevail.

Nitrate concentrations in surface water under base-flow conditions reflect the differences between the upper and lower parts of the surficial aquifer. Nitrate concentrations in samples collected during base-flow conditions from a small ditch that receives discharge primarily from the upper part range from 0.8 to more than 8 mg/L as N, whereas base-flow concentrations in samples from a large stream and river that received discharge from both parts of the aquifer are much lower—from 0.3 to 4 mg/L as N—as a result of dilution by discharge from the lower unit.

DISCUSSION AND CONCLUSIONS

Forested wetlands on the Delmarva Peninsula are found in a variety of topographic and hydrogeologic settings. Within each region studied, nitrate concentrations in ground water and surface water are inversely related to the extent of forested wetlands. To relate the regional and local differences in water quality solely to forested wetlands would be incorrect, however, because the effects of other variables, such as farming, hydrogeology, and soils, can mask the effects of forested wetlands.

The main effect of forested wetlands on ground-water nitrate concentrations is dilution and denitrification. Because fertilizers are applied only in farmed areas, water that recharges the surficial aquifer beneath forested wetlands does not contain elevated concentrations of nitrate or other constituents associated with farming. In addition, because wetland soils are generally anoxic, nitrate passing through them becomes denitrified. In contrast, water recharging the surficial aquifer through wetlands that are interspersed among farmland mixes with water from the farmed areas as it moves toward discharge areas. Hence, ground water and surface water in areas with a large amount of forested wetlands (such as poorly drained uplands) would be expected to have a lower median nitrate concentration than in areas without extensive forested wetlands, such as the well-drained uplands.

The ability of a forested wetland to denitrify ground water depends on the surrounding topographic and hydrogeologic conditions. Where forested wetlands are in a ground-water discharge area, water passing through the anoxic zone will undergo denitrification. Where forested wetlands are restricted to a narrow riparian zone underlain by an oxic aquifer (such as Locust Grove watershed), however, ground water with elevated nitrate concentrations could bypass the denitrifying wetland sediments and discharge directly into the stream.

Results of this study indicate that, within each hydrogeomorphic region, forested wetlands mitigate contamination to differing degrees, and the effect depends largely on the amount and distribution of poorly drained soils within the region. Even though other hydrologic factors could obscure this effect, it could be an important consideration in assessing best-management practices for controlling nitrate concentrations in ground water and surface water in farmed areas. The effectiveness of these practices could differ from one region to the next, however, as a result of local differences in soils and drainage, land cover, topography, and hydrogeology.

LITERATURE CITED

Bohlke, J. K., J. M. Denver, P. J. Phillips, C. J. Gwinn, L. N. Plummer, E. Busenberg, and S. A. Dunkle. 1992. Combined use of nitrogen isotopes and ground-water dating to document nitrate fluxes and transformations in small agricultural watersheds, Delmarva Peninsula, Maryland. EOS Transactions of American Geophysical Union, Spring Meeting Supplement 73:140. Washington, DC, USA.

Carpenter, D. H. 1983. Characteristics of streamflow in Maryland: Maryland Geological Survey Report of Investigations 35. Baltimore, MD, USA.

Demicco, P. M. 1982. Hydrogeology of the southern half of the Marydel Quadrangle, Delaware. Masters Thesis. University of Delaware, Newark, DE, USA.

Denver, J. M. 1989. Effects of agricultural practices and septic-system effluent on the quality of water in the unconfined aquifer in parts of eastern Sussex county, Delaware. Delaware Geological Survey Report of Investigations 45. Newark, DE, USA.

Denver, J. M. In press. Herbicides in shallow ground water at two agricultural sites in Delaware. Delaware Geologic Survey Report of Investigations. Newark, DE, USA.

Hamilton, P. A., J. M. Denver, J. M., P. J. Phillips, and R. J. Shedlock. 1993. Water-quality assessment of the Delmarva Peninsula, Delaware, Maryland, and Virginia—Effects of agricultural activities on, and distribution of, nitrate and other inorganic constituents in the surficial aquifer. U. S. Geological Survey Open File Report 93-40. Towson, MD, USA.

Hamilton, P. A., R. J. Shedlock, and P. J. Phillips. 1991. Groundwater quality assessment of the Delmarva Peninsula, Delaware, Maryland and Virginia; Analysis of available water-quality data through 1987. U. S. Geological Survey Water-Supply Paper 2355-B. Reston, VA, USA.

Korom, S. F. 1992. Natural denitrification in the saturated zone: A review. Water Resources Research 28:1657–1668.

Koterba, M. T., R. J. Shedlock, L. J. Bachman, and P. J. Phillips. 1991. Regional and targeted ground-water quality networks in the Delmarva Peninsula. p. 110–138. *In* R. G. Nash and A. R. Leslie (ed.) Groundwater Residue Sampling Design. American Chemical Society, Washington, DC, USA.

Maryland Department of State Planning. 1973. Natural soil groups technical report. No. 199. Maryland Department of State Planning, Annapolis, MD, USA.

Owens, J. P. and C. S. Denny. 1978. Geologic map of Worcester County. Scale 1:62,500. Maryland Geologic Survey, Baltimore, MD, USA.

Owens, J. P. and C. S. Denny. 1979a. Upper Cenozoic deposits of the central Delmarva Peninsula, Maryland and Delaware. U. S. Geological Survey Professional Paper 1067-A. Reston, VA, USA.

Owens, J. P. and C. S. Denny. 1979b. Geologic map of Wicomico County. Scale 1:62,500. Maryland Geological Survey, Baltimore, MD, USA.

Owens, J. P. and C. S. Denny. 1984. Geologic map of Somerset County. Scale 1:62,500. Maryland Geological Survey, Baltimore, MD, USA.

Owens, J. P. and C. S. Denny. 1986. Geologic map of Dorchester County. Scale 1:62,500. Maryland Geological Survey, Baltimore, MD, USA.

Phillips, P. J. and R. J. Shedlock. 1993. Hydrology and chemistry of groundwater and seasonal ponds in the Atlantic Coastal Plain in Delaware, USA. Journal of Hydrology 141:157–178.

Shedlock, R. J., P. A. Hamilton, J. M. Denver, and P. J. Phillips. 1993. Multiscale approach to regional ground-water quality assessment of the Delmarva Peninsula. *In* W. M. Alley (ed.) Regional Ground-Water Quality. Van Nostrand Reinhold, New York, NY, USA. (in press).

Simmons, R. H. and D. H. Carpenter. 1978. Technique for estimating magnitude and frequency of floods in Delaware. U.S. Geological Survey Water Resources Investigations 78–93. Dover, DE, USA.

U. S. Department of Agriculture. 1966. Soil Survey of Queen Anne's County, Maryland. U. S. Department of Agriculture, Soil Conservation Service, Washington, DC, USA.

U. S. Department of Agriculture. 1970. Soil Survey of Wicomico County, Maryland. U. S. Department of Agriculture, Soil Conservation Service, Washington, DC, USA.

U. S. Department of Agriculture. 1974. Soil Survey of Sussex County, Delaware: U. S. Department of Agriculture, Soil Conservation Service, Washington, DC, USA.

U. S. Department of Agriculture. 1982. Soil Survey of Kent County, Maryland. U. S. Department of Agriculture, Soil Conservation Service, Washington, DC, USA.

U. S. Geological Survey. 1979a. Land use and land cover, 1972–1973, Eastville, Virginia; North Carolina; Maryland. U.S. Geological Survey Land-Use Map Series, Map L-58. Scale 1:250,000. Reston, VA, USA.

U. S. Geological Survey. 1979b. Land use and land cover, 1972, Wilmington, Delaware; New Jersey; Pennsylvania; Maryland. U.S. Geological Survey Land-Use Map Series Map L-38. Scale 1:250,000. Reston, VA, USA.

U. S. Geological Survey. 1979c. Land use and land cover, 1973, Salisbury, Maryland; Delaware; New Jersey; Virginia: U.S. Geological Survey Land-Use Map Series Map L-65. Scale 1:250,000. Reston, VA, USA.

U. S. Geological Survey. 1980a. Land use and land cover, 1972, Washington, D.C.; Maryland; Virginia. U.S. Geological Survey Land-Use Map Series Map L-201. Scale 1:250,000. Reston, VA, USA.

U. S. Geological Survey. 1980b. Land use and land cover, 1973, Richmond, Virginia; Maryland. U.S. Geological Survey Land-Use Map Series Map L-140. Scale 1:250,000. Reston, VA, USA.

U. S. Geological Survey. 1980c. Land use and land cover, 1974–76, Baltimore, Maryland; Pennsylvania; Virginia; West Virginia. U.S. Geological Survey Land-Use Map Series Map L-113. Scale 1:250,000. Reston, VA, USA.

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