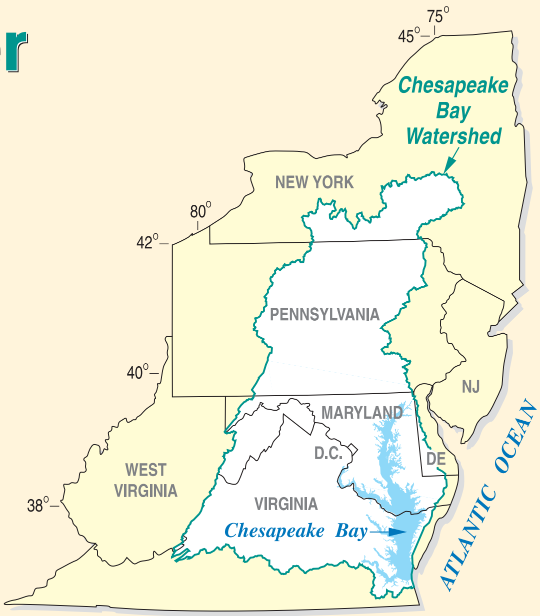
The Influence of Ground Water on Nitrogen Delivery to the Chesapeake Bay

by Scott W. Phillips and Bruce D. Lindsey



Summary of Major Findings

- *Resource managers need to understand the "lag time" between implementation of management practices and improvement in water quality in the Chesapeake Bay to help develop future nutrient- and sediment-reduction strategies. One factor affecting the lag time is the influence of ground water on the transport of nitrogen to streams in the Bay watershed.*

- *Ground water supplies a significant amount (about half) of water and nitrogen to streams in the watershed and is therefore an important pathway for nitrogen to reach the Chesapeake Bay.*

- *The age of ground water in shallow aquifers in the Chesapeake Bay watershed ranges from modern (less than 1 year) to more than 50 years, with a median age of 10 years.*

- *In addition to ground water, stream water will be influenced by surface runoff and soil water. Runoff and soil water both have very young ages (hours to months) and supply, on average, about half of the water to a stream.*

- *Proposed water-quality criteria in the Bay probably will not be met by 2010 due to the time needed to implement management practices and the effects of ground water and other watershed properties on nutrient transport.*

Efforts to Improve Water Quality in the Chesapeake Bay

The Chesapeake Bay ecosystem has been impaired by an overabundance of nutrients for several decades. Excess nutrients stimulate algal blooms, which consume dissolved oxygen as they decompose and cause large areas of low dissolved-oxygen concentration in the Bay. The low dissolved-oxygen concentrations have resulted in fish kills and have affected many bottom-dwelling organisms in the Bay. The algal blooms, along with sediment eroding from the land, also block sunlight needed by underwater grasses. Without sunlight, the Bay grasses die, removing important habitat for fish and shellfish, and food for waterfowl.

In the mid-1980s, the Chesapeake Bay Program (CBP), a partnership between jurisdictions (the States in the watershed and Washington, D.C.), the Chesapeake Bay Commission, and the Federal Government, began efforts to reduce nutrients in the Bay. However, improvement in water-quality conditions in the Bay and its rivers (fig. 1) has been slow. Because of the continued nutrient and sediment problems, the Bay was listed as an “impaired water body” under regulatory statutes related to the Clean Water Act. The CBP has developed water-quality criteria (U.S. Environmental Protection Agency, 2003), and is implementing actions to reduce nutrients and sediment entering the Bay in an attempt to meet these criteria by 2010. It is unknown how long it will take for water-quality conditions to improve in the Bay and its watershed after all the nutrient and sediment reduction actions are implemented. Resource managers need to understand the “lag time” between implementation of management practices and improvement in water quality in the Bay to help develop future nutrient- and sediment-reduction strategies. One factor affecting the lag time is the influence of ground water on the transport of nitrogen to streams in the Bay watershed.

The potential for slow improvements in stream nitrate levels due to the influence of ground water has been noted in previous studies (Shedlock, 1993; Böhlke and Denver, 1995; Phillips and Bachman, 1996). To better understand the influence of ground water on water quality in streams, the U.S. Geological Survey (USGS) conducted a multi-year study which addressed the discharge, nitrogen transport, and age of ground water into streams in the Chesapeake Bay watershed. The purpose of this fact sheet is to summarize the results of the multi-year study and its associated reports (Lindsey and others, 2003, Phillips and others, 1999; Focazio and others, 1998; Bachman and others, 1998) and discuss implications for achieving improved water-quality conditions in the Bay by 2010.

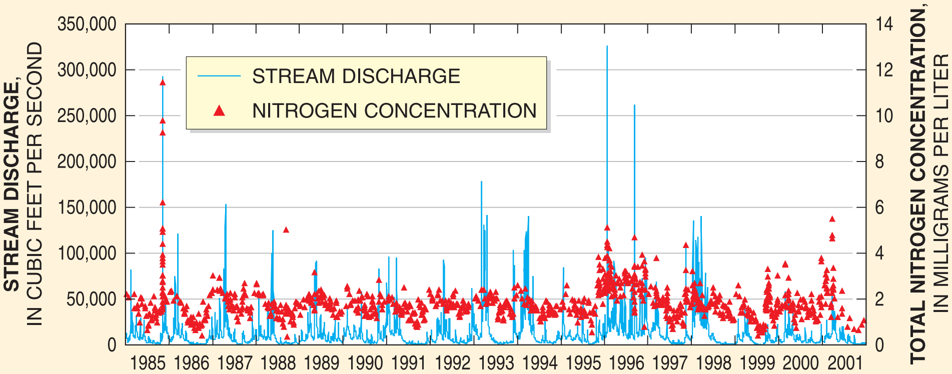


Figure 1. Stream discharge and total nitrogen concentrations in the Potomac River at Chain Bridge at Washington, D.C., 1985-2001. *(Concentrations of nitrogen have not shown a significant change over the past 15 years in the Potomac River, while some rivers including the Susquehanna, James, and Patuxent have had a slight decrease in nitrogen concentrations. Some of the factors affecting nitrogen concentrations include the amount of nutrient-source reduction, and watershed characteristics such as the influence of ground water.)*

Ground Water and Nitrogen Discharge to Streams in the Chesapeake Bay Watershed

Ground water supplies a significant amount of water and nitrogen to streams in the watershed and is therefore an important pathway for nitrogen to reach the Chesapeake Bay. Rainfall and snowmelt percolate through the soil zone and enter the ground-water system. Much of this recharge moves slowly through an aquifer and is discharged to streams. On average, just over 50 percent of the total volume of water in streams throughout the Bay watershed is from ground water, with a range in different streams of 16 to 92 percent (Bachman and others, 1998). Different lithologic and physiographic settings, known as "hydrogeomorphic regions" (HGMRs), have some influence on the amount of ground-water discharge to streams (fig. 2). The Valley and Ridge Carbonate HGMR had the highest median (64 percent) and the Mesozoic Lowland Siliciclastic HGMR had the lowest median (36 percent) contribution of ground-water discharge to streams. The remaining HGMRs had median values of greater than 50 percent of total streamflow contributed by ground water.

Ground water transports a large amount of nitrogen to streams in the Chesapeake Bay watershed. Nitrogen reaches the land surface in rainfall or through fertilizer application and other practices associated with agricultural and suburban areas. Once on the land surface, some of the nitrogen infiltrates into the underlying soil zone and ground water. In ground water, nitrogen generally is converted to nitrate and moves through the aquifer. Much of the nitrate is discharged to streams and contributes to the total nitrogen load in a stream. An average of 48 percent of the nitrogen load in streams in the Bay watershed was transported through ground water, with a range of 17 to 80 percent in different streams (Bachman and others, 1998). Additional analysis by Sprague and others (2000) found that a similar percentage (15 to 65) of the total nitrogen load in streams was contributed in the form of nitrate from ground water. The slow movement of ground water relative to surface water has a significant impact on the total time it takes for nitrogen to move through the Bay watershed.

Age of Ground-Water Discharge to Streams

To better define the time it takes ground water to move through an aquifer from the area of recharge to the area of discharge (such as a stream, spring, or well), the USGS collected samples to determine the age of ground water in shallow aquifers (the uppermost several hundred feet of shallow aquifers). Samples collected from wells are only representative of one point in an aquifer, and streams cannot be sampled directly for ground-water ages. Therefore, the USGS sampled springs because they are discharge points for ground water from an aquifer (Focazio and others, 1998). The age of ground water from a spring can be considered representative, or an average, of the age of water in an aquifer. The ages of ground water from springs were estimated using chemical isotopic tracers. Chlorofluorocarbons (CFCs) were the primary tracers used in this study. Age determinations using this method are accurate to within several years (Busenburg and Plummer, 1992).

Based on samples collected from 46 springs, the age of ground water in shallow aquifers in the Chesapeake Bay watershed ranges from modern (less than 1 year) to more than 50 years. The median age of all samples was 10 years, with 25 percent of the samples having an age of 7 years or less and 75 percent of the samples having an age of up to 13 years. Wet and dry periods (1996 and 1997, respectively) showed a small influence on the ground-water age of most springs. Samples collected from springs during wet conditions (above average rainfall) were a few years younger than samples collected during dry (below average rainfall) conditions (fig. 3).

Differences between the HGMRs in the Bay watershed (shown in fig. 2) did not significantly affect ground-water ages from springs. The range of ground-water ages (modern to more than 50 years) was similar in large HGMRs above the Fall Line, and only two small HGMRs (the Piedmont Carbonate and Mesozoic Lowland) had ground-water age ranges of modern to 10 years. The median values of ground-water ages in all HGMRs ranged from 7 to 11 years, but not enough samples were collected to detect statistical differences between the HGMRs. Only two springs were sampled in the Coastal Plain, but data from wells showed the range of ages (modern to 50 years) was similar to that in the large HGMRs above the Fall Line. The lack of age differences in ground water between HGMRs indicates that other factors influence the age of water in aquifers. The most important factor, as determined by the study, is the distance between the recharge and discharge area, which in turn will be influenced locally by aquifer geometry, permeability, and hydraulic gradient.

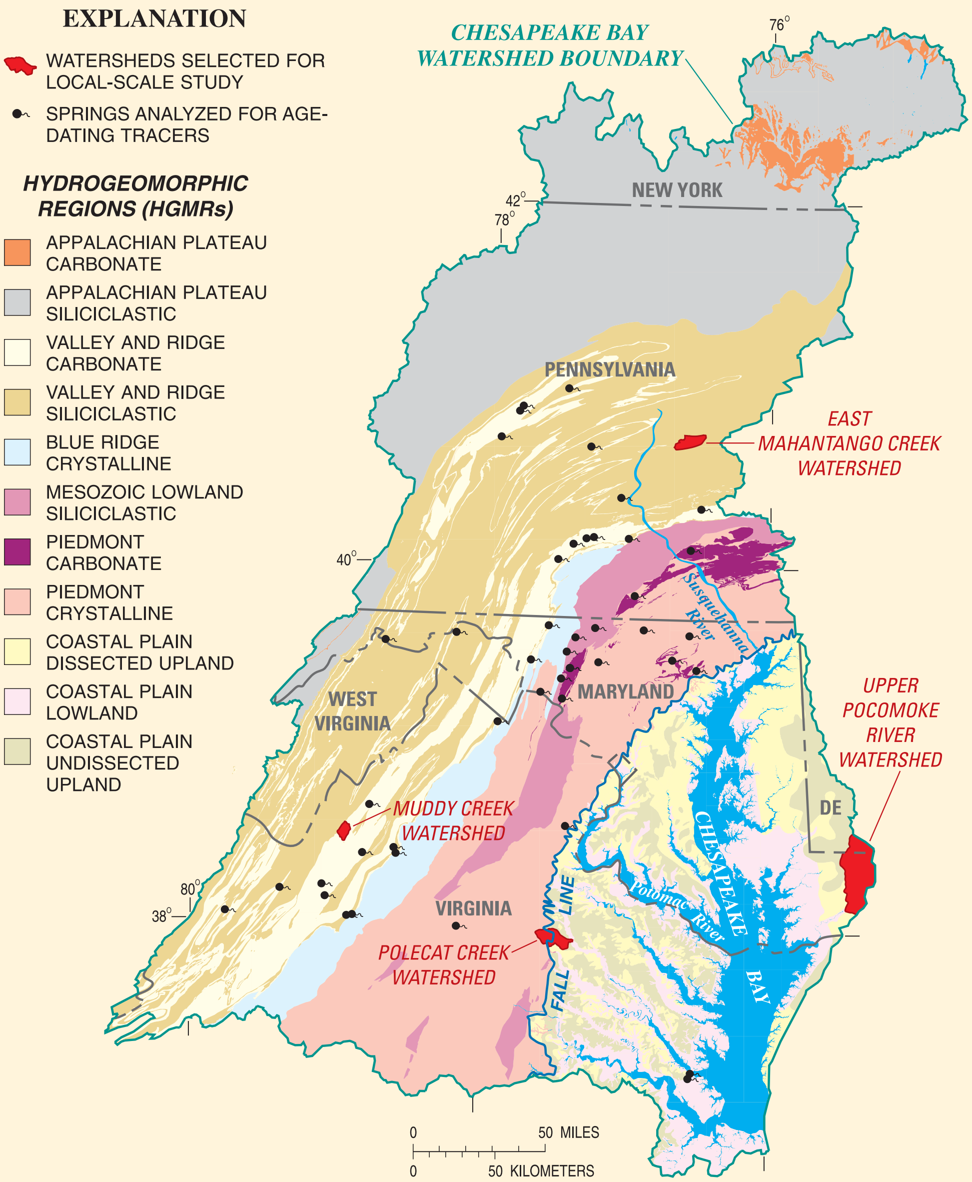


Figure 2. Location of springs and local-scale watersheds sampled in different hydrogeomorphic regions (HGMRs) in the Chesapeake Bay watershed (modified from Lindsey and others, 2003).

Age of Flow Components to Streams and Effect on Water Quality

In addition to ages of the ground water, the water in a stream will be influenced by the ages of the surface runoff and soil water (fig. 4). Surface runoff is water entering a stream after flowing across the land surface during or shortly after storms. A portion of the soil water enters a stream without reaching the water table and is delivered during storms and periods of high moisture content. Runoff and soil water both have very young ages (hours to months, respectively) and supply, on average, about half of the water to a stream (fig. 5). The remainder of the water supplied to a stream moves through the ground-water system and has a median age of 10 years. The overall result is that about half of the water entering a typical stream in the Bay watershed can be considered modern, and about 75 percent is less than 10 years old (fig. 5).

As part of the study, the relation between nutrient sources, ground-water age, and response in nitrate concentrations in a stream was analyzed in four local-scale watersheds (locations shown in figure 2). The watersheds were selected to represent areas of agricultural land use that are underlain by different lithologies. Of the major nitrogen sources (atmospheric, urban, and agricultural) in the watershed, multiple studies (Ator and Ferrari, 1997; Lindsey and others, 1997, Shedlock and others, 1999) have shown that agricultural land use has the greatest impact on nitrogen concentrations in ground water. In the East Mahantango Creek watershed, a predominantly agricultural basin underlain by fractured rock, a model was developed to predict nitrate concentrations in the stream over time (Lindsey and others, 2003). The model used information on the amount of nitrogen applied to the land surface over time in the basin, assumed a ground-water age of about 10 years, and estimated a response of the base-flow (the amount from ground water) nitrate concentrations in a stream (fig. 6). The model results indicate that the base-flow nitrate concentration of the stream increased during the last several decades (curve a) because of increases in the concentrations discharging from ground water. The increase in nitrogen sources used in the model is typical of many agricultural regions within the Chesapeake Bay watershed. Two future scenarios were examined with the model: (1) nitrogen applications continuing at current levels, and (2) elimination of all nitrogen applications. The scenario with nitrogen applications at current levels results in a continued increase in concentration of base-flow nitrate in the stream over the next several decades (curve b in fig. 6). The scenario with complete elimination of nitrogen applications shows that a 50-percent reduction in nitrate base-flow concentrations could occur in about 5 years, with a decrease likely to continue until 2040 (curve c in fig. 6). Base-flow nitrate concentrations over time in many streams in the Chesapeake Bay watershed likely will be bounded by these two scenarios.

Effects of Lag Time on Water-Quality Improvement in the Bay

The information presented in this fact sheet is designed to improve understanding of the effects of ground water on nitrogen delivery to the Chesapeake Bay. However, this factor should be considered in conjunction with all of the factors affecting the lag time between reductions of nutrient sources in the Bay watershed and improvement of water quality by 2010. The major factors affecting lag time include (a) the type of nutrient source (point and nonpoint) and time between planning and implementation of a management practice, (b) the time it takes to transport nutrients and sediment through surface and ground water in the watershed, and (c) the time between a nutrient- and sediment-source reduction and an actual improvement in Bay water quality. This information can be used to help develop strategies to reduce nutrients and sediment to the Bay and its tributaries.

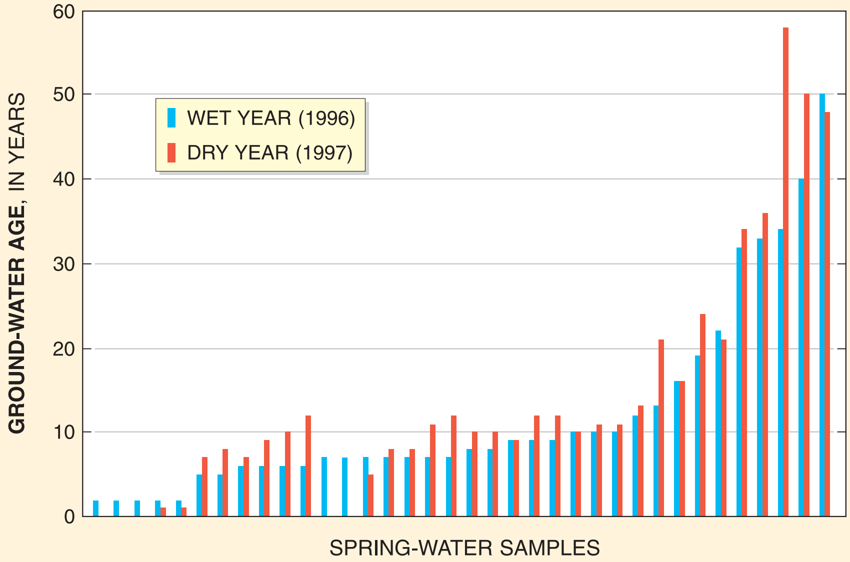


Figure 3. Ground-water age from springs in the Chesapeake Bay watershed, 1996-1997 *[The ages of ground water ranged from modern (less than 1 year) to over 50 years, with a median age of 10 years. The ages of samples collected during "wet" conditions (periods of above average rainfall) were slightly younger than those collected during "dry" conditions (periods of lower than average rainfall).]* (modified from Lindsey and others, 2003).

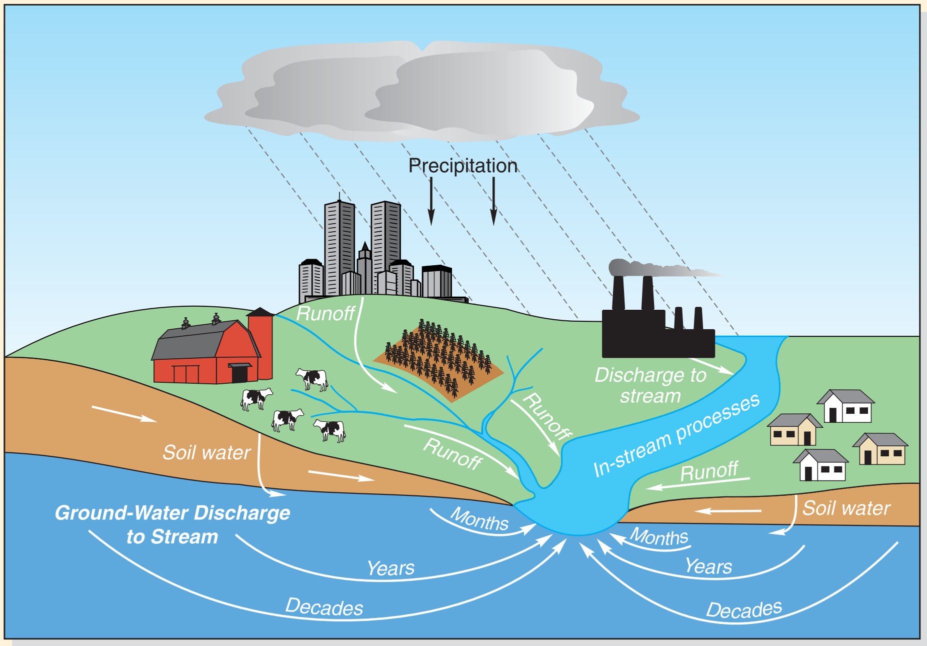


Figure 4. Conceptual watershed showing the relation between nutrient sources, streams, and ground water *(Nitrogen moves from point and nonpoint sources and is transported to a stream through runoff, soil water, and ground water. Once in the ground-water system, nitrogen may take less than a year to decades to be transported to a stream. The distribution of flow paths in the ground-water system will affect the nitrogen concentration and the "lag time" between implementation of management practices in a watershed and the decrease of nitrogen concentrations in a stream.)* (modified from Phillips and others, 1999).

Point and nonpoint sources contribute about 20 and 80 percent, respectively, of the nitrogen that is delivered to the Chesapeake Bay (U.S. Environmental Protection Agency, 2002). Planning and implementing a management practice to reduce these sources can take several years and contribute to the lag time of water-quality improvement in the Bay. Once implemented, point-source reductions would provide the most immediate improvement in water quality in the receiving stream and subsequently the Bay. Nonpoint-source reductions would have less of an immediate effect on water quality because of the slower reduction of sources and the influence of watershed properties affecting the transport of nutrients through a watershed.

Typically, nutrients in a watershed are transported either directly in water (dissolved form) or they attach themselves (primarily phosphorus) to sediment (table 1). Dissolved nitrogen and phosphorus discharged from point sources into surface water have a short transport time (days) through the watershed and to the Bay. Dissolved nitrogen from nonpoint sources is transported almost equally between two major pathways: (a) runoff and soil water, or (b) ground water. As previously discussed, dissolved nitrogen associated with runoff and soil water will have a transport time of hours to months in the watershed. Dissolved nitrogen associated with ground water may have a transport time of years to decades, with a median time of about 10 years. Nutrients associated with sediment can have much longer transport times (several decades) in the watershed because of their storage in soil and stream corridors, both of which are greatly influenced by yearly rainfall.

Information on the transport time of nutrients in a watershed can be used by resource managers to develop management strategies to achieve the most rapid

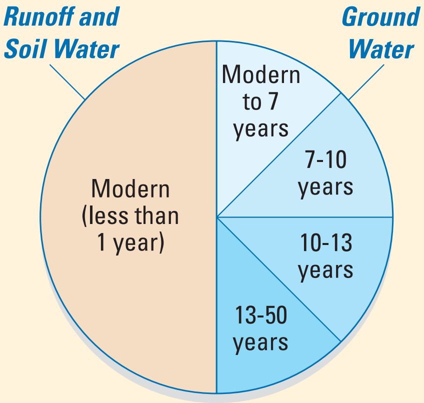


Figure 5. Ages of water being discharged to a stream. *(Runoff and soil water contribute about one half of the water to a stream, and the water can be considered "modern" as it moves to a stream in hours to months. Ground water contributes the remaining half of the water to a stream, with most of the water being less than 13 years old. Overall, about 50 percent of the water discharged to a stream is "modern" and 75 percent is less than 10 years old.)*

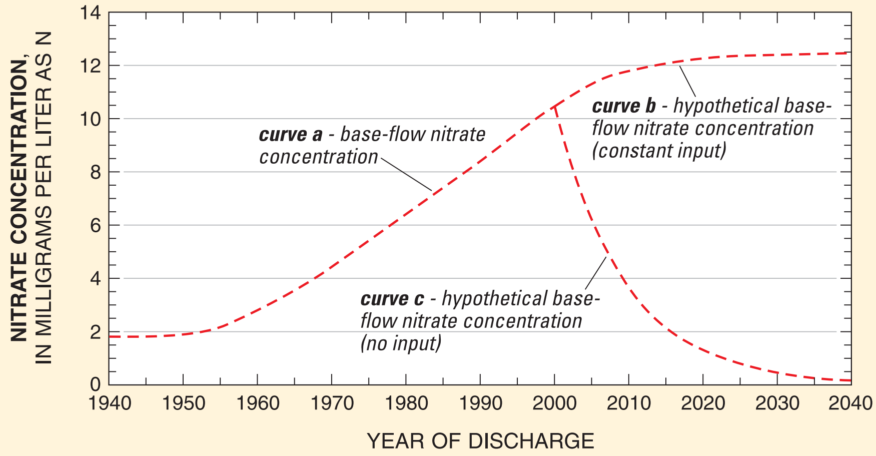


Figure 6. Predicted nitrate concentrations of base flow to a stream in the East Mahantango Creek watershed in Pennsylvania. *[A model was used to predict the stream concentrations based on nitrogen-source reductions and the influence of ground water in an agricultural watershed. The model results indicate that the base-flow nitrate concentration of the stream increased during the last several decades (**curve a**) because of increases in the concentrations discharging from ground water that are related to increases in nitrogen sources. Two future scenarios were examined with the model: (1) continuation of nitrogen applications at current levels, and (2) elimination of all nitrogen applications. Scenario (1) results in a continued increase in concentration of base-flow nitrate in the stream over the next several decades (**curve b**), while scenario (2) shows that a 50-percent reduction in nitrate base-flow concentrations could occur in about 5 years, with a decrease likely to continue until 2040 (**curve c**). Base-flow nitrate concentrations over time in many streams in the Chesapeake Bay watershed likely will be bounded by these two scenarios.]*

improvement in water quality of the Bay. Additionally, the location of the source area in the watershed will influence the lag time between implementation of management practices and improvement in water quality in the Bay. In general, designing management practices that target the highest nutrient sources in areas closest to the Bay may provide a more rapid water-quality benefit. The CBP watershed model can be used in conjunction with results of the USGS SPAtially Referenced Regressions On Watershed attributes (SPARROW) model (Brakebill and others, 2001) to help identify these target areas. Figures 7A and 7B show SPARROW model predictions of areas of highest nitrogen delivery to streams (fig. 7A) and the Bay (fig. 7B). Information on sources contributing to the nutrient loads in different areas is available (Brakebill and others, 2001) to help resource managers determine the strategies needed in different basins that would achieve the most rapid improvement in the water quality of the Chesapeake Bay.

Table 1. Factors affecting lag times, and implications for improvement in water quality in the Chesapeake Bay

Nutrient source	Management practice implementation time	Watershed residence time	Implications for load reductions in the Chesapeake Bay
Point sources (About 20 percent of nutrient load delivered to the Bay)	Several years	Hours to weeks	Would provide the most rapid improvement of water quality due to immediate reduction of source.
Nonpoint sources (About 80 percent of nutrient load delivered to the Bay) ***Dissolved nutrients***	Several years	Hours to months if associated with runoff/soil water; years to decades if associated with ground water, with a median time of 10 years	Improvement in water quality would depend on the rate of implementation of nonpoint-source reduction and amount of nutrients still in soils. Once fully implemented, there would be a fairly rapid reduction of the load associated with runoff and soil water. Nitrogen load associated with ground water would have a median time of 10 years for water-quality improvements to be evident.
Nutrients associated with sediment	Several years	Decades or longer depending on location in watershed	Load reductions would be greatly influenced by streamflow variability. Storm events would deliver sediment and associated nutrients contained on land and in stream corridors. Loads to the Bay may not show reductions for decades due to long residence times.

Based on the time needed to implement nutrient-source reductions and factors affecting the transport time of nutrients in the watershed, the proposed water-quality criteria for the Bay probably will not be met by 2010. However, the drought from 1999 through 2002 provided some insights into the response of the Bay to reduced nutrient loads. Freshwater flow into the Bay during the period was below average for all 4 years, which resulted in fewer nutrients entering the Bay. Information compiled by the CBP showed improvement in the volume of Bay water having dissolved oxygen above 5 milligrams per liter during this period, suggesting that water quality probably will improve fairly rapidly as nutrient loads to the Bay are reduced.

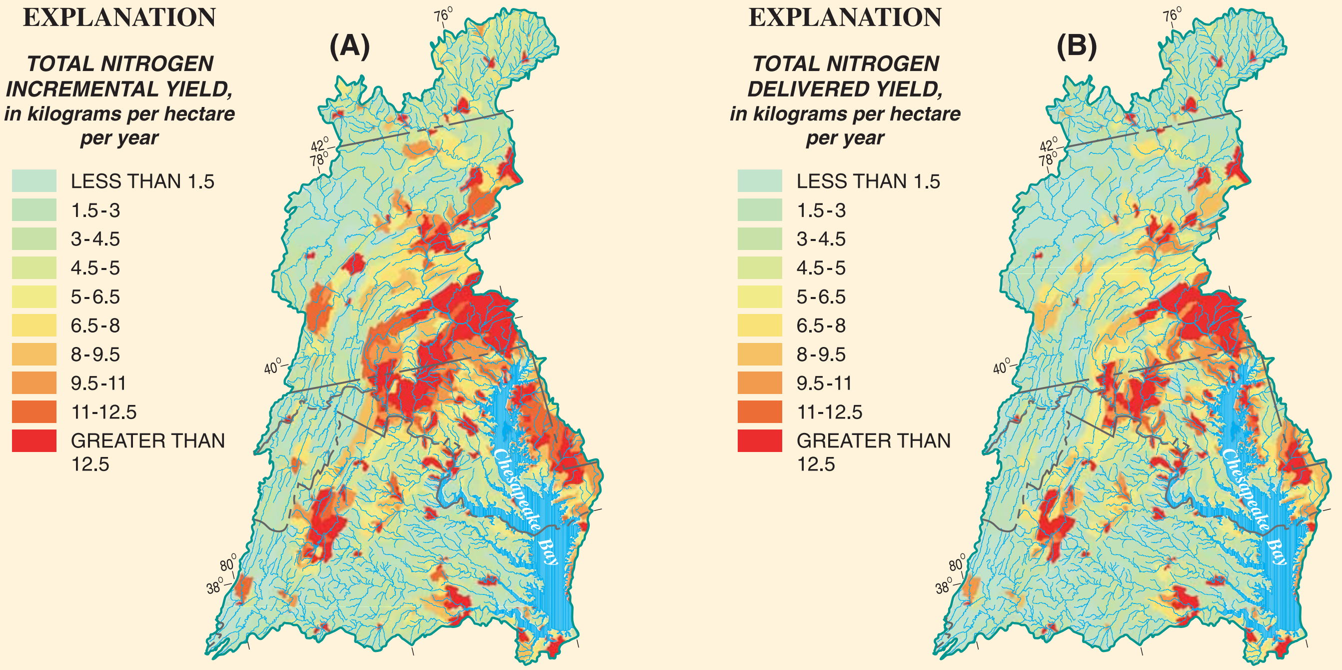


Figure 7. Predicted total nitrogen yields to **(A)** streams and **(B)** the Chesapeake Bay *(In-stream processes account for the difference between nitrogen delivered to streams and the amount delivered to the Chesapeake Bay. Targeting nutrient-reduction strategies in the areas of high nitrogen loading would probably provide the maximum benefit for the Chesapeake Bay.)* (modified from Brakebill and others, 2001).

References Cited

Ator, S.W., and Ferrari, M.J., 1997, Nitrate and selected pesticides in ground water of the Mid-Atlantic Region: U.S. Geological Survey Water-Resources Investigations Report 97-4139, 8 p.

Bachman, L.J., Lindsey, B.D., Brakebill, J.W., and Powars, D.S., 1998, Ground-water discharge and base-flow nitrate loads of nontidal streams, and their relation to a hydrogeomorphic classification of the Chesapeake Bay Watershed, Middle Atlantic Coast: U.S. Geological Survey Water-Resources Investigations Report 98-4059, 71 p.

Böhlke, J.K., and Denver, J.M., 1995, Combined use of ground-water dating, chemical, and isotopic analyses to resolve the history and fate of nitrate contamination in two agricultural watersheds, Atlantic Coastal Plain, Maryland: Water Resources Research, v. 31, no. 9, p. 2,319-2,339.

Brakebill, J.W., Preston, S.D., and Martucci, S.K., 2001, Digital data used to relate nutrient inputs to water quality in the Chesapeake Bay, version 2.0: U.S. Geological Survey Open-File Report 01-251, [variously paged].

Busenberg, E. and Plummer, L.N., 1992, Use of chlorofluorocarbons (CCl3F and CCl2F2) as hydrologic tracers and age-dating tools: The alluvium and terrace system of central Oklahoma: Water Resources Research, v. 28, no. 9, p. 2,257-2,283.

Focazio, M.J., Plummer, L.N., Böhlke, J.K., Busenburg, E., Bachman, L.J., and Powars, D.S., 1998, Preliminary estimates of residence times and apparent ages of ground water in the Chesapeake Bay Watershed, and water quality data from a survey of springs: U.S. Geological Survey Water-Resources Investigations Report 97-4225, 75 p.

Lindsey, B.D., Loper, C.A., and Hainly, R.A., 1997, Nitrate in ground water and stream base flow in the Lower Susquehanna River Basin, Pennsylvania and Maryland: U.S. Geological Survey Water-Resources Investigations Report 97-4146, 66 p.

Lindsey, B.D., Phillips, S.W., Donnelly, C.A., Speiran, G.K., Plummer, L.N., Böhlke, J.K., Focazio, M.J., and Burton, W.C., 2003, Residence time and nitrate transport in ground water discharging to streams in the Chesapeake Bay Watershed: U.S. Geological Survey Water-Resources Investigations Report 03-4035, 202 p.

Phillips, P.J., and Bachman, L.J., 1996, Hydrologic landscapes on the Delmarva Peninsula Part 1: Drainage basin type and base-flow chemistry: Water Resources Bulletin, v. 32, no. 4, p. 767-778.

Phillips, S.W., Focazio, M.J., and Bachman, L.J., 1999, Discharge, nitrate load, and residence time of ground water in the Chesapeake Bay Watershed: U.S. Geological Survey Fact Sheet FS-150-99, 6 p.

Shedlock, R.J., 1993, The Delmarva study: Geotimes, December 1993, v. 38, no. 12, p. 12-14.

Shedlock, R.J., Denver, J.M., Hayes, M.A., Hamilton, P.A., Koterba, M.T., Bachman, L.J., Phillips, P.J., and Banks, W.S.L., 1999, Water-quality assessment of the Delmarva Peninsula, Delaware, Maryland, and Virginia: Results of investigations, 1987-91, U.S. Geological Survey Water-Supply Paper 2355-A, 41 p.

Sprague, L.A., Langland, M.J., Yochum, S.E., Edwards, R.E., Blomquist, J.D., Phillips, S.W., Shenk, G.W., and Preston, S.D., 2000, Factors affecting nutrient trends in major rivers of the Chesapeake Bay Watershed: U.S. Geological Survey Water-Resources Investigations Report 00-4218, 109 p.

U.S. Environmental Protection Agency, 2002, The state of the Chesapeake Bay: U.S. Environmental Protection Agency Report 903-R-02-002, 60 p.

_______ , 2003, Ambient water-quality criteria for dissolved oxygen, water clarity, and chlorophyll *a* for Chesapeake Bay and its tidal tributaries: U.S. Environmental Protection Agency Report 903-R-03-002, [variously paged].

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