A simulation of groundwater discharge and nitrate delivery to Chesapeake Bay from the lowermost Delmarva Peninsula, USA

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Abstract A groundwater model has been developed for the lowermost Delmarva Peninsula, USA, that simulates saltwater intrusion into local confined aquifers and nitrate delivery to the Chesapeake Bay from the surficial aquifer. A flow path and groundwater-age analysis was performed using the model to estimate the timing of nitrate delivery to the bay over the next several decades. The simulated mean and median residence times of groundwater in the lowermost peninsula are 30 and 15 years, respectively. Current and future nitrate concentrations in coastal groundwater discharge were simulated based on local well data that include nitrate concentrations and groundwater age. A simulated future-trends analysis indicates that nitrate that has been applied to agricultural regions over the last few decades will continue to discharge into the bay for several decades to come. This study highlights the importance of considering the groundwater lag time that affects the mean transport time from diffuse contamination sources.

Key words groundwater model; submarine groundwater discharge; nitrate; Chesapeake Bay, USA

INTRODUCTION

The Chesapeake Bay in the eastern USA is an impaired water body that has been adversely affected for decades by an oversupply of nutrients that feeds algal blooms and creates regions of low dissolved oxygen. In the mid-1980s, the Chesapeake Bay Program was created as a partnership between the states and the federal government to reduce nutrient loading to the bay. Although criteria have been developed for water-quality levels and remedial actions have begun, it is unknown how long it will take for conditions in the bay to improve. One important factor in estimating the timing of loadings from the land surface to the bay is the influence of groundwater on the transport time. Studies have shown that typical residence times of groundwater in subwatersheds within the bay watershed are ten years or more (Lindsey *et al*., 2003; Phillips & Lindsey, 2003). A substantial portion of dissolved nitrogen (primarily nitrate) loading to the bay is from agricultural regions, and one of the largest of these regions is on the Delmarva Peninsula, which lies between the bay and the Atlantic Ocean (Fig. 1(a)). If future levels of dissolved nitrogen loading to the bay are to be estimated accurately, a better understanding of the movement of groundwater that discharges to the bay from agricultural regions would be required.

The southernmost part of the Delmarva Peninsula is called the Eastern Shore of Virginia (Fig. 1(a)). The Eastern Shore contains a long topographic high that divides the peninsula into two watersheds (Fig 1(b)), with the western side draining to the

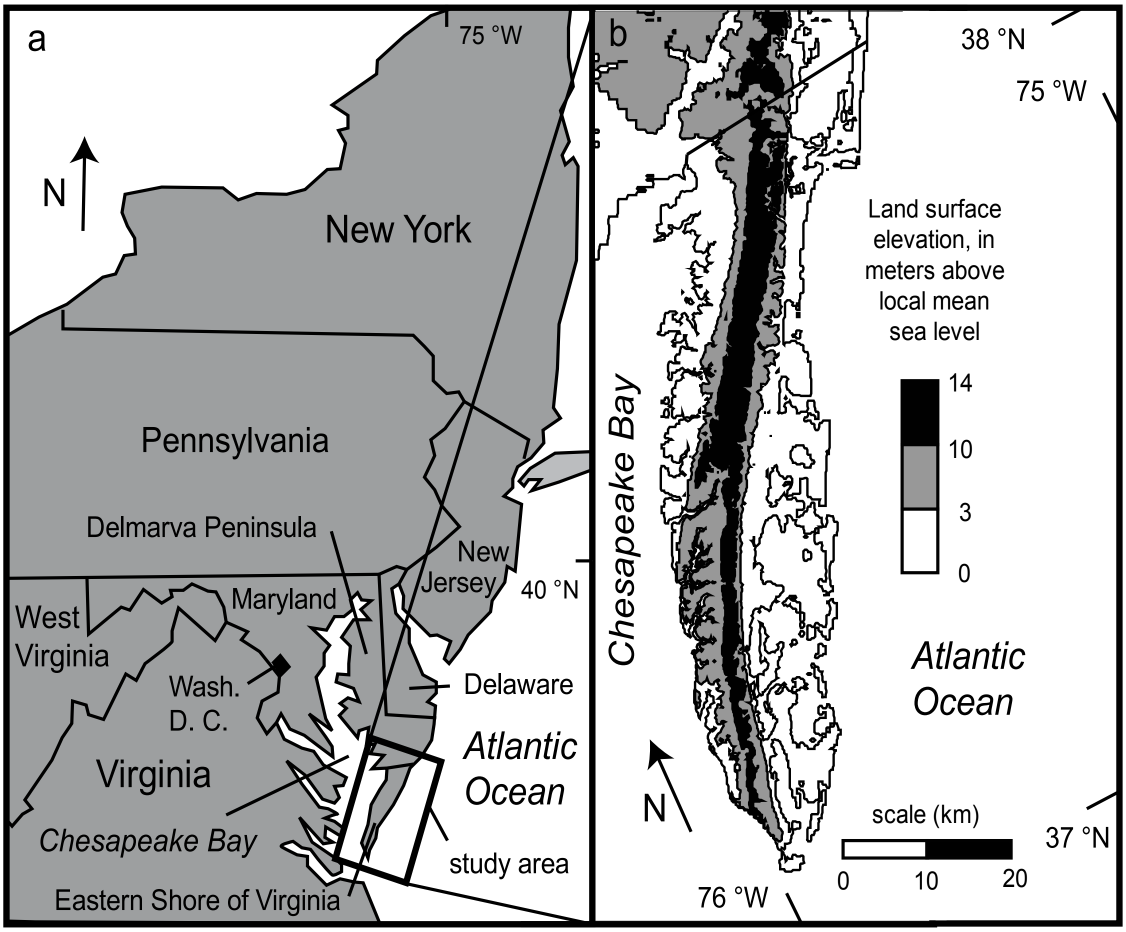

Fig. 1 Maps showing: (a) the location and (b) topography of the Eastern Shore of Virginia.

Chesapeake Bay. Agriculture has long been a substantial portion of the land-use cover on the Eastern Shore (Fig. 2(a)). In the absence of streams on the Eastern Shore, groundwater from a confined aquifer system is the only source of potable water (Richardson, 1994). There is also a shallow water-table aquifer that is used primarily for agricultural irrigation. The water table in this aquifer is close to land surface and thus mimics the topography (Fig. 2(b)). The shallow aquifer is contaminated in many areas by high nitrate levels, and is the primary source of nitrogen loading to the bay from the Eastern Shore of Virginia (Raey *et al.*, 1992; Gallagher *et al.*, 2001). The purpose of this study was to use a recently developed groundwater model of the Eastern Shore to study the movement and discharge of nitrogen-laden groundwater to the bay, and to simulate future changes in nitrogen loadings in response to changes in nitrogen (mostly fertilizer) application rates.

GROUNDWATER FLOW MODEL

A groundwater flow model of the Eastern Shore of Virginia is currently (2007) being developed as a joint project between federal, state, and local government offices. The model will be used primarily by water-resources managers to help plan future

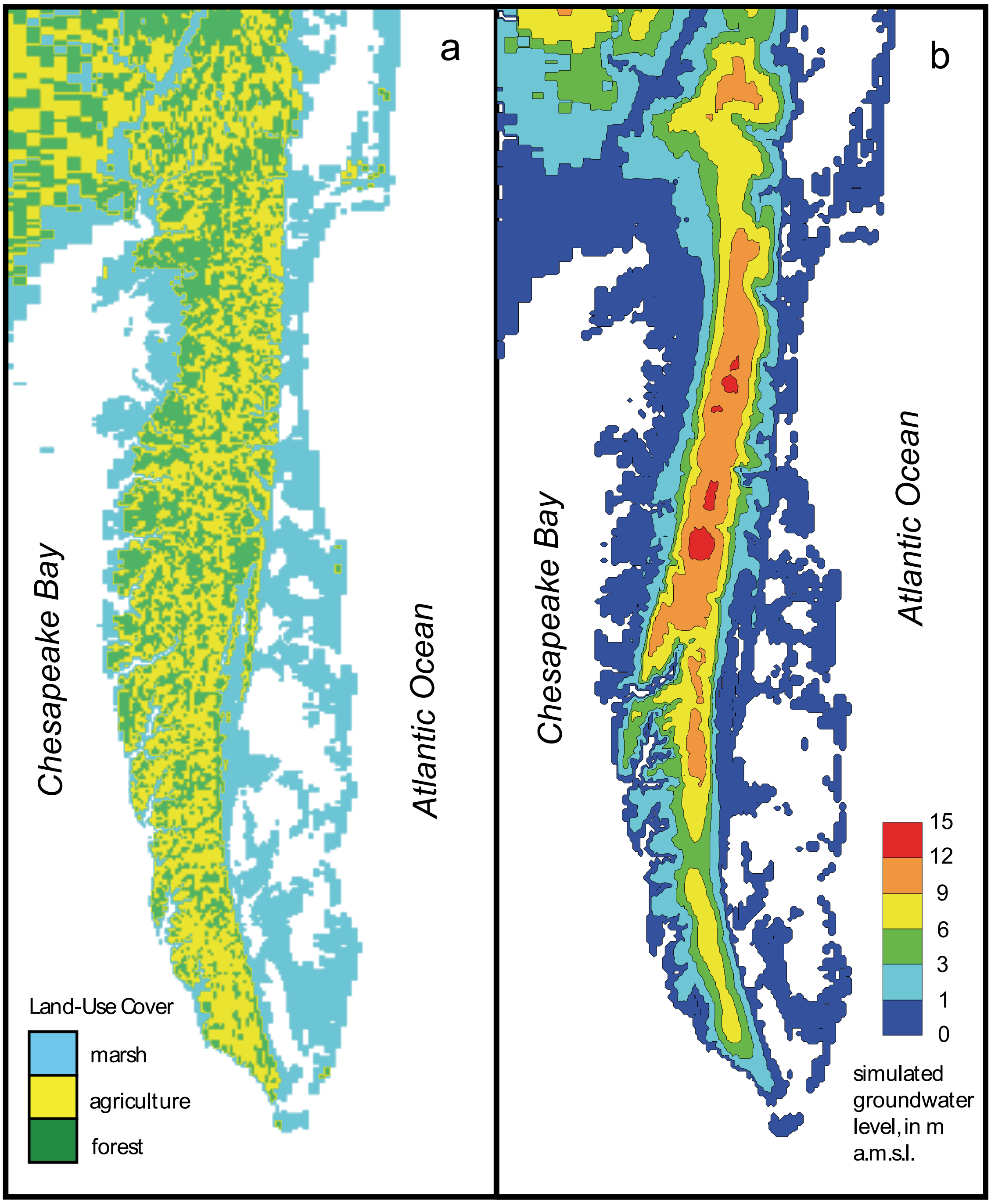

Fig. 2 Maps of the Eastern Shore of Virginia showing: (a) land use from 1992 USGS National Land Cover Data Set (http://landcover.usgs.gov/natllandcover.php), and (b) simulated groundwater levels in the surficial aquifer.

groundwater development within the region, and to assess adverse impacts such as lowering of regional water levels and saltwater encroachment. The US Geological Survey (USGS) code SEAWAT (Langevin *et al.*, 2003) was used to construct the groundwater flow model. SEAWAT can account for the differences in density between groundwater and seawater and so can simulate the encroachment of saltwater into the confined freshwater aquifer system.

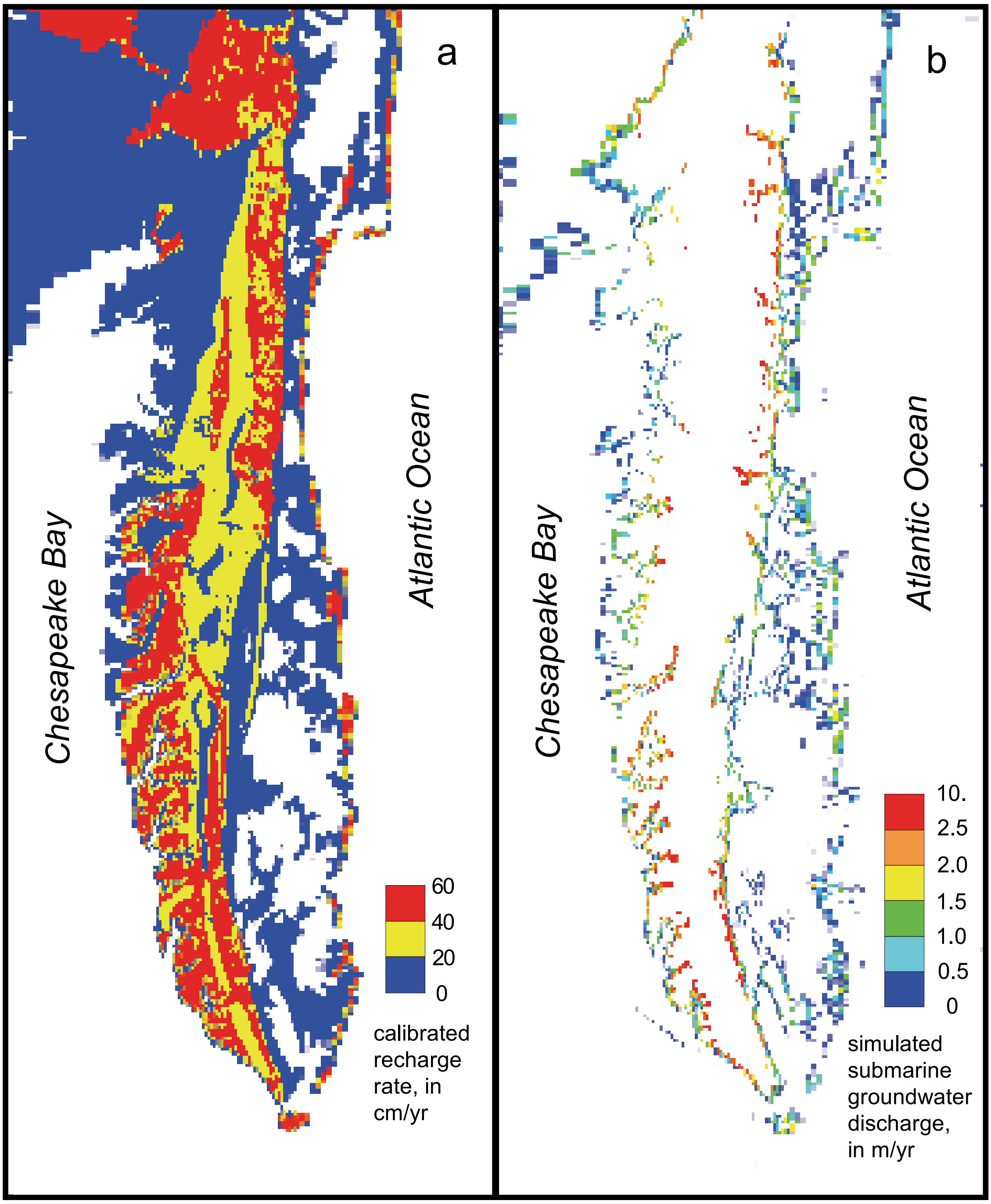

Fig. 3 Maps showing: (a) calibrated recharge rates assigned by zones based on soil texture, and (b) simulated fluxes of submarine groundwater discharge.

The model was calibrated using over 500 groundwater levels in wells spanning over 50 years. In the confined aquifer, these water levels have been declining because of regional pumping stresses. The model also includes the shallow water-table aquifer. In the shallow aquifer, young groundwater ages were measured in wells (Spieran, 1996; USGS, unpublished data), and these were used to help calibrate the shallow part of the model. In the shallow system, evapotranspiration rates were calibrated along with hydraulic conductivities and recharge rates. Recharge rates were assigned by zones (Fig. 3(a)) that coincided with soil textures as defined and mapped by the US Department of Agriculture. The model also simulates the distribution and magnitude of submarine groundwater discharge from the shallow aquifer along the coastal inlets (Fig. 3(b)).

GROUNDWATER TRANSPORT OF NITRATE

To simulate the transport of nitrate through the shallow aquifer to discharge zones along the coastal inlets, an approach was taken that combines groundwater-flowpath simulation with the estimation of historical nitrate concentrations in the recharge zone. Flowpaths throughout the shallow aquifer were calculated using the USGS code MODPATH (Pollock, 1994). One simulated pathline was started in every recharge grid cell of the model and tracked forward to its discharge location. A similar approach has been taken in previous studies (Modica *et al*., 1998; Kauffman *et al*., 2001). In the current study, travel times for the pathlines were calculated using an effective porosity of 0.25. The thousands of pathlines were then sorted by recharge location, travel time, land use at the recharge point, and discharge location. Nitrate was considered to be conservative along the flow path, but consumed by denitrification if it intercepted the root zone at the discharge cell. As the faster flow paths tend to be shallower (and in the root zone), denitrification was assigned in the discharge cell only to the faster pathlines. The proportion that was assigned denitrification was pro-rated according to the ratio of evapotranspiration to total discharge in the cell. Only pathlines that were not assigned denitrification were used to tally the total nitrogen load to the bay. An estimate of historical nitrate concentrations over time (Bohlke & Denver, 1995) was used to assign nitrate concentration to those pathlines that originated at cells with an agricultural land-use cover (Fig. 2(a)). Pathlines that originated in other areas were assigned lower, ambient concentrations. By combining the pathline travel-time distribution with nitrate concentration history, current and future trends in nitrogen loading to the bay were calculated for various scenarios of change in nitrate application load at the land surface. A runoff component was estimated from hydrograph separation at a small creek on the peninsula.

RESULTS

The age distribution for groundwater discharging to the bay is highly skewed (Fig. 4). The mean simulated travel time of all groundwater from recharge to discharge on the Eastern Shore is 30 years. The median simulated travel time is 15 years. The mean and median ages of groundwater directly discharging to coastal inlets are 40 and 18 years, respectively. The mean direct-discharge travel time is older than the mean recharge travel time because much of the younger water escapes by evapotranspiration, which is not counted in the directed discharge mean age. Mean and median ages varied by land-use type at the recharge location. Water recharged in agricultural areas that directly discharged had a mean and median age of 31 and 17 years, respectively, whereas water from forest land had means and median ages of 28 and 18 years, respectively, and

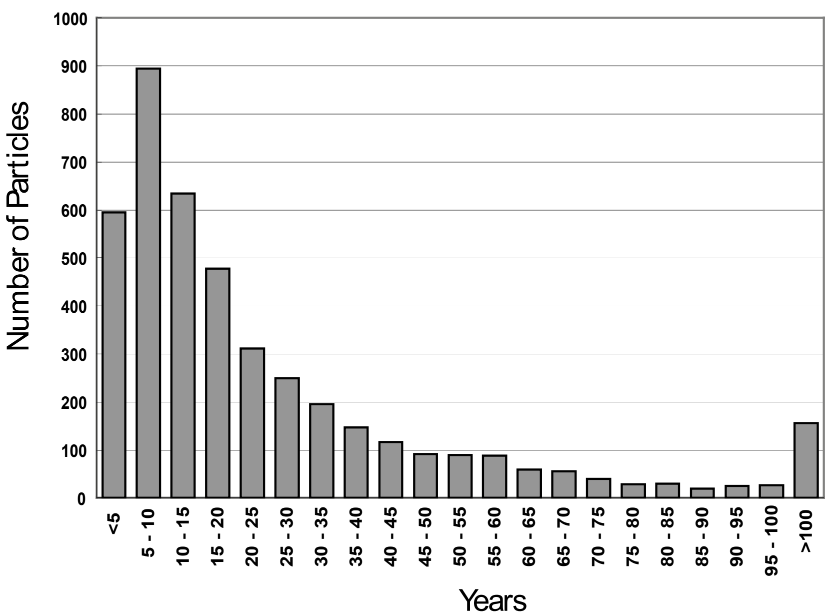

Fig. 4 The distribution of groundwater age on the Eastern Shore of Virginia according to simulated pathlines in the flow model.

marsh lands had 200 and 37 years respectively. Low recharge rates in the marsh soils resulted in very slow flow through those regions.

Even with a median age of 18 years for groundwater discharge, a substantial fraction of the water has an age of many decades (Fig. 4). Nitrate concentrations began rising substantially only in the last 30 years or so, when fertilizer application rates began increasing greatly (Bohlke & Denver, 1995). Therefore, much of the groundwater with elevated concentrations of nitrate is not yet discharging to the bay. Thus we expect that with no change in current nitrate application at the land surface, nitrogen load to the bay will continue to increase until the discharge load equals the recharge load, which will take many decades to occur. The path-line age distribution was used to calculate future trends in the nitrogen load to the bay, given possible changes in future nitrogen application rates (Fig. 5). The load calculation is made by multiplying the flux associated with each pathline by the concentration during the year of recharge, and the year is calculated from the travel time. The load estimates include a runoff component as well as the groundwater discharge component. As is expected, a "no change" in application load scenario led to increasing nitrogen discharge over the next several decades. Cutting the nitrogen application by half resulted in loads staying close to those currently observed. Eliminating the nitrogen input altogether resulted in an initial small decline caused by the loss of the runoff component, but several decades were required before the loads were reduced to substantially lower levels.

IMPLICATIONS FOR ESTIMATING NUTRIENT DISCHARGE

For the Eastern Shore of Virginia, our simulated estimates of nitrogen loading were similar to the cap load allocations (Fig. 5) for this section of the bay suggested by the

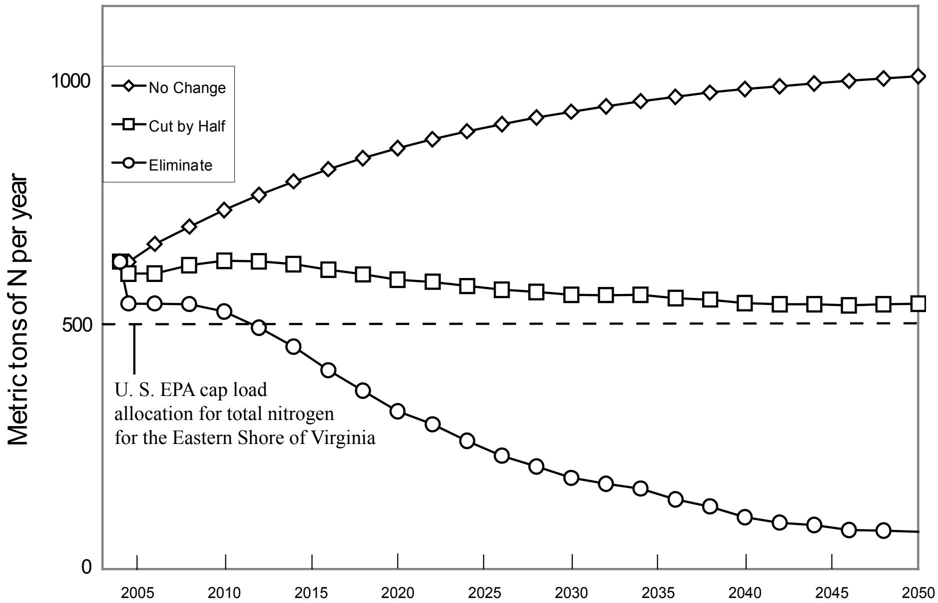

Fig. 5 Future trends in nitrogen loading to the Chesapeake Bay from the Eastern Shore of Virginia calculated with the model groundwater age distribution and three different scenarios for future nitrogen application.

US Environmental Protection Agency (Koroncai *et al*., 2003). Assessments of contaminant loading to coastal water bodies, such as the Chesapeake Bay, are sometimes performed using models that primarily account for the surface-water transport components of the hydrological system (Linker *et al*., 1996). Although such models may be appropriate for constituents, such as phosphorus or sediment, that are transported predominantly by surface water, our study has shown that for dissolved constituents that are transported by groundwater, such as nitrate, the lag time introduced by the flow system can be the dominant factor affecting loading trends for many decades. Models of nitrogen loading that neglect the groundwater-flow component will likely perform poorly if used to estimate future trends, and will underestimate the time required for total loads to respond to changes in management practices.

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