Ground Water Flow Analysis of a Mid-Atlantic Outer Coastal Plain Watershed, Virginia, U.S.A.

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Abstract

Models for ground water flow (MODFLOW) and particle tracking (MODPATH) were used to determine ground water flow patterns, principal ground water discharge and recharge zones, and estimates of ground water travel times in an unconfined ground water system of an outer coastal plain watershed on the Delmarva Peninsula, Virginia. By coupling recharge and discharge zones within the watershed, flowpath analysis can provide a method to locate and implement specific management strategies within a watershed to reduce ground water nitrogen loading to surface water. A monitoring well network was installed in Eyreville Creek watershed, a first-order creek, to determine hydraulic conductivities and spatial and temporal variations in hydraulic heads for use in model calibration. Ground water flow patterns indicated the convergence of flow along the four surface water features of the watershed; primary discharge areas were in the nontidal portions of the watershed. Ground water recharge zones corresponded to the surface water features with minimal development of a regional ground water system. Predicted ground water velocities varied between < 0.01 to 0.24 m/day, with elevated values associated with discharge areas and areas of convergence along surface water features. Some ground water residence times exceeded 100 years, although average residence times ranged between 16 and 21 years; approximately 95% of the ground water resource would reflect land use activities within the last 50 years.

Introduction

Nonpoint sources of pollution are one of the greatest threats to coastal water quality (National Research Council 1993; Carpenter et al. 1998). The importance of ground water as a contributor of pollutants, in particular nutrients, to coastal and estuarine water is receiving increasing attention (Lapointe et al. 1990; Weiskel and Howes 1991; Valiela et al. 1992; Paerl 1997). Because areal recharge is the dominant source of water for the shallow ground water systems within the coastal plain region of Chesapeake Bay, ground water quality is vulnerable to contamination and strongly linked to land use. Annual estimates of nitrogen loadings to shallow ground water are on the order of 20 to 43 kg ha^{-1} for dominant row-crop land uses in the mid-Atlantic Coastal Plain (Gambrill et al. 1975; Peterjohn and Correll 1984; Shirmohammadi et al. 1991; Johnson and Parker 1993; Staver and Brinsfield 1995). Septic tank nitrogen loading rates are on the order of 7 to 11 kg $household^{-1}$ yr^{-1} (Stewart and Reneau 1988; Maizel et al. 1997; Reay, in review); areal rates are dependent on housing density. Streams within the coastal watersheds of the Chesapeake Bay exhibit significant interaction with surficial aquifers of the region making baseflow a dominant source of water along the nontidal portion of these streams (Bohlke and Denver 1995; Jordan et al. 1997). Accordingly, stream water quality within Chesapeake Bay watersheds is related to land use (Correll et al. 1992; Jordan et al. 1997). Nitrogen transport through baseflow and direct ground water discharge has contributed to the nitrogen enrichment of surface water within the Chesapeake Bay watershed (Libelo et al. 1990; Simmons et al. 1992; Reay et al. 1992; Gallagher et al. 1996; Staver and Brinsfield 1996).

Because ground water provides a hydrological link between landscapes within a watershed, ground water flowpath analysis can be an extremely important tool for land-use planning and water resources management. Watersheds within the Chesapeake Bay coastal plain can be broadly classified as inner and outer coastal plain watersheds (Correll et al. 1992; Phillips et al. 1993). Inner coastal plain watersheds are on the western shore of Chesapeake Bay and a relatively small upper portion of the Delmarva Peninsula. These watersheds are characterized by a gently rolling topography, a high degree of stream incision, and relatively thin surficial aquifers. Outer coastal plain watersheds primarily occupy the lower Delmarva Peninsula. In general, outer coastal plain watersheds display relatively flat topography compared to inner coastal plain systems, low to high degree of stream incision, and deeper unconfined aquifer systems. Given the complexity of shallow ground water flow systems in the Chesapeake Bay coastal plain watershed, numerical ground water simulations of specific watersheds can be used to contribute to our understanding and quantification of the regional ground water system.

This paper describes the use of the ground water model MODFLOW and the particle-tracking model MODPATH to investigate the unconfined ground water flow system in an outer coastal plain watershed on the Delmarva Peninsula. Specific objectives of this

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Received December 2000, accepted August 2001.

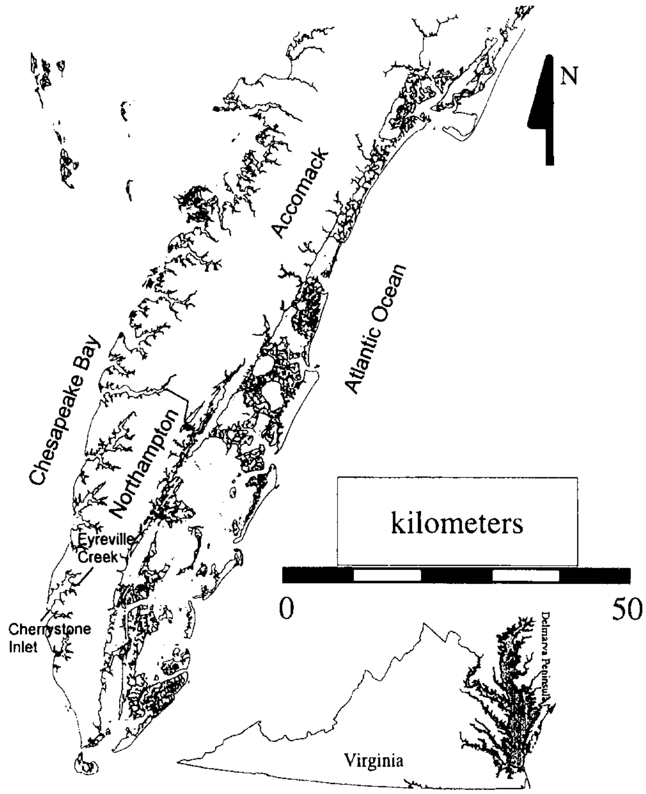

Figure 1. Location map of Cherrystone Inlet and Eyreville Creek watershed.

study were to describe primary ground water flow patterns, which includes identification of principal ground water discharge and associated recharge zones; to estimate ground water travel or residence times; and to address management implications of model results with respect to ground water nitrogen loading to surface water.

The Study Area

The study was conducted in Eyreville Creek watershed, located in the southern portion of the Delmarva Peninsula within the Chesapeake Bay drainage basin (Figure 1). Eyreville Creek is a first-order, outer coastal plain watershed with an area of 6.2 km^2 (1520 acres) and land use of 54% cultivated, 36% forested, and 10% developed or other land uses. The land surface gently slopes from approximately 12 m above sea level in the eastern uplands to 1 m above sea level in the lower lying regions adjacent to Cherrystone Inlet. Eyreville Creek flows east to west and consists of a series of three impoundments, a short stretch of free-flowing stream that connects the upper two impoundments, and a short tidal region that drains into Cherrystone Inlet. The impoundments, downstream from the headwaters, are designated as the railroad pond, the upper pond, and the lower pond. The tidal region has an area of 0.23 km^2 (57 acres) while the railroad, upper, and lower ponds have areas of 0.008 km^2 (2 acres), 0.08 km^2 (20 acres), and 0.08 km^2 (20 acres), respectively. The impoundments were created by the construction of earthen dams. At times, the upper and lower ponds provide water for irrigation.

The unconfined Columbia aquifer and the confined Upper, Lower, and Middle Yorktown-Eastover aquifers constitute the fresh ground water flow system on the Eastern Shore of Virginia. The Columbia aquifer comprises primarily Pleistocene sediments, which range from fine silty sands to coarse and gravelly clean sands, with thin, discontinuous finer textured lenses (Richardson 1992). Depth to the water table ranges from 0 m at surface water and wetland systems to more than 3 m in upland portions. The Upper Yorktown confining unit forms the base of the Columbia aquifer with a depth to the top of the confining unit at approximately 10 m below mean sea level (msl) within the Eyreville Creek watershed. The western extent of the Columbia aquifer in the watershed is bounded by the salt water boundary along the shoreline, while the eastern extent is bounded by the natural ground water divide of the Delmarva Peninsula. Natural recharge to the Columbia aquifer on the Eastern Shore of Virginia is estimated at 9.5×10^5 m^3/day or 30.5 cm/year (257 Mgal/day or 12 in/year) (Richardson 1992). The recharge flows vertically toward the base of the Columbia aquifer and laterally toward discharge sites, such as springs, streams, marshes, estuaries, the Chesapeake Bay, and the Atlantic Ocean. About 8% to 14% of the recharge permeates the Upper Yorktown-Eastover confining unit into the confined aquifer system, while the largest fraction flows laterally through the Columbia aquifer. Irrigation ponds intersecting the Columbia aquifer provide water for agricultural purposes.

Development of the Ground Water Model

MODFLOW, a three-dimensional finite-difference ground water flow model (McDonald and Harbaugh 1988), and MODPATH (Pollock 1989), a particle-tracking program, were used to simulate ground water flow in the Columbia aquifer and to estimate ground water travel time, recharge locations, and flowpaths. The Columbia aquifer was represented by a uniform rectangular grid of 80 columns, 35 rows, and four layers. Individual cells measured 76.2 m by 76.2 m (250 feet by 250 feet). The vertical dimension of the bottom three layers was 3.0 m (9.8 feet). The vertical dimension of the top layer varied as a function of the water-table elevation. Eyreville Creek was represented by 157 river cells. A short portion of the perennial stream downstream of the railroad pond flows through a culvert under a four-lane divided highway. Because this portion of Eyreville Creek has no hydraulic connection with the ground water system, it was not represented in the model by river cells.

The upper boundary of the aquifer was simulated as a free-surface boundary able to fluctuate in response to a specified recharge uniformly distributed to the top layer of the model grid. The upland no-flow boundary of the grid coincided with the ground water divide of the larger Cherrystone Inlet watershed, while lateral no-flow boundaries coincided with the local interstream ground water divides. Ground water salinity measurements at the shoreline, from this study and a previous study (Robinson et al. 1998), confirmed the presence of a relatively sharp salt water transition zone. Therefore, the lower three layers of the grid at the shoreline boundary were modeled as no-flow boundaries while the top layer of the grid was defined as a constant head boundary. These cells in the top layer allowed for direct discharge of ground water to Cherrystone Inlet. The upland ground water divide and the local interstream ground water divides were assumed to correspond to topographic divides.

Recharge zones were determined by the reverse particle-tracking procedure in MODPATH. Based on calculated ground water flow velocities, the particles were tracked back toward their point of origin into the ground water system. In this manner, recharge zones for individual surface water features were determined. Because particle tracking within MODPATH simulates

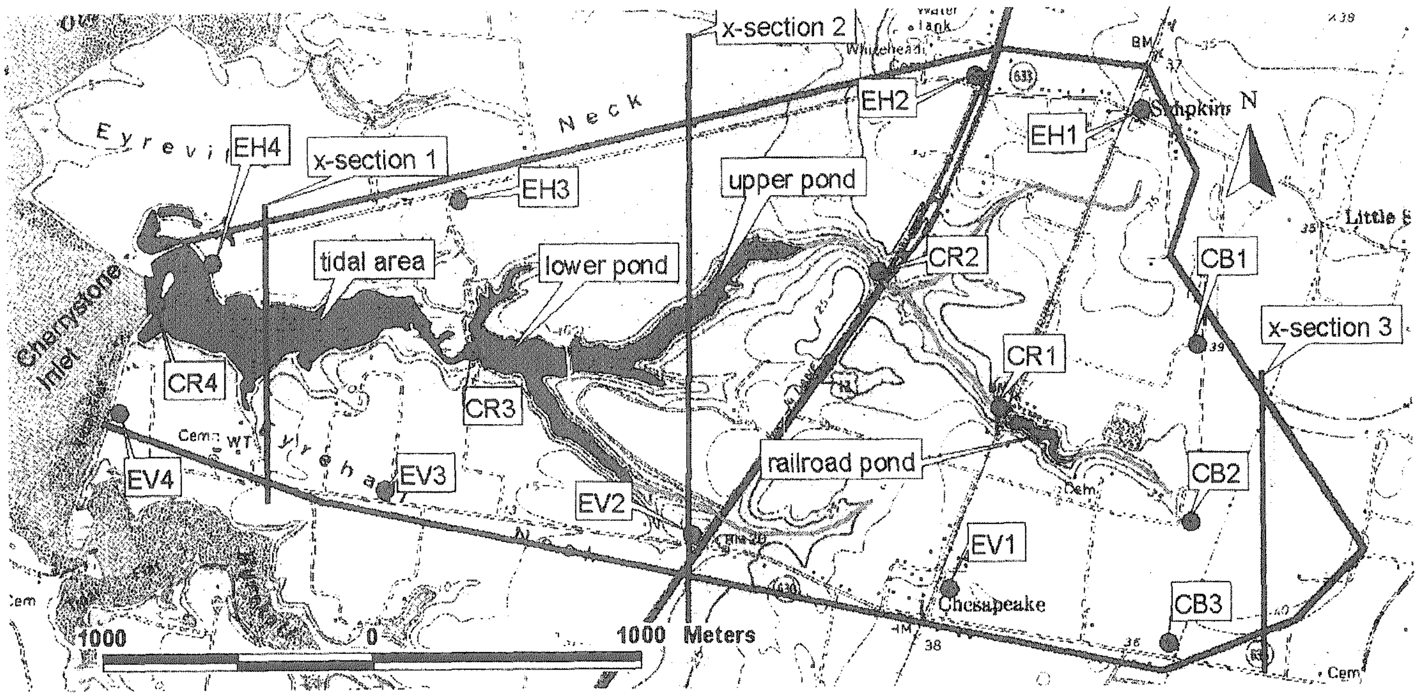

Figure 2. Monitoring well network within Eyreville Creek watershed. Locations of the individual monitoring well stations are indicated by blackened circles. Vertical lines indicate location of vertical head transects shown in Figure 5.

only advective transport, the effect of dispersive transport cannot be accounted for with the particle-tracking analysis. Time-of-travel estimates were determined by the forward particle-tracking procedure available in MODPATH. Based on calculated ground water flow velocities, the particles were tracked toward their point of discharge from the ground water system.

Collection of Field Data

Field sampling for this study occurred over a 16-month period from November 1995 to February 1997. Three east-west monitoring well transects, designated as the Eyreville transect (EV), Eyrehall transect (EH), and Creek transect (CR), and several additional upland monitoring wells (CB) were installed in the watershed (Figure 2). Each transect had four monitoring stations and each station had between four and seven monitoring wells. The wells were installed to various depths in a clustered configuration with no more than three wells per borehole. Well depths in each borehole were staggered to achieve maximum vertical separation between individual well screens. Wells were constructed of 3.2 cm (1.25 inch) diameter schedule 40 polyvinyl chloride (PVC) casing with 30 cm (12 inch) of 0.025 cm slotted PVC screen. The well annulus around the screen was backfilled with gravel while the remaining annulus was backfilled with granular bentonite. Shallow water-table wells ranging to 3 m deep were installed with a hand auger while deeper wells were installed using a recirculating hydraulic jet drill. Monitoring well and land topography elevations, relative to mean local sea level, were determined by differential leveling techniques. Water levels were measured monthly with an electrical water probe to an accuracy of 0.30 cm.

Monitoring wells were broadly classified as shallow, mid-depth, or deep based on their penetration into the aquifer. Shallow monitoring wells, placed in the top third of the aquifer, had depths ranging from 0.0 to 2.7 m below the water table. Mid-depth monitoring wells, placed in the middle third of the aquifer, had depths ranging from 3.3 to 8.9 m below the water table. Deep monitoring wells, placed in the lower third of the aquifer, had depths ranging from 10.6 to 15.7 m below the water table. The water-table elevations represent the elevation of the water table at or near the time of monitoring well installation.

Saturated horizontal hydraulic conductivity (K_h) was determined at the monitoring wells that terminated at the base of the cluster borehole. The slug test procedure of Bouwer and Rice (1976) was used to account for the unconfined aquifer and partial aquifer penetration conditions. Vertical saturated hydraulic conductivity (K_v) of the surficial pond sediments in the tidal region, lower pond, and upper pond were measured using collected sediment cores and the falling-head method (Klute 1965).

Field Study Results

Water-table elevations within the easternmost upland ground water divide region ranged between 8.8 and 10.6 m above msl while water-table elevations along the creek transect remained relatively constant, fluctuating less than 0.5 m throughout the study period. Water-table elevations near the shoreline ranged between 0.0 and 0.5 m above msl. Tidal influences on the shoreline water table are on the order of 20 cm with no measurable influence on water-table elevations beyond 400 m inland from the shoreline.

Vertical movement of ground water within the watershed was determined by measuring the variation in hydraulic head with depth along the monitoring well transects. At the ground water divide and upland area of the watershed, hydraulic head decreased with depth indicative of the downward flow of ground water. Conversely, at the shoreline, hydraulic head increased with depth indicative of the upward flow of ground water. Within the midsection of the watershed, there was little variation in hydraulic head with depth and ground water flow was predominantly horizontal.

Horizontal hydraulic conductivity within the Columbia aquifer ranged from 0.01 to 6.9 m/day. Median K_h values were 3.0, 3.2, and 0.2 m/day for shallow, mid-depth, and deep wells, respectively. Shallow and mid-depth aquifer K_h values were indicative of fine to medium well-sorted sands while K_h values of the deeper aquifer

Table 1
Values of Model Parameters in Calibrated Model

Parameter	Calibration Value
Anistropic factor	
All layers	1.0
Vertical leakance (T^{-1})	
Layer 1, 2, and 3	0.01
Hydraulic conductivity (L/T)	
Layer 1	11.3 m/day
Transmissivity (L^2/T)	
Layer 2, 3, and 4	33.8 m^2/day
Storage coefficient	
Layer 1	0.15
Layer 2, 3, and 4	0.0001
Recharge (L/T)	
Layer 1	0.006535 m/day
Streambed conductance (L^2/T)	
River cells of railroad pond	465 m^2/day
All other river cells	929 m^2/day

material were characteristic of sand intermixed with finer grained sediments. A Kruskal-Wallis single factor analysis of ranks test showed that K_h values were significantly different between aquifer depth intervals ($0.002 < \alpha < 0.005$). A Tukey multiple comparison test ($\alpha < 0.05$) indicated that significant differences in K_h occurred between the shallow and deep intervals, and between the mid-depth and deep intervals. No significant differences were observed between the shallow and mid-depth intervals.

Vertical saturated hydraulic conductivity (K_v) measurements for the tidal region, lower pond, and upper pond of Eyreville Creek ranged from 0.01 m/day to 2.42 m/day. A mix of sand and silt-clay sediments characterized the tidal region. Substrates within the nontidal ponds displayed high levels of compacted, fibrous, organic material.

Calibration of the Ground Water Model

The ground water flow model was calibrated with a trial-and-error iterative calibration process to transient conditions measured in the Columbia aquifer from November 1995 through February 1997. Calibration of the model was achieved by matching predicted heads with observed heads. Base flow measurements from the ponds were limited and, therefore, were used only as a check on the calibration process. Initial estimates of horizontal hydraulic conductivity (layer 1), transmissivity (layers 2, 3, and 4), vertical leakance (layers 1, 2, and 3), streambed conductance, recharge, and storage coefficient were based on values either from field measurement or previously published studies conducted in the watershed. Values for the initial head conditions were generated through an initial steady-state simulation of the ground water system. A sensitivity analysis was performed to determine the uncertainty in the calibrated model due to possible errors in the estimates of the model parameters.

Specifying streambed conductance required both the streambed thickness and the vertical hydraulic conductivity of the streambed material. Although cores of the streambed material were collected and tested, there was significant uncertainty in the values for both streambed thickness and hydraulic conductivity. Streambed con-

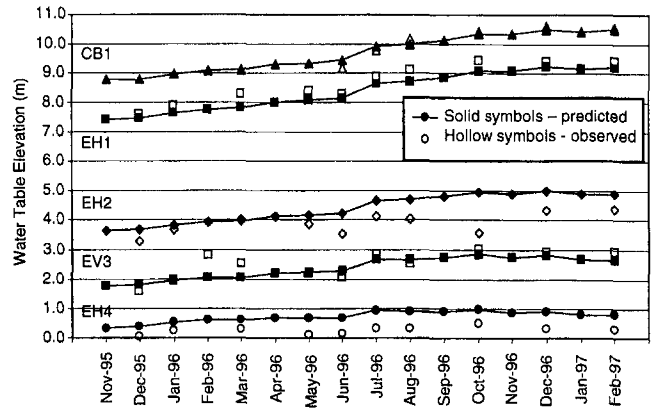

Figure 3. Comparison of observed (solid symbols) and predicted (hollow symbols) water-table elevations for selected monitoring wells—CB1, EH1, EH2, EV3, EH4.

ductance was, therefore, adjusted during the calibration procedure. The three-dimensional ground water system was modeled as a homogeneous, anisotropic system with both horizontal hydraulic conductivities (K_x and K_y) equal but not equal to the vertical hydraulic conductivity (K_z). Refinement of the hydraulic conductivity values within selected zones of the model grid was not used for the final calibration as the homogeneous values resulted in an acceptable calibration.

Relatively few estimates of ground water recharge to surficial aquifers of the Delmarva Peninsula are available. Reported rates of recharge range from 22 to 33 cm/year (8.5 to 13 in/year (Rasmussen and Andreasen 1959; Johnston 1976; Cushing et al. 1973). For model calibration, 74 cm (29 in) of the 197 cm (78 in) of precipitation was assumed to recharge the surficial aquifer. This percentage (37.9%) of the precipitation was greater than recharge estimates by Cushing et al. (1973) (20%; 10-year study) for the Delmarva Peninsula and Rasmussen and Andreasen (1959) (28%; two-year study) for Beaverdam Creek Basin in Maryland's coastal plain. Johnston (1976), from a 10-year study, reported that 38% to 40% of the rainfall recharged the surficial aquifer in Delaware's coastal plain. Recharge was assumed to be uniformly distributed throughout the watershed. The July 1996 recharge percentage was reduced because unusually high precipitation occurred from several intense rainfall periods that would result in a relatively higher percent of surface water runoff.

Final parameter values for the calibrated model are given in Table 1. Although the calibrated hydraulic conductivity value, 11.3 m/day, was higher than the median values measured in the field, 3.0 m/day and 3.2 m/day, predicted flow rates from the ponds were in agreement with measured flow rates (data not shown), thus supporting the argument that both the hydraulic conductivity and recharge values were reasonable estimates. The R-squared linear correlation coefficient was 0.96 (n = 131) between observed and predicted heads. Observed and predicted water-table elevations at selected monitoring wells are shown in Figure 3. Predicted water- table elevations agreed reasonably well with observed water-table elevations. In contrast to normally observed seasonal trends in water-table elevations, water-table elevations within the upland regions of the watershed (stations EV-1, EV-2, EH-1, EH-2, CR-1, CR-2, CB-1, CB-2, and CB-3) increased continuously during the first 14 months of the study period. A decrease in water-table elevations was observed in the last two months of the study period. In the humid, eastern United States the effects of evapotranspiration generally end in October and

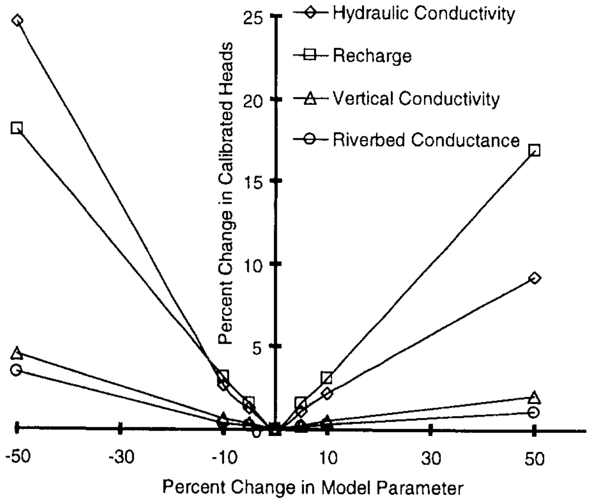

Figure 4. Plot of sensitivity-analysis results for calibrated model testing hydraulic conductivity, recharge, vertical conductivity, and riverbed conductance.

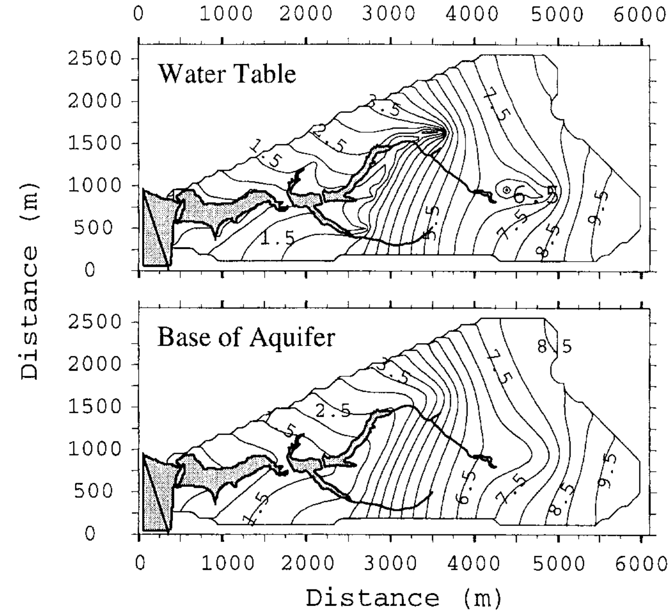

Figure 5. Contours of predicted heads at the water table and base of the aquifer. Contours are given in meters above mean sea level.

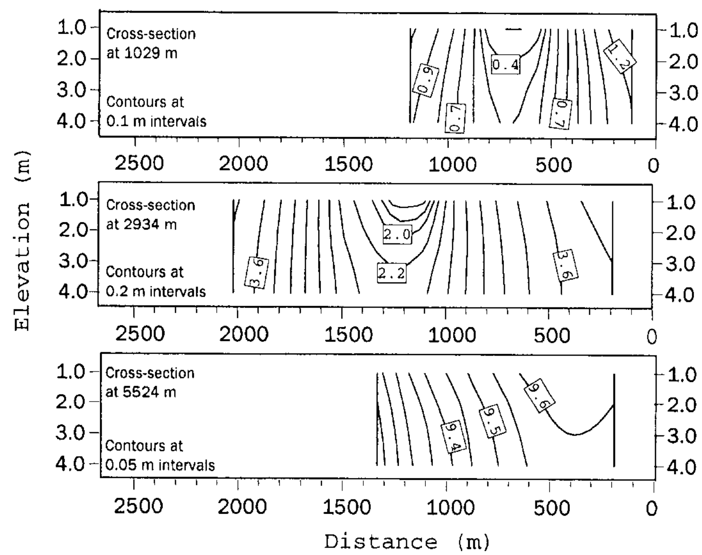

Figure 6. North-south cross-sectional contours of predicted heads in Eyreville Creek watershed. The location of the cross-sectional plots are from top to bottom 1029, 2934, and 5524 m (Figure 2). Contours are given in meters above mean sea level.

signal the beginning of the period of ground water recharge. This yields elevated water tables in the late winter/early spring recharge periods and low water-table elevations in the late fall. Deviation from this general seasonal pattern can be explained, in part, by rainfall patterns during the study. In July 1996, a period normally associated with soil moisture deficits, 36.6 cm (14.4 inches) of rain from Hurricane Bertha fell on the Eastern Shore. This resulted in recharge to the local ground water system and subsequent rise in water-table elevation prior to the normal recharge period.

For the sensitivity analysis of the calibrated model, the calibrated values of hydraulic conductivity, vertical conductivity, recharge rate, and streambed conductance were varied, and the average of the absolute percent change of the predicted heads at the 15 monitoring well stations was calculated (Figure 4). A less than 5% change in the calibrated heads was noted when vertical conductivity or streambed conductance were increased/decreased by 50%. Hydraulic conductivity and recharge rate were the most sensitive parameters in the model, with maximum changes in the calibrated heads of 25% and 18% respectively, for a 50% change in parameter value. Recharge and hydraulic conductivity are interrelated parameters with respect to hydraulic head but are not related with respect to discharge to streams. Therefore, the limited discharge data from the ponds in the watershed provided an independent check on the calibrated recharge and hydraulic conductivity values.

Discussion of Model Results

The flow of ground water toward Eyreville Creek is indicated by the general pattern of the hydraulic head contours at the water table (layer 1) and base (layer 4) of the aquifer (Figure 5). A prominent feature in Figure 5 is the V-shaped deflection of the equipotential contours along the length of the creek. The V-shaped deflection results from the depression of the water table at the stream channel. Higher discharge rates occur where the contours exhibit maximum deflection toward the headwaters of the creek. Modica et al. (1997) developed similarly shaped equipotential contours, but because the hypothetical aquifer was much thicker, the deflections were a less prominent feature of the ground water system. Cherkauer and McKereghan (1991), investigating ground water discharge patterns to lakes, also reported the convergence of equipotential lines and elevated discharge rates along lake embayments. This amplification of ground water discharge was controlled by a bays penetration into the ground water system and was not a function of shore length. Cross-sectional contour plots of hydraulic head (Figure 6), show the vertical variation in head along an east-west transect, perpendicular to Eyreville Creek at 1029, 2934, and 5524 m along the creek (see Figure 2 for location of the transects). Vertical ground water flow is indicated by the curvature of the equipotential lines. Typical horizontal ground water velocities for the Columbia aquifer on the Delmarva Peninsula are reported to vary between 0.01 to 0.60 m/day (Hamilton and Shedlock 1992; Reay et al. 1993; Gallagher et al. 1996) while model-predicted ground water velocities varied between < 0.01 to 0.24 m/day. The elevated predicted ground water velocities are associated with discharge regions and areas of convergence along Eyreville Creek.

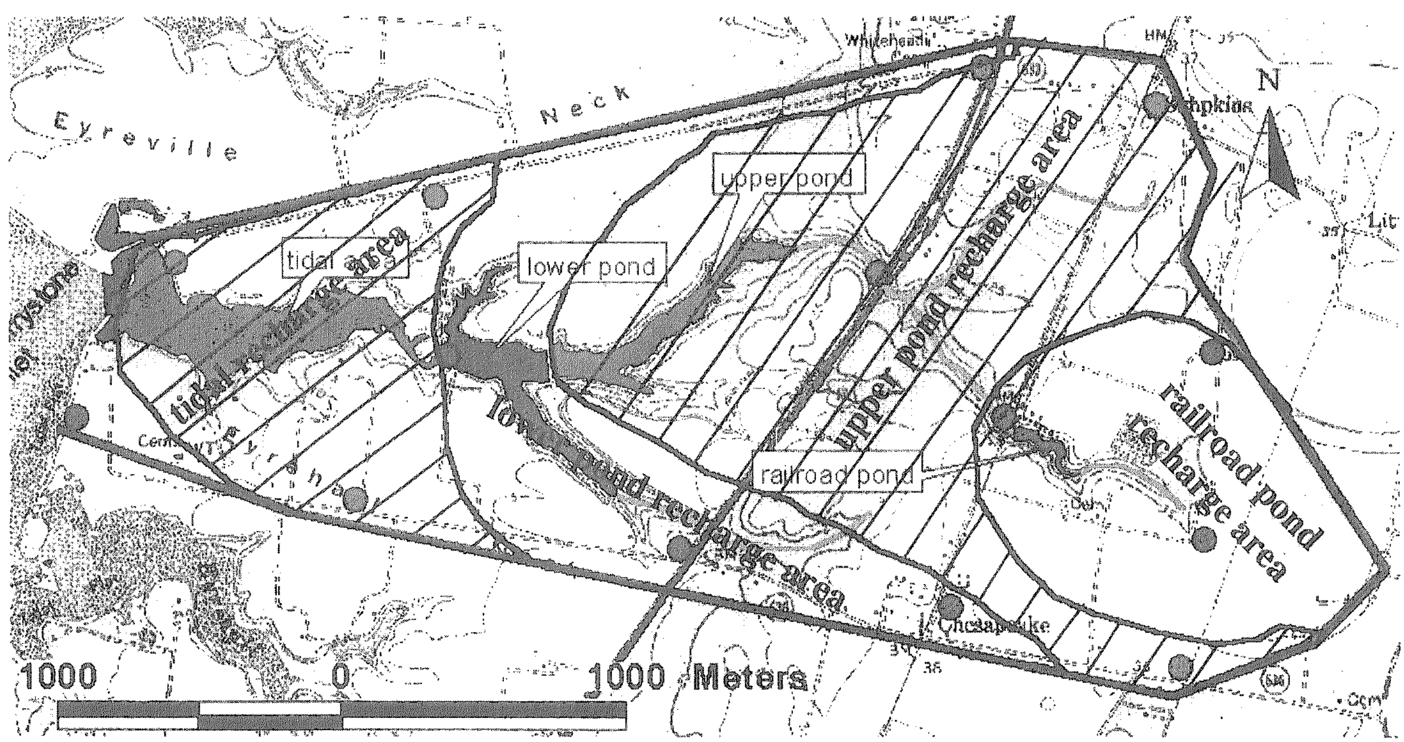

Figure 7. Recharge zones in Eyreville Creek watershed.

Table 2
Agricultural Land Use Within Ponds of Eyreville Creek

	Percent of Total Watershed Area	Percent of Agricultural Land Use in Recharge Area	Percent of Total Agricultural Land Use in Watershed
Railroad pond	18.1	71.1	24.6
Upper pond	46.5	45.0	39.9
Lower pond	17.4	58.8	19.5
Tidal pond	16.3	51.5	16.0

Recharge zones for the four dominant features of Eyreville Creek, the three impoundments and the tidal inlet, are shown in Figure 7. Percent of recharge source area by surface water feature are presented in Table 2. The shallow aquifer depth precluded the development of a significant regional ground water system. In investigating the relationship between aquifer thickness and the development of regional ground water systems, Modica et al. (1997) showed that, with decreasing aquifer thickness, the stream recharge zone occupies an increasing larger fraction of the watershed, thereby reducing the land area available to provide recharge to a regional ground water system. A relatively small recharge area immediately adjacent to Cherrystone Inlet provided direct discharge to the inlet and minor recharge areas along the boundaries of the watershed contribute to the regional ground water system.

Ground water residence times, the advective travel time from the recharge zone to the discharge zone within Eyreville Creek, are shown in Figure 8. Average residence time by surface water feature is presented in Table 3. The average residence time of a surface water feature was calculated as the mean of the residence times for all cells within the recharge zone of that surface water feature. Residence times ranged to greater than 100 years with residence times greater than 50 years located on the boundaries of the watershed. The distribution of residence times within the watershed is shown in Figure 9. Greater than 90% of the watershed had residence times less than 50 years, while the average residence time of ground water within Eyreville Creek watershed was 21 years. Previously reported values of ground water residence time in the Columbia aquifer are on the order of decades. For the Columbia aquifer on Virginia's Eastern Shore, Speiran et al. (1998) reported the age of ground water at discharge zones to vary from zero to 53 years. Dunkle et al. (1993), using chlorofluorocarbon as a dating tool, reported ground water ages dating to recharge years from older than 1940 to modern in surficial aquifers of the Delmarva Peninsula.

Although maximum residence times represent the time required to flush the entire ground water system, average residence times provide a convenient measurement to compare recharge zones within the watershed (Table 3). Average ground water residence times varied between 16 and 21 years for the four surface water recharge zones. The lower pond recharge zone had the shortest average ground water residence time, 16 years. The residence time for ground water originating from agricultural land within the lower pond ground water recharge zone was slightly greater at 17 years. Because agricultural land tends to be in the upland regions away from the surface water, ground water residence times calculated from agricultural land will be greater than the average residence times for the entire recharge zone.

Implications for Land-Use Management

Management efforts to protect ground water and surface water from excess nitrogen loadings must consider both land-use activities and landscape processes. Due to the relatively high percentage of agricultural land use, shallow water-table depths, low topographic relief, and permeable sandy aquifer material, and the high degree of stream incision, unconfined aquifer nitrogen contamination potential and subsequent transport to surface water is high in well-drained outer coastal plain watersheds. Ground water–dissolved inorganic nitrogen levels up to 67.1 mg/L have been reported within the

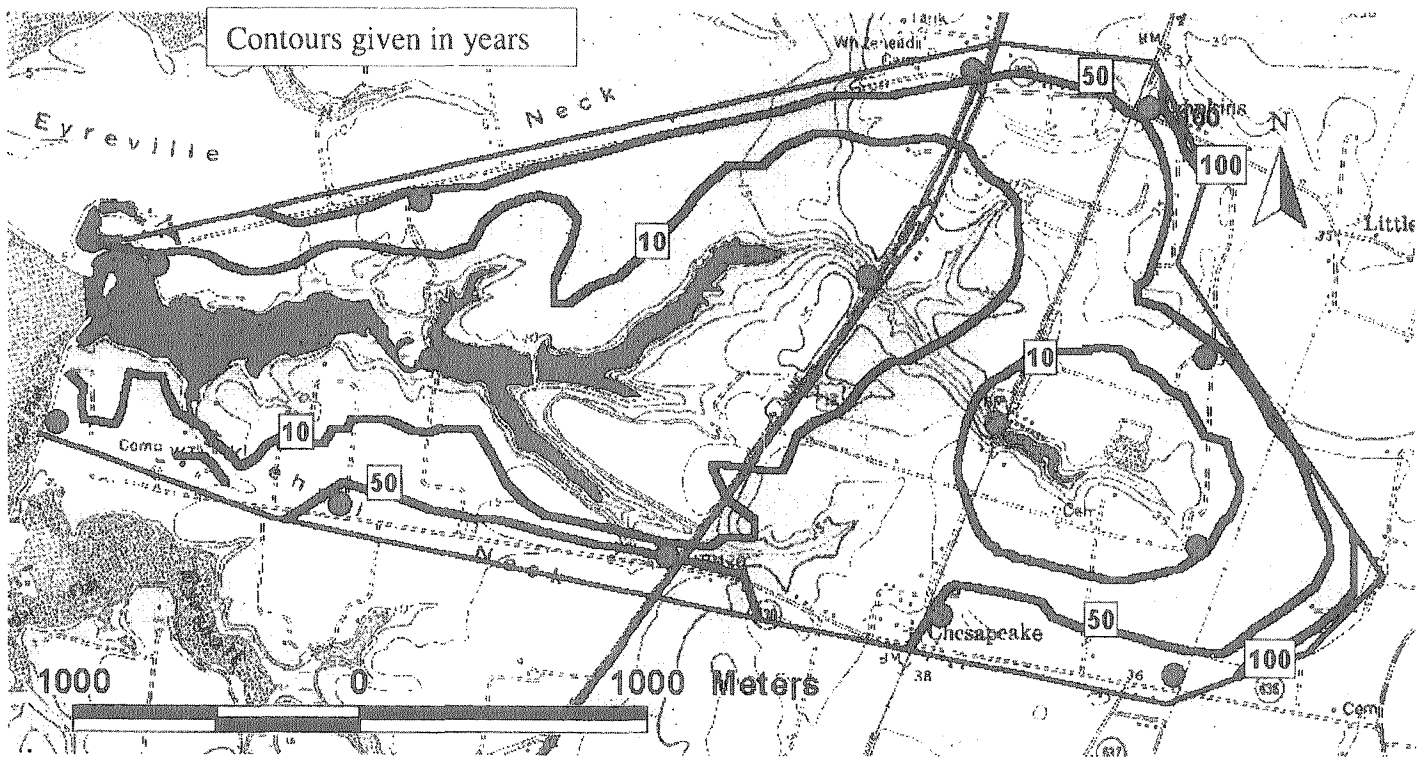

Figure 8. Ground water residence times (in years) within Eyreville Creek watershed.

Table 3 Ground Water Residence Times for Ponds of Eyreville Creek		
	Average Residence Time (in years)	Average Residence Time from Agricultural Land Use (in years)
Railroad pond	17	17
Upper pond	21	24
Lower pond	16	16
Tidal pond	17	22

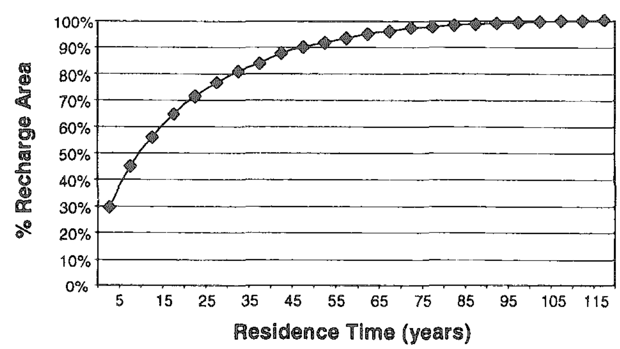

Figure 9. Distribution of ground water residence times (in years) in Eyreville Creek watershed.

Eyreville Creek watershed (Robinson and Reay 1999). Shallow ground water quality within the Cherrystone Inlet watershed has been shown to reflect land-use activity. Reported mean dissolved nitrogen concentrations underlying agricultural, developed, and forested lands are 7.1, 4.7, and 0.8 mg/L, respectively (Reay 1996). With respect to first-order stream water quality, Reay et al. (1992) reported a mean DIN level of 2.3 mg/L for the multiple stream headwaters of Cherrystone Inlet. Water discharging from the uppermost pond (Railroad pond) on Eyreville Creek exhibited a mean DIN level of 3.7 mg/L (Reay, in review).

Reduction of nitrogen in ground water can occur through several processes; these include the reduction of land-applied nitrogen, the reduction of leached nitrogen from the vadose zone, the reduction of nitrogen along the upland saturated flowpath, and the reduction of nitrogen prior to its discharge into surface water. Management considerations regarding nitrogen contamination of ground water from agricultural croplands include the timing and amount of fertilizer, placement of fertilizer within the crop-soil system, crop sequences and cover crops, and timing and amount of irrigation (Hubbard and Sheridan 1989). Once nitrogen leaches below the root zone, nitrogen storage (i.e., biological immobilization, soil binding via cation exchange) and removal processes (microbial denitrification) are dependent on subsoil and aquifer substrate characteristics, microbial populations, energy sources, and environmental conditions. Nitrate has been shown to persist due to relatively high dissolved-oxygen levels, the lack of carbon substrate, and the limited microbial denitrifier populations in well-drained soils of the Delmarva Peninsula (Parkin and Meisinger 1989; Smedley 1993). Likewise, nitrogen storage and removal is limited in the shallow unconfined aquifer underlying these soils. Within deeper portions of the unconfined aquifer, limited oxygen supply in conjunction with longer residence times may result in significant microbial reduction of nitrate (Dunkle et al. 1993). Finally, interception and reduction of nitrogen associated with subsurface drainage can occur within regions of ground water discharge. Ground water discharge zones are commonly associated with riparian areas, wetlands, streams and ponds, and nearshore sediments. Biological processes within these regions may be more conducive to microbial denitrification and plant uptake (Seitzinger et al. 1980; Kaspar 1982; Peterjohn and Correll 1984; Fail et al. 1986; Davidson and Swank 1986; Hanson et al. 1994; Seitzinger 1994).

By coupling regions of recharge and discharge, ground water flowpath analysis can be used to provide a hydrologic relationship between land use and surface water or shoreline nitrogen loadings. Management efforts can be targeted to specific regions of a watershed based on land use within specific recharge areas and associated discharge areas where contaminant loading reductions are desired. The percent agricultural land use within each of the local recharge zones is given in Table 2. The railroad pond has the smallest recharge area, 18% of the total watershed area, but the largest fraction of agricultural land (71%) within its recharge area. Conversely, the upper pond has the largest recharge area, 47% of the total watershed, but the smallest fraction of agricultural land (45%) within its recharge area. Because of the size of its recharge area, however, the upper pond receives the largest fraction of recharge from agricultural lands (40%) within the watershed. Therefore, assuming uniform water-table nitrogen loadings and no reduction of nitrogen along the upland saturated flowpath, ground water discharged into the railroad pond would have the highest nitrogen concentrations in the watershed. However, ground water discharged into the upper pond would result in the highest nitrogen loading rates in the watershed. Based on the previous assumptions, a near-stream best management practice (BMP) that intercepted all ground water discharge placed at the railroad pond would improve the worst water quality in the watershed, while a similar BMP placed at the upper pond would maximize the total nitrogen removal from the watershed.

Estimates of ground water residence times can be used to predict a time frame in which one can expect to see improvements in surface water quality based on reductions of nitrogen input to the watershed. Ninety percent of the ground water resource in Eyreville Creek watershed reflect land-use activities of the last 50 years. It should be noted that accelerated use of inorganic nitrogen fertilizer began in the 1940s; fertilizer sales data indicate that the sharp increase in national fertilizer sales stopped in the early 1980s with sales being relatively stable since then (Hargett and Barry 1985). BMPs based on management considerations (timing and amount of fertilizer, placement of fertilizer within the crop-soil system, crop sequences and cover crops, and timing and amount of irrigation) will begin to yield a reduction in surface water nitrogen loadings only after the minimum residence time of the applicable land area has passed, while the ultimate performance of the BMP cannot be evaluated until the maximum residence time has passed. In addition, results of ground water flow analysis can also be coupled to basic kinetic equations for specific solutes to estimate contaminant attenuation and transport within the aquifer. In summary, ground water flowpath analysis is an important tool to increase our understanding of shallow Chesapeake Bay coastal plain ground water systems and can aid in the implementation of management practices to reduce nitrogen loading to surface water resources. Ground water flow patterns indicated the convergence of flow along the four surface water features of the watershed with minimal development of a regional ground water system. Model-predicted ground water velocities varied between < 0.01 to 0.24 m/day, resulting in average ground water residence times on the order of 17 to 21 years. Approximately 95% of the ground water resource would reflect land-use activities within the last 50 years.

Acknowledgments

The authors thank Roger Byrne, Furlong Baldwin, D.W. Peacock, C. Turner, and the Eastern Shore Railroad for access to their property. This work was supported by the Virginia Division of Soil and Water Conservation through a grant from the Environmental Protection Agency, Chesapeake Bay Program. This publication represents Contribution No. 2341 of the Virginia Institute of Marine Science, College of William and Mary.

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