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Ground-Water Quality and Discharge to Chincoteague and Sinepuxent Bays Adjacent to Assateague Island National Seashore, Maryland

by Jonathan J.A. Dillow, William S.L. Banks, and Michael J. Smigaj

Water-Resources Investigations Report 02-4029

In cooperation with the
National Park Service
Assateague Island National Seashore

Baltimore, Maryland
2002

U.S. Department of the Interior
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CONVERSION FACTORS, ABBREVIATIONS, AND VERTICAL DATUM

Multiply	By	To obtain
inch per year (in/yr)	2.54	centimeter per year
foot (ft)	0.3048	meter
foot per foot (ft/ft)	1	meter per meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8$$

Vertical datum: In this report, ìsea levelî refers to the National Geodetic Vertical Datum of 1929ó a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

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Abstract

The U.S. Geological Survey, in cooperation with the National Park Serviceó Assateague Island National Seashore, conducted a study of the transport of nutrients in ground water in the surficial aquifer to estuaries adjacent to Assateague Island National Seashore. The study area includes Assateague Island, Chincoteague and Sinepuxent Bays, and the surface-water drainage basins of the bays. The purpose of the study was to describe ground-water-flow paths that carry freshwater to Chincoteague and Sinepuxent Bays and their tributary streams, and to collect water-quality data, particularly nutrient concentrations, associated with these freshwater inputs.

Twenty-eight ground-water monitoring wells were drilled and constructed in the surficial aquifer and underlying confining bed within the study area to collect water-level and water-quality data at various depths. Base flow was measured and water-quality samples were collected at 17 nontidal streams within the study area during the winters of 1999 and 2000 to determine the nutrient concentrations being transported to the coastal bays from each stream.

Ground-water-flow paths in the surficial aquifer are highly variable in length, ranging from less than 500 feet to longer than 5 miles. Many of the shorter flow paths end by discharging ground water as base flow to both the nontidal and tidal sections of streams, whereas longer flow paths end by discharging ground water directly to Chincoteague Bay or the Atlantic Ocean. Travel-times inferred from sulfur hexafluoride gas analyses for ground water following shorter flow paths before discharging to a stream range from less than 1 year to as long as 5 years. Ground water flowing along longer flow paths may take 30 years or more to reach the discharge point at the end of the flow path.

Dissolved ammonia and dissolved nitrate are the dominant nutrients in ground water in the study area. Ammonia concentrations as high as 23.4 milligrams per liter as nitrogen were detected in anoxic ground-water samples. Nitrate concentrations in ground-water samples collected from wells ranged from below 0.05 milligram per liter as nitrogen to 15.5 milligrams per liter as nitrogen, and were highest in oxic ground water. Ammonia is less mobile in ground water than nitrate, so if it remains in the reduced state, transport to the discharge zones would be slower.

Nitrate concentrations in samples of stream base flow ranged from below 0.05 milligram per liter as nitrogen to 5.28 milligrams per liter as nitrogen, and showed a significant, positive correlation with the percentage of the stream basin area used to cultivate row crops. The majority of base-flow nitrate concentrations were above 0.4 milligram per liter as nitrogen, the upper limit of the level found in natural waters in the study area, which indicates that the water quality of stream base flow at most sampled stream sites in the study area is affected by anthropogenic activi-

ties. Previous U.S. Geological Survey estimates of ground-water nitrate loads to Chincoteague and Sinepuxent Bays assumed an average stream base-flow nitrate concentration of 0.72 milligram per liter as nitrogen. The average stream base-flow nitrate concentration in samples collected during this study was 1.75 milligrams per liter as nitrogen. In addition, the presence of ammonia and organic nitrogen in stream base-flow samples may have implications for the eutrophication of the coastal bays, as these nitrogen species are available as nutrients to microorganisms and plants.

INTRODUCTION

Assateague Island National Seashore (ASIS) is a National Park located on Assateague Island, a barrier island in Worcester County, Maryland (fig. 1). The Park, established in 1965, is managed by the National Park Service (NPS). It is composed of the Maryland part of Assateague Island except for a small area, Assateague State Park, which is operated by the State of Maryland. Assateague Island is bordered by the Atlantic Ocean to the east and Chincoteague and Sinepuxent Bays to the west; the National Park boundaries extend into each of the adjacent water bodies (fig. 2).

The mission established for ASIS by Congress includes preserving and protecting the natural resources of Assateague Island in Maryland. The NPS cooperates with other Federal, State, and local agencies, as well as local citizens, to understand and manage factors and mechanisms affecting the natural resources of ASIS, both within and outside the National Park boundaries (fig. 2). This study, conducted by the U.S. Geological Survey (USGS) in cooperation with the NPS at ASIS, concerns the transport of nutrients in ground water in the surficial aquifer to estuaries adjacent to Assateague Island.

Background

The delivery of nutrients generated by anthropogenic activities, such as row-crop agriculture, septic system use, and golf course maintenance, to the estuaries of the Mid-Atlantic Coastal Plain is a regional natural resource management problem because of the

Figure 1. Location of Delmarva Peninsula, Assateague Island, and Chincoteague and Sinepuxent Bays in Worcester County, Maryland.

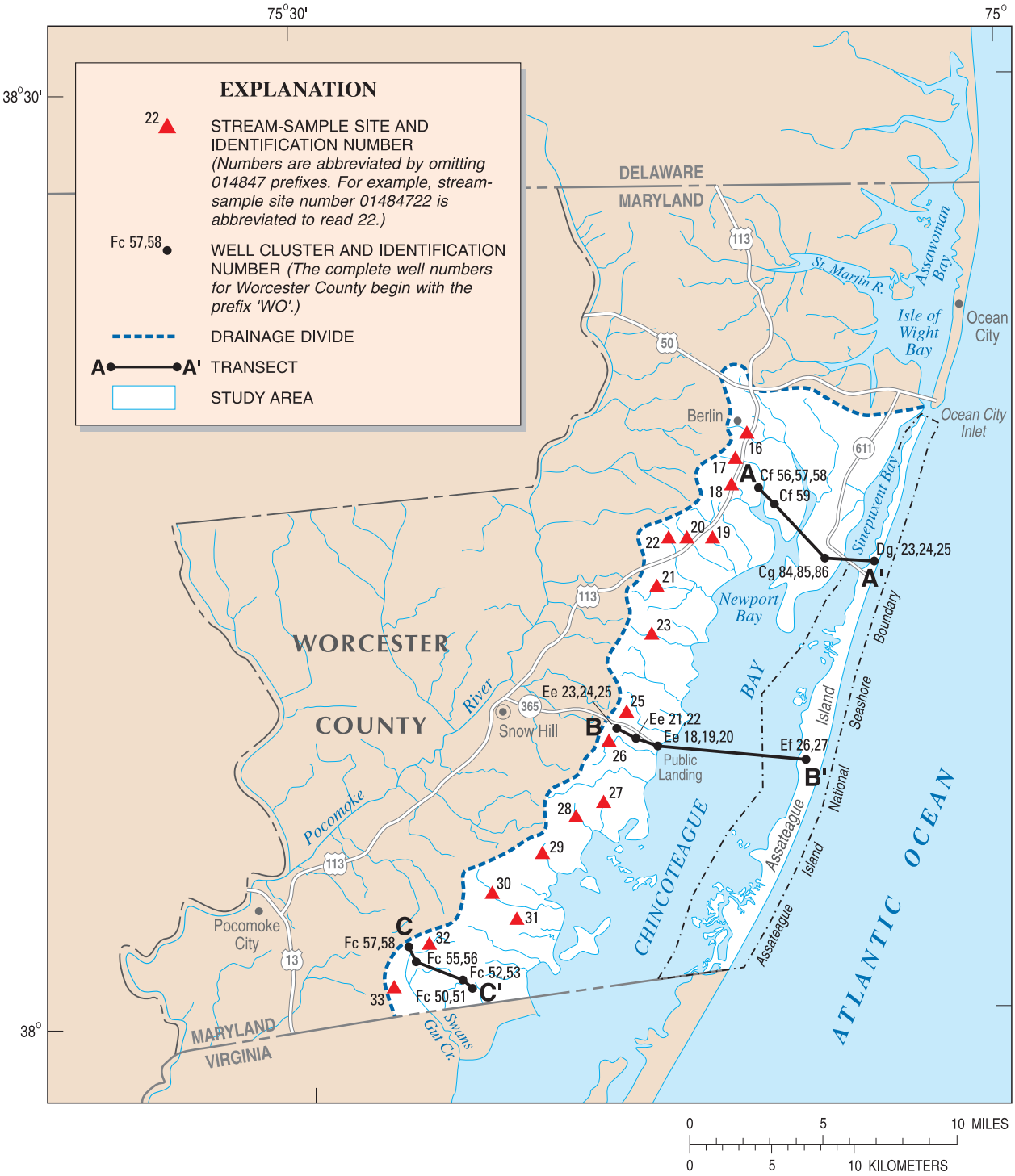


Figure 2. Location of wells, transects, stream-sample sites, Assateague Island National Seashore boundary, and drainage divide in the study area, Worcester County, Maryland.

potential for adverse effects on estuarine ecosystems. The introduction of nutrients in amounts that are in excess of natural levels in the environment may lead to increased growth of phytoplankton, as well as epiphytic algae. Excessive amounts of phytoplankton and algae can harm estuarine ecosystems directly by blocking sunlight to seagrasses, and indirectly by removing dissolved oxygen from the water when dead phytoplankton and algae decompose (Maryland Coastal Bays Program, 1997). These effects, which are part of the eutrophication process, degrade water quality and stress biotic communities. Recent surveys of the biotic resources of the coastal bays behind Assateague barrier island in Maryland and Virginia have documented measurable stress to the ecosystem and changes in community structure (Chaillou and others, 1996).

Previous studies, including Andres (1987, 1992), Richardson (1994), Speiran (1996), and Speiran and others (1998) analyzed ground-water flow and nutrient transport in physical settings similar to the study area (fig. 2). Various other studies have documented levels of nutrients above background levels in ground water throughout the Delmarva Peninsula (Bachman, 1984; Denver, 1986, 1989; Shedlock and others, 1999; Dillow and Greene, 1999). These studies showed that nutrient concentrations in excess of those found in natural environments can be found at all depths in the surficial aquifer.

Ground-water discharge of nitrate accounts for a major part of the total nitrogen load to Chincoteague and Sinepuxent Bays (Dillow and Greene, 1999). Ground water from the surficial aquifer discharges to nontidal streams, tidal tributaries, and directly through the bed sediments of the bays, transporting nutrients originating from nonpoint sources within the coastal bays watershed. The distribution of nutrients in source areas, ground-water-flow paths, and the subsurface geochemical environment, as well as the areal distribution of the nutrient load in the estuaries, currently are not well understood.

The NPS performs ongoing monitoring programs within the ASIS boundary to assess water quality in Chincoteague and Sinepuxent Bays. The information on the condition of the estuarine environment provided by these programs is valuable. However, a more comprehensive assessment of nutrient transport, concentrations, and effects in the bay watersheds, including a study of nutrient source areas, is required to formulate a resource management plan that will protect against the delivery of excessive amounts of nutrients to the affected estuaries. An effective assessment should include water-quality and ground-water-flow information from all parts of the watershed that contribute flow to the coastal bays, as well as from the bays themselves.

Purpose and Scope

This report presents the results of a joint study between the NPS at ASIS and the USGS to investigate ground-water nutrient contributions to Chincoteague and Sinepuxent Bays. The study area covers approximately 193 mi^2 (square miles) and consists of Chincoteague, Newport, and Sinepuxent Bays, their combined watersheds, and Assateague barrier island (fig. 2). The bays and other major water bodies account for approximately 90 mi^2 of the total study area.

Ground water flowing into the coastal bays enters either through the bay-bed sediments as direct discharge, or at the shoreline as stream base flow. Data collection was designed to identify ground-water-flow paths that carry freshwater to Chincoteague and Sinepuxent Bays and their tributary streams, and to analyze nutrient concentrations associated with these freshwater inputs.

Data from 28 ground-water monitoring wells and 17 nontidal stream base-flow measurement sites were used to characterize ground-water-flow paths in the study area and ground-water nutrient contributions to Chincoteague and Sinepuxent Bays (fig. 2). The 28 monitoring wells were drilled and constructed in the surficial aquifer and the underlying confining bed in 12 clusters within the study area to collect water-level data and water-quality data at various depths. Water samples also were collected from the wells for age-dating analysis to define flow-path lengths. Water-quality samples were collected from all 17 nontidal stream base-flow measurement sites when streamflows were measured to define the concentrations and amounts of nutrients being contributed to the coastal bays by base flow at each stream site.

Description of Study Area

The study area is on the southeastern Delmarva Peninsula, along the Maryland coast of the Atlantic Ocean (fig. 1). The study area includes the parts of

Assateague Island and Chincoteague Bay that are in Maryland, as well as Sinepuxent Bay, and the watersheds of each of the bays. The part of the Maryland Coastal Bays watershed that contributes to Chincoteague and Sinepuxent Bays covers approximately 103 mi^2. The area is characterized by low topographic relief with altitudes ranging from sea level to about 40 ft (feet) above sea level.

The climate of the study area is temperate. Average temperatures range from about 36 °F (degrees Fahrenheit) in the winter to about 78 °F in the summer. Rain and snowfall vary seasonally and average about 45 in/yr (inches per year) (National Oceanic and Atmospheric Administration, 1977).

The study area is mostly rural, with Berlin, Maryland (population 2,600) being the largest municipality. During the summer months, the population in Ocean City, Maryland, just north of the study area in figure 2, can increase to more than 300,000 people. Rural residents in the study area are dependent on septic systems for sewage disposal.

Acknowledgments

The authors thank Carl Zimmerman and the staff of the Natural Resource Management Division of the National Park Service at Assateague Island National Seashore for their assistance in providing access to remote parts of the study area within the Park, and in carrying out the water-quality sampling associated with the study. The authors also thank Roger Starsoneck of the U.S. Geological Survey for his work in planning and installing the well network used in the study.

HYDROGEOLOGIC SETTING

The study area is underlain by a sequence of unconsolidated sediments in the Atlantic Coastal Plain Physiographic Province. The sediments form a wedge of unconsolidated sands, silts, and clays that is over 7,000 ft thick and range in age from Cretaceous to Tertiary. These sediments compose the regional confined aquifer system in the Atlantic Coastal Plain (Owens and Denny, 1979). In the study area, the confined aquifer system is overlain by younger sediments ranging in age from Tertiary to Quaternary. These sediments were deposited in a variety of environments including alluvial, tidal marsh, back barrier, and marine marginal, and form an unconfined, surficial aquifer.

In the Maryland Coastal Bays watershed, the surficial aquifer is unconfined because the uppermost layers have a direct hydrologic connection with the land surface that is unimpeded by intervening layers of low-permeability material. The saturated thickness of the surficial aquifer ranges from less than 40 ft in the southern part of the study area to more than 120 ft in the northern part of the study area (Owens and Denny, 1978). The lower boundary of the surficial aquifer within the study area is defined by its contact with the uppermost bed in the confined aquifer system. In 1989, the uppermost confined bed was defined as belonging to the Eastover Formation in all but the southernmost part of the study area, where the Yorktown Formation is present (Ward and Powars, 1989).

The Beaverdam Sand and the Sinepuxent Formation compose the majority of the surficial aquifer in the study area. Where present, the Beaverdam Sand generally is overlain by the Omar, Sinepuxent, and (or) Ironshire Formations of the Pleistocene Epoch (fig. 3). The Omar Formation consists of clayey silts and poorly sorted sands, whereas the Sinepuxent Formation is a silty sand, and the Ironshire Formation is a gravelly sand (Owens and Denny, 1979).

Water levels in the surficial aquifer in the study area vary from land surface to as deep as 10 ft below land surface; however, the water table often is less than 3 ft below land surface. As a result, constructed drainage ditches are common in the study area, particularly in areas where row crops are cultivated. These ditches tend to be less than 3 ft deep and drain to larger, deeper ditches that in turn connect to natural stream channels.

Geology

The geology of southeastern Worcester County, Maryland, affects the ground-water-flow paths and nutrient concentrations that are the focus of this report. Data for the study were collected from wells in the surficial aquifer and the underlying confining bed, in southeastern Worcester County, Maryland (Hansen, 1983). The surficial aquifer is overlain by discontinuous Holocene Series deposits. The surficial aquifer is underlain by a confining bed that is underlain by the Pocomoke aquifer, the uppermost confined aquifer in the study area, and the deepest unit discussed in this report (table 1). The following paragraphs describe

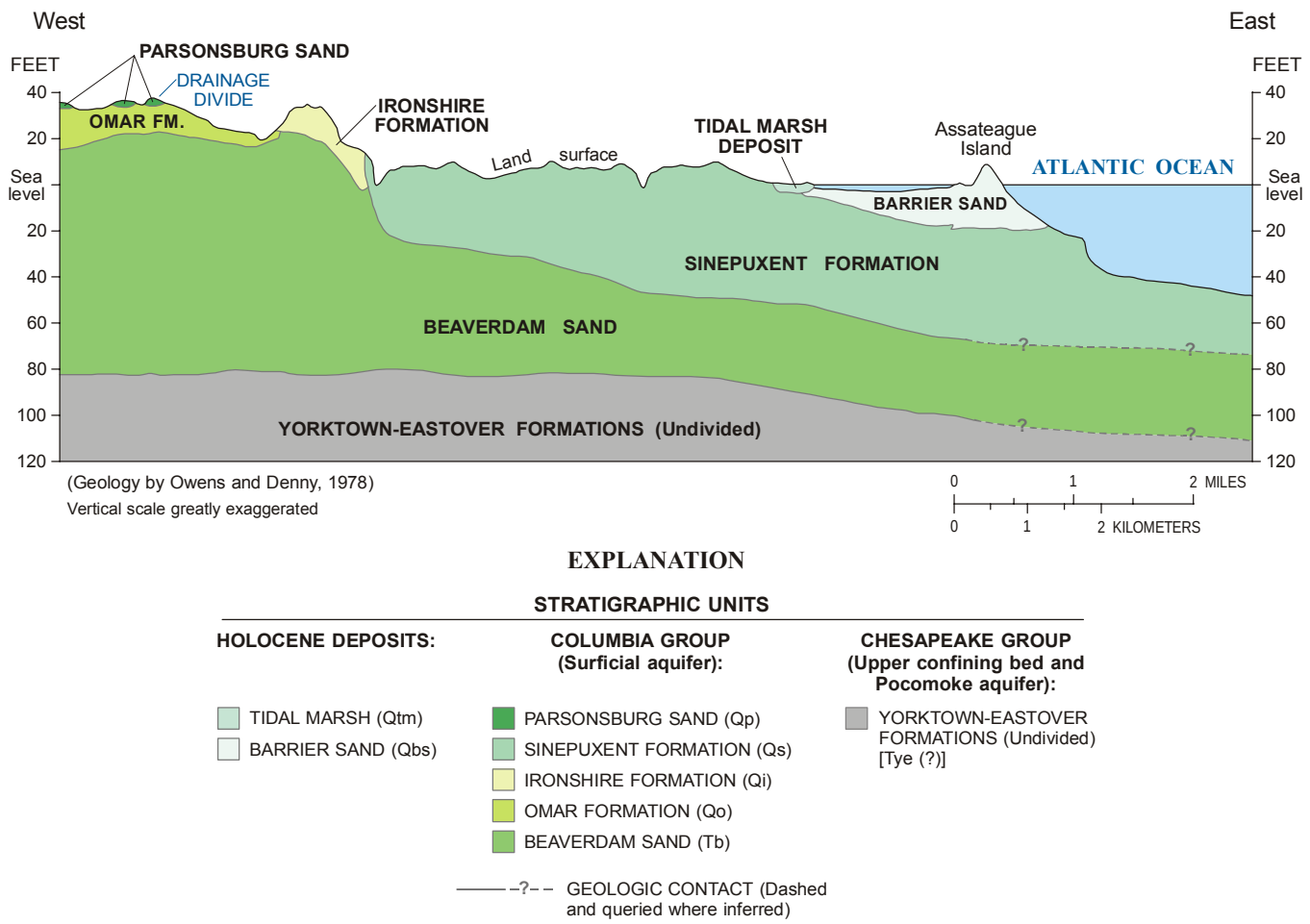


Figure 3. Geologic cross section showing the relations of stratigraphic units in the study area, Worcester County, Maryland.

the stratigraphic units that compose the surficial and Pocomoke aquifers.

Alluvium, tidal marsh, and barrier sands are all recent deposits of the Holocene Series. The alluvium deposits formed almost exclusively where streams incised the Beaverdam Sand or the Ironshire Formation. These sediments are composed of sands, gravelly sands, and swamp deposits that are up to 8 ft thick. The tidal marsh deposits consist of clay and silt that are rich in organic matter. These deposits form near estuarine environments on either the coastal bay mainland or barrier island shores and rarely are more than 10 ft thick. Barrier sands are present in long narrow deposits that form the barrier islands that parallel the coast. These sands are light-colored, moderately well-sorted, and fine- to very coarse-grained with scattered fine gravel. The barrier sands can be as much as 40 ft thick (Owens and Denny, 1978).

The Parsonsburg Sand east of the Pocomoke River forms isolated ridges bordered by lagoonal deposits of the Omar Formation (Owens and Denny, 1978, 1979). These sediments are light-colored, medium- to coarse-grained quartz sands that likely are deposited by aeolian processes. The Parsonsburg Sand can be as much as 15 ft thick, with a radiocarbon date from the late Wisconsinan Stage (Denny and others, 1979).

The Sinepuxent Formation underlies lowlands just west of Sinepuxent and Chincoteague Bays. The Sinepuxent is considered a marginal marine unit that represents a major transgressive event in the middle Wisconsinan Stage. These sediments were identified by Owens and Denny (1979) as poorly sorted, silty, fine-to-medium, light-orange, tan-to-gray sand. The underlying contact with the Beaverdam Sand is unconformable. The Sinepuxent Formation thickens as it

Table 1. *Hydrogeologic and stratigraphic units in southeastern Worcester County, Maryland*

[Modified from Rasmussen and Slaughter (1955); Weigle and Achmad (1982); Mixon (1985); and Achmad and Wilson (1993)]

Not to scale

SYSTEM	SERIES	HYDROGEOLOGIC UNIT	STRATIGRAPHIC UNIT		APPROXIMATE THICKNESS (feet)	LITHOLOGY
Quaternary	Holocene		Alluvium		0 - 8	Sands, gravelly sands, and swamp deposits
			Tidal Marsh Deposit		0 - 10	Clay and silt, rich in organic matter
			Barrier Sand		0 - 40	Light-colored, well-sorted fine- to very coarse-grained sand with gravel
	Pleistocene	Surficial aquifer	COLUMBIA GROUP	Parsonsburg Sand	0 - 15	Light-colored sands rich in organic matter
				Sinepuxent Formation	0 - 70	Poorly sorted, silty, fine-to-medium, light orange, tan to gray sand
				Ironshire Formation	0 - 25	Light-colored sand, and gravelly sand
				Omar Formation	0 - 65	Light-colored sand overlaying a dark-colored sandy clay silt or silty clay
Tertiary	Pliocene			Beaverdam Sand	60 - 90	Light-colored fine- to coarse-grained sand, with fine-grained silty sands in the upper part
	Upper Miocene	Upper confining bed	CHESAPEAKE GROUP	Yorktown-Eastover Formations (undivided)	8 - 10	Lenticular silts, clays, and fine sands
		Pocomoke aquifer			30 - 65	Gray, medium- to fine-grained shelly sand

dips to the southeast, with a maximum known thickness of 70 ft.

The Ironshire Formation, paralleling and slightly east of a prominent east-facing scarp along the Atlantic Coast, consists of a light medium- to coarse-grained sand with some gravel and a maximum thickness of 25 ft. The Ironshire Formation unconformably overlies the Beaverdam Sand and the Omar Formation at various locations. The Ironshire is a barrier-back barrier sequence of deposits, and is considered to be from the Upper Sangamon Stage (Owens and Denny, 1979).

The eastern exposure of the Omar Formation divides Worcester County, Maryland, from north to south as a topographic high that creates a natural drainage divide between the Pocomoke River and the coastal bays. The Omar consists of light-brown to yellow-tan, fine-to-medium sand interstratified with thin silty beds, with a maximum thickness of approximately 65 ft. The Middle or Upper Pleistocene Series sediments of the Accomack Member of the Omar Formation defined by Mixon (1985) in Virginia may correlate with beds encountered in the southern part of the study area. Owens and Denny (1979) place the origin of the Omar Formation sediments in the Lower Sangamon Stage according to microflora recovered in peaty beds.

The Beaverdam Sand is a light-colored, fine- to coarse-grained sand, with fine-grained silty sands in the upper part. The Beaverdam Sand unconformably overlies the upper confining bed of the Pocomoke aquifer in eastern Worcester County, Maryland. Owens and Denny (1979) determined that the Beaverdam Sand is part of the Pliocene Series on the basis of microflora contained in peat beds. In the study area,

the Beaverdam Sand has a maximum known thickness of more than 90 ft.

The Yorktown and Eastover Formations have similar lithologies that, either singularly or combined, compose the Pocomoke aquifer. Mixon (1985) identified the Yorktown Formation in Pocomoke City, Maryland, and projected that it thickens to the east, overlying the Eastover Formation in southeastern Worcester County. Achmad and Wilson (1993) showed the Eastover Formation underlying the Beaverdam Sand at Ocean City, Maryland, and farther south at Assateague Island, with the upper sands of the Eastover identified as part of the Pocomoke aquifer. In this report, the beds below the Beaverdam Sand and Omar Formation are referred to as the Yorktown-Eastover Formations (undivided).

The Pocomoke aquifer was defined by Hansen (1981) as the first confined sand below the Columbia Group. It consists predominantly of gray, medium- to fine-grained shelly sand, and is an important local water source. A thin (8- to 10-ft) upper confining bed, the upper aquiclude presented in Rasmussen and Slaughter (1955), composed of lenticular silts, clays, and fine sands, overlies the Pocomoke aquifer, separating it from the surficial aquifer. The Pocomoke aquifer consists partially of the lower, shelly sands of the Yorktown Formation of early Pliocene Series, and the uppermost sands of the Eastover Formation of late Miocene Series, and can be as much as 65 ft thick in the study area.

Bay-Bed Sediments

Detailed knowledge of the morphologic structure and composition of the surficial sediments underlying the coastal bays generally is limited. This limitation is particularly true of Chincoteague Bay, which ranges from 3 to 6 mi (miles) wide. Some information on the probable history of sediment deposition and distribution beneath the coastal bays in the study area is available, however.

Halsey (1978) offered a description of how the modern Assateague barrier island was formed, and how it developed in terms of geology and morphology. A more detailed explanation of the development of the barrier-back barrier system, including proposed locations of major paleochannels underlying the modern coastal bays, was presented in Halsey (1979). These publications indicate that there may be a number of filled paleochannels beneath Chincoteague Bay that could have an appreciable effect on the flow paths and discharge locations of ground water in the surficial aquifer. An infilled paleochannel may act as a flow conduit or a flow barrier depending on whether the infilling material is finer or coarser than the sediment in which the channel originally was incised.

Additional data and interpretation of the composition of the near-surface bay-bed sediments were compiled by Wells (2001). These data describe the top 3 to 7 ft of bay-bed sediments with regard to grain-size distribution. Whereas the western half of the bed of Chincoteague Bay consists of predominantly silty sediments, sediment samples from the eastern half of the bay overwhelmingly are characterized as sand (fig. 4).

Information obtained from a limited bay-bed coring effort by USGS in Chincoteague Bay indicates that near the western shore of the bay, the first 5 to 10 ft of the bay-bed sediments are silt and clay (D.E. Krantz, U.S. Geological Survey, written commun., 2000). This description is consistent with the data obtained by Wells (2001).

Hydrology

The surficial aquifer is under water-table conditions, with the water table generally between 0 and 10 ft bls (below land surface). The lesser water-table depths usually occur in low-lying areas, whereas greater water-table depths are evident in areas of locally large topographic relief. The saturated thickness of the surficial aquifer is variable within the study area because of changes in the thickness of the deposits. Gamma logs were obtained for the deepest wells drilled in each cluster during the study and are on file at the USGS District office in Baltimore, Maryland. Well lithologies from this study and previous geologic studies were used in conjunction with the log data to project a hydrogeologic framework across the constructed transects (figs. 5añc). Saturated thickness commonly exceeds 40 ft, and can be greater than 90 ft in deposits near the northern and eastern edges of the study area.

The topographic features of the study area indicate that the predominant flow direction in the surficial aquifer is from northwest to southeast. Measured water levels and corresponding ground-water-flow gradients along transects AñA' and BñB' are consistent with the expected flow direction in these areas (figs. 5a and 5b). Data from transect CñC', shown in figure

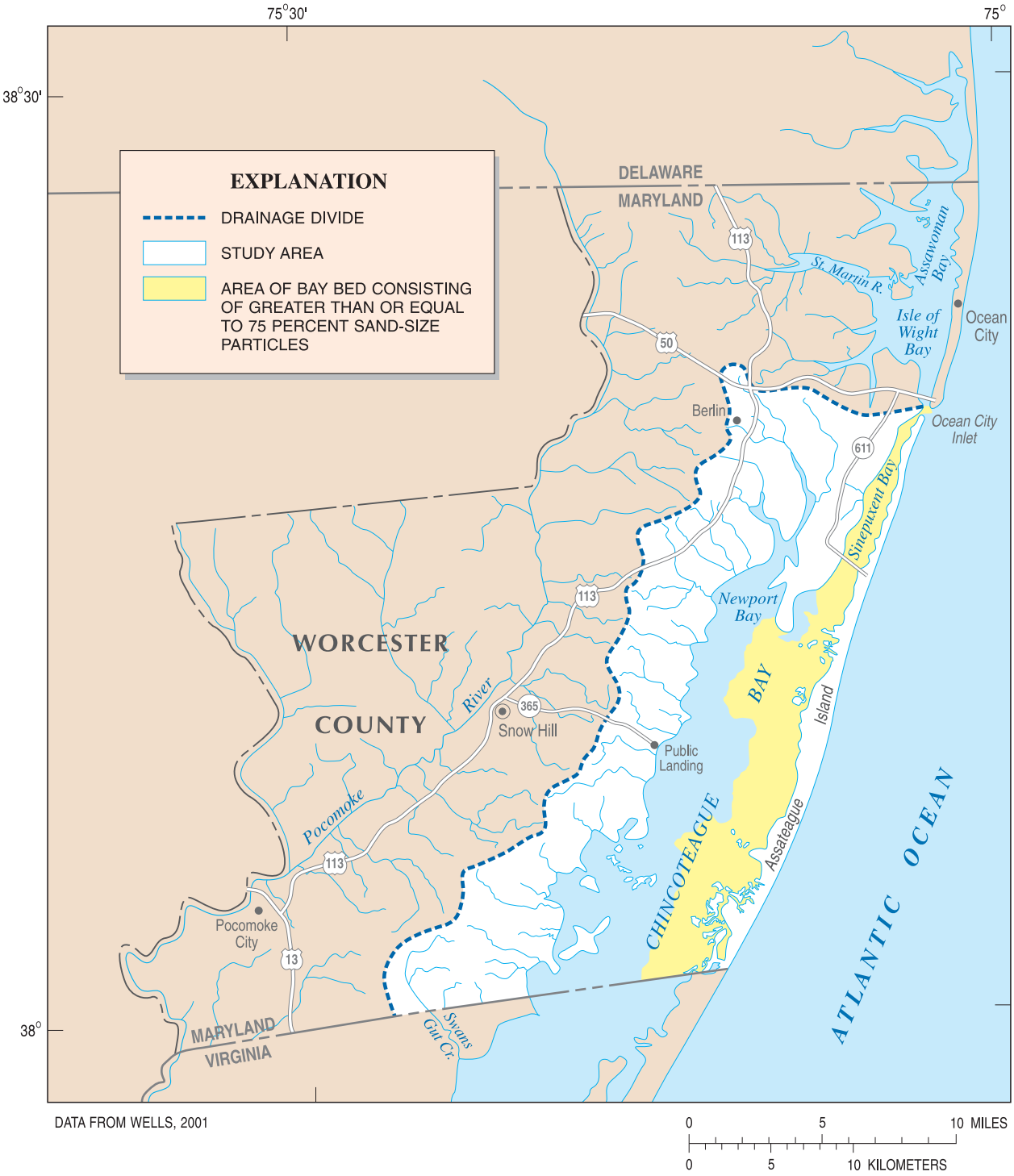


Figure 4. Sand-dominated area of the beds of Chincoteague and Sinepuxent Bays in Worcester County, Maryland.

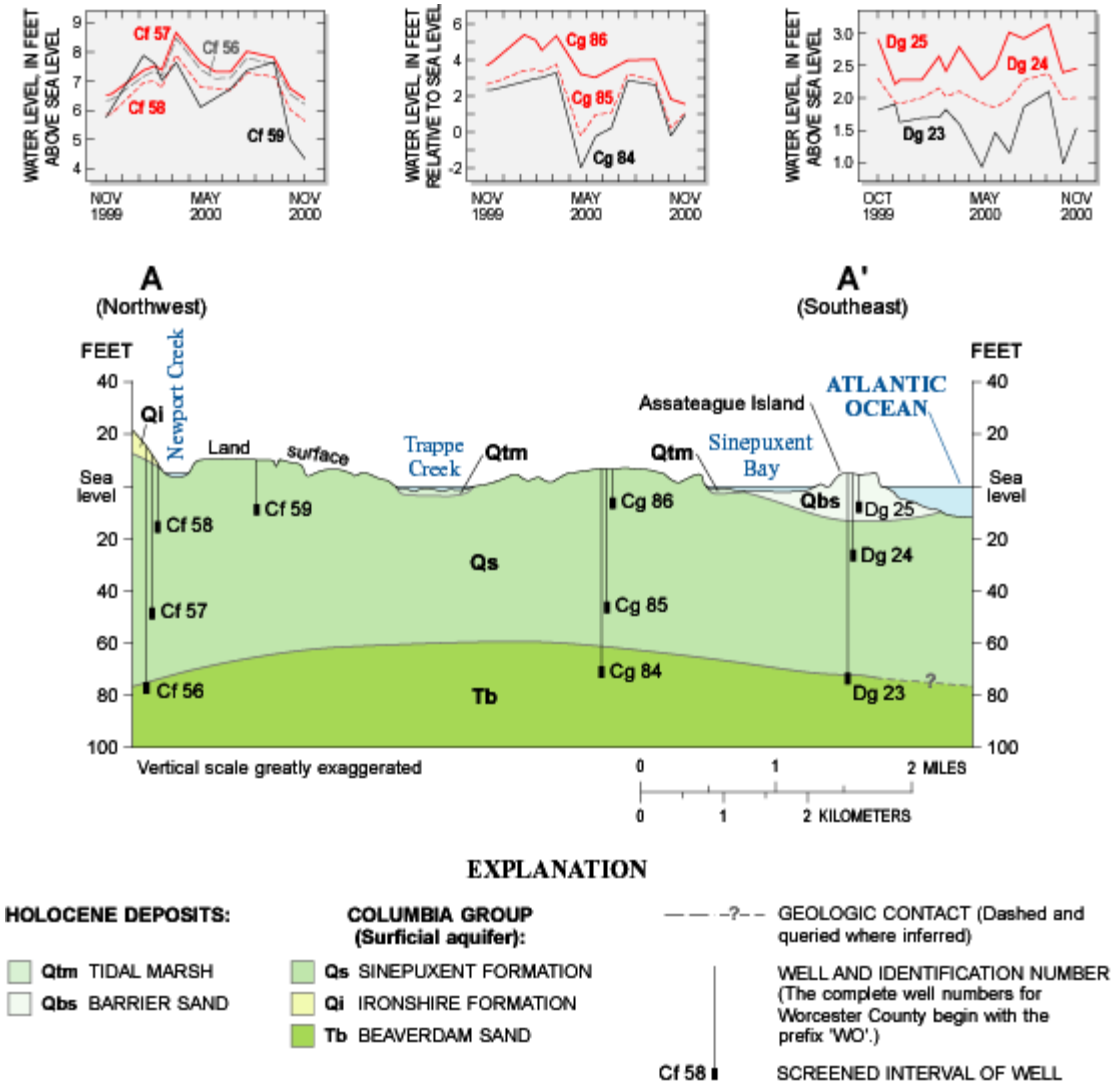


Figure 5a. Water levels for wells along transect A-A', Worcester County, Maryland (shown in figure 2).

5c, indicate a radial ground-water-flow pattern that is consistent with the topography of the Swans Gut Creek drainage basin (fig. 2). However, this pattern cannot be effectively shown in cross section, so it is not apparent in figure 5c. Deep ground-water-flow paths that discharge to the coastal bays or the Atlantic Ocean can be up to 5 mi long, whereas intermediate and shallow flow paths that discharge to streams, drainage ditches, ponds, and tidal marshes can be less than 500 ft long (Hamilton and others, 1993).

GROUND-WATER OCCURRENCE AND QUALITY

Ground water flowing into the coastal bays can enter the bays through the bay-bed sediments as direct discharge or can discharge to streams and be transported to the coastal bays as stream base flow. This study was designed to collect data that describe ground-water-flow paths and to collect water-quality data at various locations along the flow paths, with particular regard to nutrient concentrations.

Twenty-eight ground-water monitoring wells were drilled and constructed in the surficial aquifer and the underlying confining bed at 12 locations in the study area (fig. 2). Wells are identified based on a

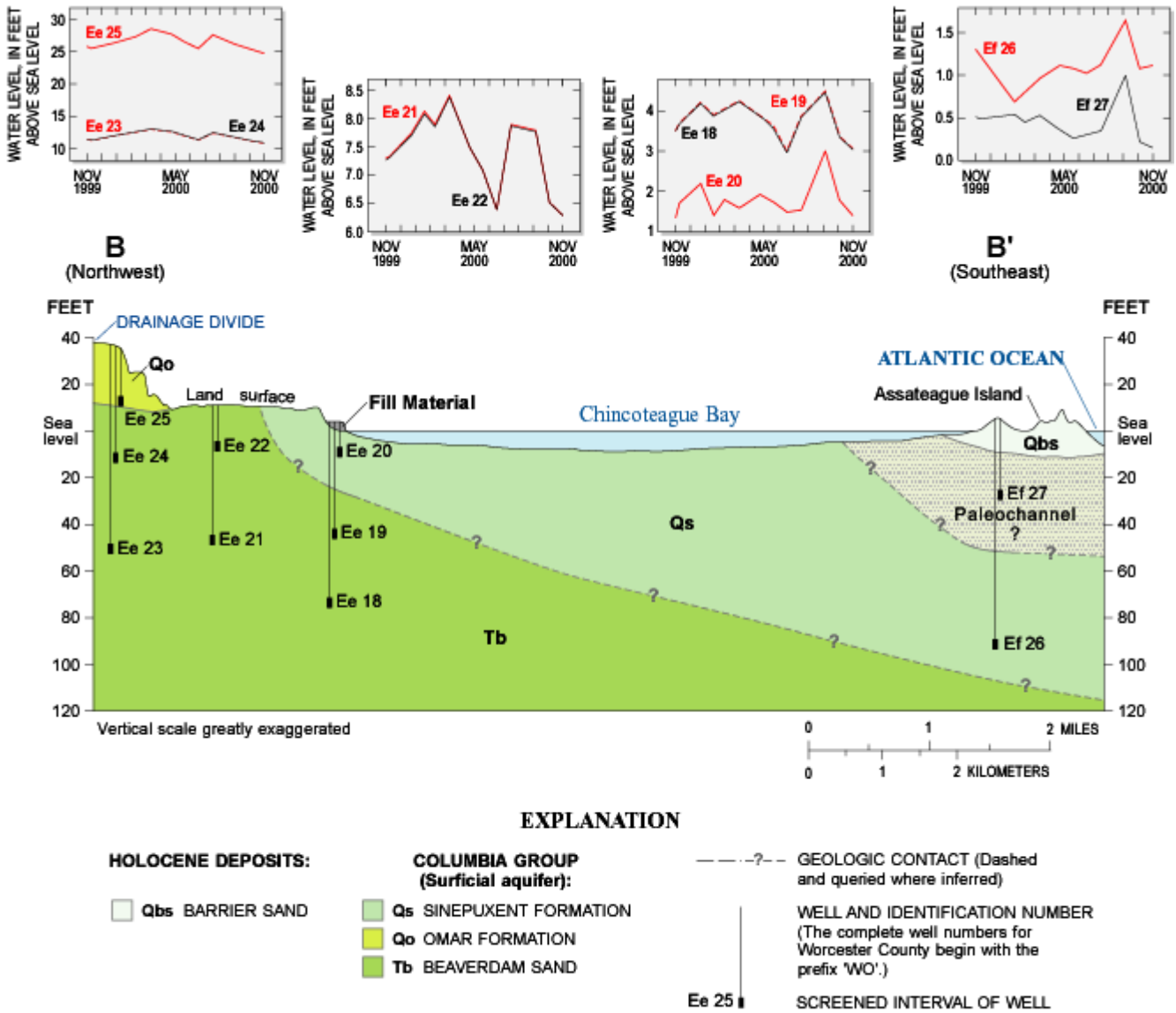


Figure 5b. Water levels for wells along transect B-B', Worcester County, Maryland (shown in figure 2).

numbering system established by the Maryland Geological Survey (Smigaj and others, 2001). Water levels were measured once a month for a 1-year period during the study to characterize ground-water-flow gradients for various flow paths. Water-quality data also were collected using the techniques described by Wilde and others (1999), for each well, representing the range of average ground-water age and flow-path length at various depths within the study area. Additional samples were collected from the wells for age-dating analysis to define relative flow-path lengths.

Base flow was measured at 17 sites on nontidal streams in the study area (fig. 2). Water-quality samples were collected using the techniques described by Wilde and others (1999) when flows were measured to define the concentrations and amounts of nutrients being transported to the coastal bays by base flow and to characterize water quality at each site. In the results of a study performed in a similar hydrogeologic environment, Modica (1999) indicated that such samples are characteristic of relatively young ground water from shorter, subsurface flow paths.

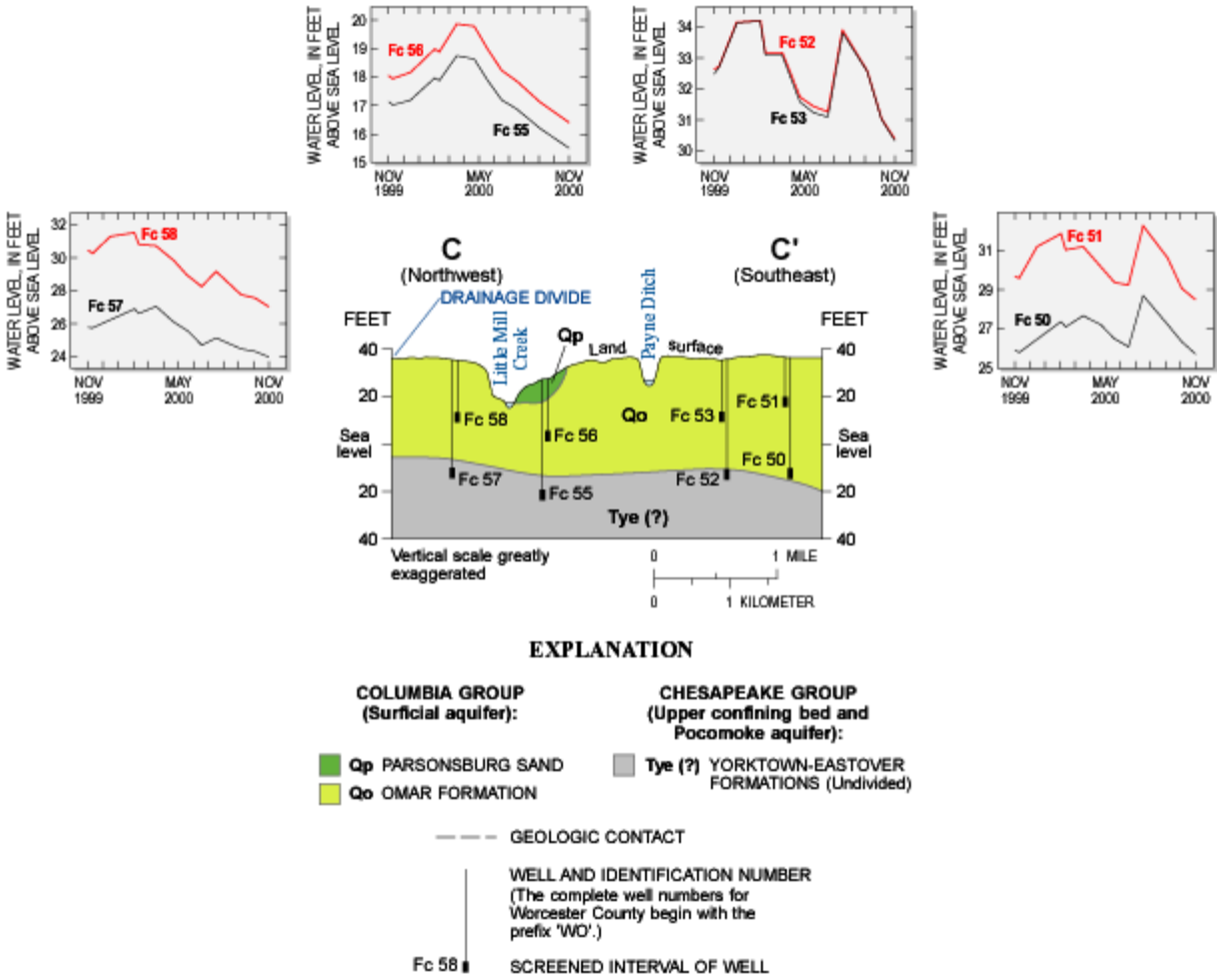


Figure 5c. Water levels for wells along transect C-C', Worcester County, Maryland (shown in figure 2).

Ground-Water Data

Water levels were measured at the 28 wells once a month from October 1999 through November 2000. With one exception (well WO Cf 59, fig. 2), wells were installed so that two or three wells of differing depths are at the same location. Future references to wells will omit the WO county prefix for brevity. Well depths ranged from 15 to 100 ft bls, with depth differences within well clusters as great as 70 ft (figs. 5añc). Three of the 28 wells (wells Dg 24, Fc 51, and Fc 52) were screened in low hydraulic conductivity material and could not be developed. These wells were not sampled to determine water quality.

The 25 remaining wells (of the 28 wells described above) were sampled to characterize water quality at each well. Water-quality samples were collected during two sampling periods, January and February 2000, and April 2000. One sample was collected at each location during each sampling period. In addition, a set of samples that allowed the relative ages of ground water from each of the wells to be determined was collected during the first sampling period. The results of both sampling rounds are similar, as shown in table 2.

Ground-Water Elevations

Monthly measurements of ground-water elevations at the 28 wells within the study area were recorded from October 1999 through November 2000. Elevations were reported relative to sea level and

ranged from 2 ft below sea level to 34 ft above sea level (figs. 5añc).

Ground-water elevations in all wells within each well cluster had similar hydrologic response patterns, as shown in figures 5añc. In some cases, two or three wells within a cluster had identical response patterns and similar water elevations. Wells within a cluster with identical ground-water elevations have good hydraulic connections, indicating that the intervening aquifer material conducts water freely. In well clusters where one or more wells have different water elevations, there may be geologic material located in the interval between two or more well-screen depths that is somewhat less conductive. The well logs recorded during the study indicate that three of the deep wells along transect CñC' (wells Fc 52, Fc 55, and Fc 57) actually are screened in the Yorktown-Eastover Formations (undivided).

Water Quality

Ground water in the area is characterized by a variety of water types, ranging from water that is chemically similar to precipitation to water that is much more saline than seawater, known as hypersaline. Ground-water quality in the surficial aquifer generally is characterized by low to neutral pH and low total dissolved solids (table 2). The weakly acidic, dilute nature of shallow ground water in most of the study area reflects that of precipitation, the principal source of recharge in the study area. Hypersaline water was detected in well Ef 27 (fig. 2, table 2) on Assateague Island, and probably is a result of overwash and evaporation. Other water types present in ground-water samples include calcium-bicarbonate waters (in samples from wells Cg 84 and 85, and Fc 53), calcium-magnesium-sulfate waters (in samples from wells Ee 19 and 20), and mixed waters of various types. The relative amounts of the major ions found in ground water from the 25 wells sampled during the study are shown in figure 6. The ionic composition of ground water sampled varies based on sample location, and probably is affected by source area and local conditions, such as proximity to the ocean or anthropogenic influences.

Nutrients frequently are an important aspect of ground-water chemistry on the Delmarva Peninsula because the discharge of nutrients to the bays and other water bodies can cause eutrophication. Nitrate is the dominant form of nitrogen and the dominant nutrient in oxic ground water in the study area, but only about one-third of the ground-water samples collected for this study contained more than 1 mg/L (milligram per liter) dissolved oxygen (table 2), which indicates that most of the ground-water samples essentially were anoxic. As a result of anoxic conditions, other forms of nitrogen such as ammonia and organic nitrogen were detected more frequently than nitrate in ground-water samples collected during this study (table 2) and could represent very important components of the nutrient loads to the coastal bays.

Hamilton and others (1993), in a survey of 296 wells screened in the surficial aquifer on the Delmarva Peninsula, determined a threshold value of 0.4 mg/L of nitrate as N (nitrogen) to be indicative of anthropogenic influence. In areas where anthropogenic influences, such as agricultural chemicals and septic effluents, are present however, nitrate reduction can be an important microbial process in ground water (Chapelle, 1993). Although denitrification to molecular nitrogen can occur in many cases, Chapelle (1993) stated that many bacteria reduce nitrate either to nitrite or to ammonia. This process of nitrate reduction to ammonia appears to be important in ground water within the study area.

Ammonia was detected in high concentrations (as much as 23.4 mg/L as N) (table 2) in two areasó wells Ef 26 and 27 at the eastern end of transect BñB' on Assateague Island, and wells Fc 57 and 58 at the western end of transect CñC' near Swans Gut Creek (fig. 2). In each of the samples from these wells, dissolved ammonia was the dominant form of nitrogen present in ground water (table 2).

The ultimate fate and transport of dissolved ammonia in ground water in the study area is not known, but various factors may be important. Ammonia is a nitrogen species that is readily available to microorganisms and plants, or transformable in the presence of oxygen into nitrite or nitrate through nitrification (Brady, 1974). Therefore, ammonia could be a factor in eutrophication of the coastal bays if it is transported to surface water. Ammonia, however, is less mobile in ground water than nitrate and is adsorbed readily onto organic matter, clay, and silt (Freeze and Cherry, 1979). As a result, transport of dissolved ammonia in ground water is slowed considerably, which may reduce the concentrations that would reach the discharge zones (Drever, 1988).

The majority of wells sampled during this study contained no dissolved oxygen, and many had a noticeable hydrogen sulfide odor during sample col-

Table 2. *Chemical characteristics of ground water in the Maryland Coastal Bays drainage area, JanuaryñFebruary and April 2000*

[The U.S. Geological Survey (USGS) well identification number is a 15-digit numberó the first 6 digits are the latitude, the next 7 digits are the longitude, and the last 2 digits refer to the sequence number for identifying one or more wells at a particular latitude and longitude; ft, feet; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; ∝C, degrees Celsius; µg/L, micrograms per liter; <, less than; **E**, estimated; ñ, no data collected]

Local well number	USGS well identification number	Date	Well depth (ft)	Oxygen, dissolved (mg/L)	pH, water, whole (standard units)	Specific conductance (µS/cm)	Temperature, air (∝C)	Temperature, water (∝C)
WO Cf 56	381713075123501	02/04/2000	90	0	5.7	78	0	13.1
		04/03/2000	90	0	5.9	102	18	14.9
WO Cf 57	381713075123502	02/04/2000	60	4.4	5.7	70	2	13.1
		04/03/2000	60	5.3	5.5	70	19	14.8
WO Cf 58	381713075123503	02/04/2000	25	4.2	6.4	95	5	11.8
		04/04/2000	25	7.0	5.9	80	20.5	18.4
WO Cf 59	381640075120801	02/03/2000	21	2.3	6.7	184	4	10.7
		04/04/2000	21	0	5.7	171	16.5	14.4
WO Cg 84	381526075095001	02/02/2000	80	0	7.0	313	2	14.5
		04/04/2000	80	0	7.1	309	17.5	14.7
WO Cg 85	381526075095002	02/02/2000	55	0	7.2	492	2	14.2
		04/04/2000	55	0	6.6	485	17	14.9
WO Cg 86	381526075095003	02/03/2000	15	3.0	5.1	161	7	13.4
		04/04/2000	15	3.8	5.1	97	18	13.4
WO Dg 23	381428075081401	01/21/2000	85	0	6.5	275	-4	14.6
		04/07/2000	85	0	6.2	235	15.5	15.6
WO Dg 25	381428075081403	01/21/2000	15	0	7.2	1,400	-4	13.5
		04/07/2000	15	0	6.9	1,440	14.5	12.6
WO Ee 18	380859075171101	01/20/2000	80	0	5.8	180	.5	14.7
		04/06/2000	80	0	5.7	180	16	15.8
WO Ee 19	380859075171102	01/20/2000	50	0	6.3	355	1.5	15
		04/06/2000	50	0	6.0	351	17.5	16.6
WO Ee 20	380859075171103	01/20/2000	15	0	6.2	208	1	14.8
		04/06/2000	15	0	6.1	212	23	15.6
WO Ee 21	380930075180601	01/14/2000	60	ñ	5.3	157	-2	13.7
		04/06/2000	60	2.1	5.8	160	24	14.2
WO Ee 22	380930075180602	01/14/2000	20	ñ	5.9	91	-1	13.4
		04/06/2000	20	4.3	7.0	93	25	13.8
WO Ee 23	380942075185501	01/19/2000	90	0	5.4	136	3	14.5
		04/07/2000	90	0	5.4	135	20	15.7
WO Ee 24	380942075185502	01/19/2000	50	.6	5.3	178	4.5	14.1
		04/07/2000	50	0	5.1	182	21	16

Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Potassium, dissolved (mg/L as K)	Sodium, dissolved (mg/L as Na)	Alkalinity (mg/L as $CaCO_3$)	Bicarbonate (mg/L as HCO_3)	Chloride, dissolved (mg/L as Cl)	Local well number
3.1	0.91	0.78	9.6	21	26	10	WO Cf 56
3.3	.93	.83	9.9	23	28	11	
2.3	.96	.71	8.7	21	26	7.7	WO Cf 57
2.3	.96	.76	8.4	20	25	7.9	
4.3	2.1	.99	9.6	31	38	9	WO Cf 58
3.5	2.0	1.0	9.0	29	36	9.5	
6.7	5.8	1.2	18	75	91	16	WO Cf 59
6	5.0	1.1	17	58	70	21	
36	7.5	1.9	12	128	160	16	WO Cg 84
37	7.5	1.7	12	133	160	17	
59	13	2.1	17	213	260	22	WO Cg 85
60	13	2.0	17	221	270	23	
.73	3.5	.63	10	10	12	ñ	WO Cg 86
.49	3.3	.63	9.3	1	1	18	
12	5.5	3.6	31	64	78	40	WO Dg 23
10	5.1	3.4	24	36	44	33	
53	34	13	147	156	190	320	WO Dg 25
57	33	13	155	155	190	330	
8.3	4.4	1.9	15	54	66	17	WO Ee 18
8	4.7	1.6	15	13	16	17	
24	14	14	8.9	51	62	15	WO Ee 19
24	14	15	9.0	53	64	14	
11	7.0	.98	15	38	47	16	WO Ee 20
12	7.3	.64	15	30	37	15	
5.9	2.5	1.3	16	56	68	20	WO Ee 21
6.2	2.5	1.1	17	17	21	20	
2.4	.91	1.1	13	19	24	15	WO Ee 22
2.6	.91	1	13	19	23	14	
4.6	1.6	1.6	16	8	10	23	WO Ee 23
3.8	1.6	1.4	15	11	14	23	
5	2.6	1.5	19	11	14	28	WO Ee 24
4.8	2.7	1.3	19	10	12	27	

Table 2. *Chemical characteristics of ground water in the Maryland Coastal Bays drainage area, JanuaryñFebruary and April 2000ó* Continued

Local well number	USGS well identification number	Date	Well depth (ft)	Oxygen, dissolved (mg/L)	pH, water, whole (standard units)	Specific conductance (µS/cm)	Temperature, air (∝C)	Temperature, water (∝C)
WO Ee 25	380942075185503	01/19/2000	25	4.7	4.8	228	3.5	15.8
		04/07/2000	25	6.5	4.7	235	21	16.1
WO Ef 26	380837075112201	02/16/2000	100	0	6.6	57,900	9	13.8
		04/05/2000	100	0	6.5	58,300	8	14.7
WO Ef 27	380837075112202	02/16/2000	35	0	7.0	93,700	9.5	12.9
		04/05/2000	35	0	7.2	86,400	9	12.8
WO Fc 50	380129075253701	01/12/2000	50	0	5.8	299	10	14.5
		04/12/2000	50	0	5.6	306	15.5	15
WO Fc 53	380138075260102	01/12/2000	25	.2	7.9	469	6	15
		04/12/2000	25	0	7.7	464	15.5	14.1
WO Fc 55	380215075271701	01/13/2000	50	0	5.9	137	15	14.8
		04/12/2000	50	0	6.0	137	16	15
WO Fc 56	380215075271702	01/13/2000	25	6.8	5.5	269	16	16.2
		04/12/2000	25	7.3	5.4	281	17	15.1
WO Fc 57	380255075274601	01/13/2000	49	ñ	6.3	205	13.5	14.8
		04/12/2000	49	0	6.2	218	16	15.3
WO Fc 58	380255075274602	01/13/2000	25	ñ	6.0	172	8.5	14.4
		04/12/2000	25	0	5.9	170	17	15.5

Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Potassium, dissolved (mg/L as K)	Sodium, dissolved (mg/L as Na)	Alkalinity (mg/L as $CaCO_3$)	Bicarbonate (mg/L as HCO_3)	Chloride, dissolved (mg/L as Cl)	Local well number
9.1	12	1.5	7.2	6	7	23	WO Ee 25
9.1	13	1.4	6.8	1	1	22	
1,200	1,690	250	11,400	390	480	23,000	WO Ef 26
1,200	1,740	280	12,400	370	450	24,000	
600	2,990	760	22,400	380	460	43,000	WO Ef 27
560	2,740	720	20,800	437	530	39,000	
17	8.4	1.2	19	9	11	25	WO Fc 50
15	8.3	1.3	19	13	16	25	
76	3.6	1.8	14	122	150	30	WO Fc 53
71	3.6	1.9	14	157	190	27	
6.2	2.5	1.9	11	11	14	12	WO Fc 55
6.0	2.3	1.8	11	20	25	11	
19	13	1.9	5.0	7	9	15	WO Fc 56
18	14	1.8	5.4	12	15	15	
9.3	5.6	5.4	14	84	100	16	WO Fc 57
8.8	5.4	5.7	14	91	110	16	
4.6	2.6	.98	18	34	42	23	WO Fc 58
4.3	2.4	.93	19	34	42	21	

Table 2. *Chemical characteristics of ground water in the Maryland Coastal Bays drainage area, JanuaryñFebruary and April 2000*ó Continued

Local well number	Date	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Sulfate, dissolved (mg/L as SO_4)	Nitrogen, ammonia, dissolved (mg/L as N)	Nitrogen, ammonia plus organic, dissolved (mg/L as N)	Nitrogen, ammonia plus organic, total (mg/L as N)	Nitrogen, nitrite plus nitrate, dissolved (mg/L as N)	Nitrogen, nitrite, dissolved (mg/L as N)
WO Cf 56	02/04/2000	<0.10	31	3.0	0.037	<0.10	0.49	<0.050	<0.010
	04/03/2000	< .10	31	3.4	< .020	< .10	.23	< .050	< .010
WO Cf 57	02/04/2000	< .10	19	3.1	< .020	< .10	< .10	.479	< .010
	04/03/2000	< .10	19	2.7	< .020	< .10	**E** .05	.461	< .010
WO Cf 58	02/04/2000	< .10	26	3.3	.079	< .10	.37	< .050	< .010
	04/04/2000	< .10	25	3.8	.079	**E** .10	3.20	< .050	< .010
WO Cf 59	02/03/2000	.14	30	2.2	.141	.24	6.30	< .050	< .010
	04/04/2000	< .10	34	2.1	.148	.14	.29	< .050	< .010
WO Cg 84	02/02/2000	.16	36	< .31	.332	< .10	.43	< .050	< .010
	04/04/2000	.11	37	< .31	.353	.32	.39	< .050	< .010
WO Cg 85	02/02/2000	.14	35	< .31	.536	< .10	.65	.127	< .010
	04/04/2000	.10	35	< .31	.568	.50	.53	< .050	< .010
WO Cg 86	02/03/2000	< .10	10	ñ	< .020	< .10	< .10	< .050	< .010
	04/04/2000	< .10	9.3	8.4	< .020	< .10	< .10	< .050	< .010
WO Dg 23	01/21/2000	< .10	12	9.4	.197	.38	.40	< .050	< .010
	04/07/2000	< .10	10	15	.157	.29	.34	< .050	< .010
WO Dg 25	01/21/2000	< .10	14	37	.575	.73	.76	< .050	< .010
	04/07/2000	< .10	14	35	.498	.73	.69	< .050	< .010
WO Ee 18	01/20/2000	< .10	26	29	< .020	< .10	< .10	1.77	< .010
	04/06/2000	< .10	27	28	< .020	< .10	< .10	1.92	< .010
WO Ee 19	01/20/2000	< .10	17	94	< .020	< .10	< .10	< .050	< .010
	04/06/2000	.16	16	93	< .020	**E** .10	**E** .08	< .050	< .010
WO Ee 20	01/20/2000	.10	17	41	.131	.20	.19	< .050	< .010
	04/06/2000	< .10	16	41	.113	.16	.28	< .050	< .010
WO Ee 21	01/14/2000	< .10	32	23	.033	< .10	**E** .06	< .050	< .010
	04/06/2000	< .10	31	24	.035	**E** .10	.11	< .050	< .010
WO Ee 22	01/14/2000	< .10	32	1.1	< .020	< .10	< .10	< .050	< .010
	04/06/2000	< .10	32	1.2	.020	< .10	**E** .10	< .050	< .010
WO Ee 23	01/19/2000	< .10	30	10	.027	< .10	< .10	.158	< .010
	04/07/2000	< .10	31	9.5	< .020	< .10	**E** .08	.244	< .010
WO Ee 24	01/19/2000	< .10	24	24	.022	< .10	**E** .06	< .050	< .010
	04/07/2000	< .10	25	23	< .020	< .10	.12	< .050	< .010
WO Ee 25	01/19/2000	< .10	17	25	< .020	< .10	< .10	9.77	< .010
	04/07/2000	< .10	17	23	< .020	< .10	.13	10.0	< .010

Phosphorus, dissolved (mg/L as P)	Phosphorus, ortho, dissolved (mg/L as P)	Phosphorus, total (mg/L as P)	Solids residue, at 180 °C, dissolved (mg/L)	Iron, dissolved (µg/L as Fe)	Manganese, dissolved (µg/L as Mn)	Carbon, organic, dissolved (mg/L as C)	Average age (years)	Local well number
0.051	0.046	0.140	79	3,000	32	1.74	ñ	WO Cf 56
< .006	< .010	.054	72	470	31	ñ	16	
< .006	.011	< .008	56	47	7.1	1.04	ñ	WO Cf 57
< .006	< .010	< .008	53	14	4.9	ñ	10	
.019	< .010	.208	78	2,100	57	1.61	ñ	WO Cf 58
E .005	< .010	2.01	70	2,100	71	ñ	9	
.022	.024	4.05	118	3,800	226	2.22	ñ	WO Cf 59
.055	.055	.173	118	5,300	161	ñ	5	
.164	.135	.178	201	490	402	2.06	ñ	WO Cg 84
.181	.165	.183	195	450	397	ñ	33	
.135	.095	.178	296	910	525	2.49	ñ	WO Cg 85
.168	.162	.184	287	960	523	ñ	ñ	
< .006	< .010	.018	64	**E** 6.6	14	2.02	ñ	WO Cg 86
< .006	< .010	< .008	54	< 10	12	ñ	3	
.081	.091	.085	165	620	46	6.42	ñ	WO Dg 23
.057	.050	.057	131	590	39	ñ	ñ	
.074	.070	.074	748	69	35	5.28	ñ	WO Dg 25
.075	.054	.073	764	83	31	ñ	5	
.008	< .010	**E** .007	126	98	**E** 1.2	1.79	ñ	WO Ee 18
.006	< .010	**E** .006	119	17	**E** 1.3	ñ	18	
.012	.010	.014	227	1,300	25	1.57	ñ	WO Ee 19
.011	< .010	.014	208	1,400	27	ñ	12	
.028	.035	.044	143	3,300	117	2.16	ñ	WO Ee 20
.016	.022	.196	126	2,900	118	ñ	5	
.008	.016	.012	117	2,400	50	4.18	ñ	WO Ee 21
.011	.014	.039	110	2,300	50	ñ	14	
.007	.030	.009	81	530	36	1.33	ñ	WO Ee 22
.008	.014	.039	76	260	30	ñ	16	
.009	< .010	.009	106	960	36	1.09	ñ	WO Ee 23
E .005	< .010	**E** .007	99	990	35	ñ	20	
.023	.019	.022	130	2,400	59	1.14	ñ	WO Ee 24
.023	.017	.036	116	2,500	60	ñ	14	
< .006	< .010	< .008	140	**E** 7.2	53	.98	ñ	WO Ee 25
< .006	< .010	< .008	125	13	48	ñ	5	

Table 2. *Chemical characteristics of ground water in the Maryland Coastal Bays drainage area, JanuaryñFebruary and April 2000*ó Continued

Local well number	Date	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Sulfate, dissolved (mg/L as SO_4)	Nitrogen, ammonia, dissolved (mg/L as N)	Nitrogen, ammonia plus organic, dissolved (mg/L as N)	Nitrogen, ammonia plus organic, total (mg/L as N)	Nitrogen, nitrite plus nitrate, dissolved (mg/L as N)	Nitrogen, nitrite, dissolved (mg/L as N)
WO Ef 26	02/16/2000	<0.50	22	2,600	22.5	23	22	<0.050	<0.010
	04/05/2000	< .10	22	2,800	23.4	24	25	< .050	.011
WO Ef 27	02/16/2000	.23	20	5,600	6.80	7.0	7.0	< .050	< .010
	04/05/2000	.28	17	5,600	6.54	7.6	7.5	< .050	< .010
WO Fc 50	01/12/2000	< .10	25	83	.021	< .10	**E** .06	< .050	< .010
	04/12/2000	< .10	24	81	.026	**E** .10	**E** .08	< .050	< .010
WO Fc 53	01/12/2000	< .10	25	42	.130	**E** .10	.18	< .050	< .010
	04/12/2000	< .10	24	37	.108	.15	.13	< .050	< .010
WO Fc 55	01/13/2000	< .10	25	22	.029	< .10	**E** .08	< .050	< .010
	04/12/2000	< .10	24	22	.029	**E** .10	**E** .10	< .050	< .010
WO Fc 56	01/13/2000	< .10	16	30	< .020	< .10	**E** .09	15.5	< .010
	04/12/2000	< .10	15	30	< .020	**E** .10	**E** .08	15.2	< .010
WO Fc 57	01/13/2000	< .10	57	< .31	4.12	4.4	5.1	< .050	< .010
	04/12/2000	< .10	54	< .31	4.29	4.6	5.1	< .050	< .010
WO Fc 58	01/13/2000	.10	40	15	1.42	1.5	1.9	< .050	< .010
	04/12/2000	< .10	37	13	1.33	1.5	1.6	< .050	< .010

Phosphorus, dissolved (mg/L as P)	Phosphorus, ortho, dissolved (mg/L as P)	Phosphorus, total (mg/L as P)	Solids residue, at 180 ∝C, dissolved (mg/L)	Iron, dissolved (µg/L as Fe)	Manganese, dissolved (µg/L as Mn)	Carbon, organic, dissolved (mg/L as C)	Average age (years)	Local well number
0.047	0.027	0.254	42,200	20,300	1,590	12.77	ñ	WO Ef 26
.222	.150	.156	45,300	21,300	1,630	ñ	<37	
.744	1.570	.712	77,500	<300	<132	11.17	ñ	WO Ef 27
.270	.411	.391	75,600	2,700	374	ñ	<11	
.033	.030	.036	204	6,700	137	0.97	ñ	WO Fc 50
.031	.024	.035	201	6,500	126	ñ	15	
.097	.097	.102	314	190	35	1.06	ñ	WO Fc 53
.094	.083	.109	286	120	31	ñ	23	
.072	.062	.079	100	4,800	163	1.41	ñ	WO Fc 55
.093	.048	.110	101	4,500	152	ñ	15	
.006	.013	**E** .006	163	26	6.7	2.47	ñ	WO Fc 56
.006	< .010	**E** .007	164	**E** 5.7	4.5	ñ	4	
.596	.613	.745	170	6,800	103	5.55	ñ	WO Fc 57
.557	.619	.618	170	6,500	94	ñ	20	
.179	.191	.263	135	6,900	81	3.12	ñ	WO Fc 58
.177	.174	.202	131	5,600	73	ñ	7	

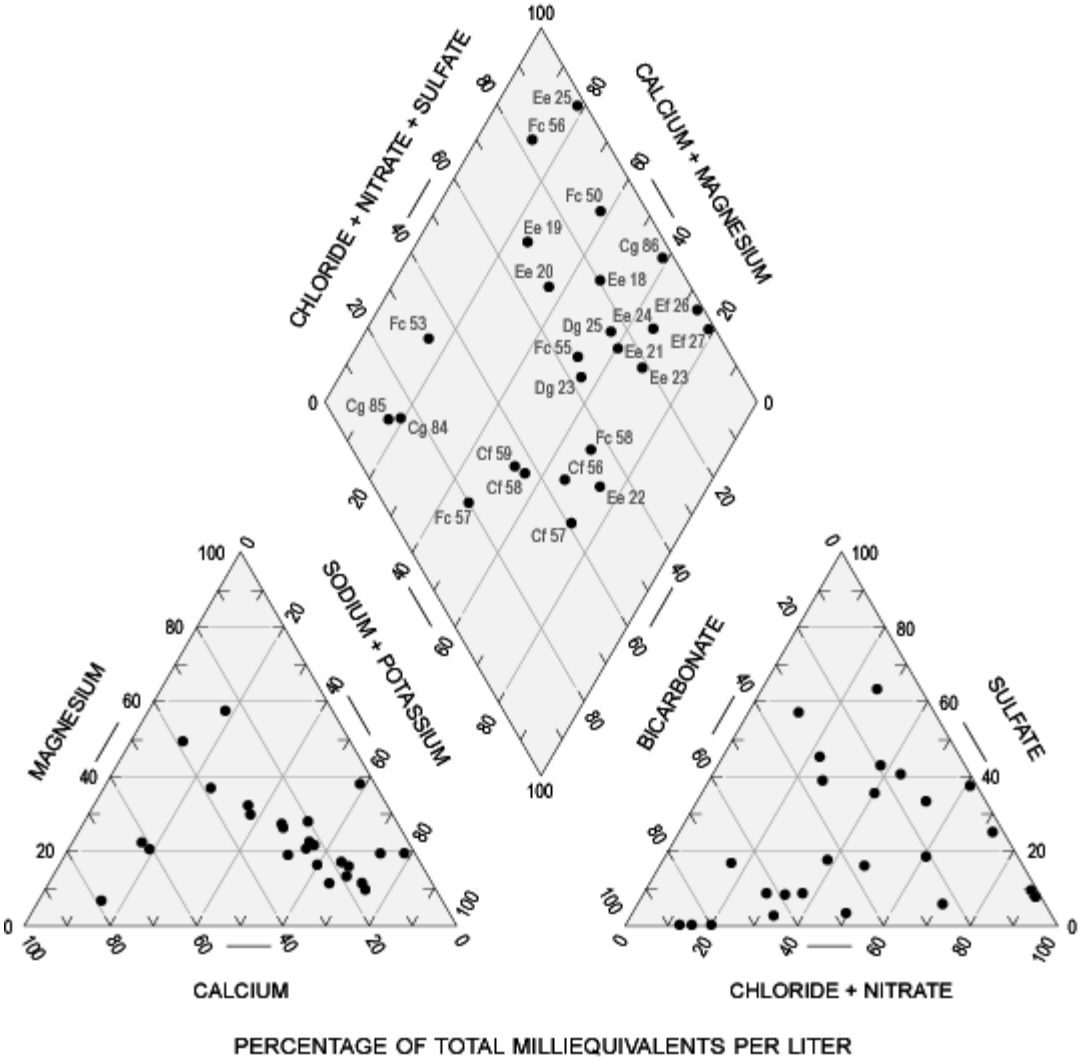


Figure 6. Chemical composition of water from wells in the study area, Worcester County, Maryland.

lection. The presence of dissolved hydrogen sulfide gas in a water sample is evidence of sulfate reduction at the depth from which the sample was collected. In this environment, nitrate tends to be reduced to nitrite, ammonia, or nitrogen gas. In the study area, nitrate concentrations in shallow ground water ranged from less than 0.05 mg/L to more than 15.0 mg/L of nitrate as N. Most well samples that did not contain measurable concentrations of nitrate had dissolved-oxygen concentrations that were below detection levels (table 2).

Nitrate concentrations were above the anthropogenic effect threshold of 0.4 mg/L as N identified by Hamilton and others (1993) in four wells, three of which (Fc 56, Ee 25, and Ee 18) contained measurable dissolved oxygen (table 2). The highest levels of detectable nitrate were found in wells Fc 56 (15.5 mg/L as N) and Ee 25 (10.0 mg/L as N) (table 2). Both of these wells are screened in an oxic environment. Well Ee 18 had 1.92 mg/L of nitrate as N, but no detectable dissolved oxygen. The presence of nitrate in an apparently reducing environment indicates that either trace amounts of dissolved oxygen continue to inhibit the reduction of nitrate, or the well is screened in a region where the transition from oxidizing to reducing conditions is in progress. All three wells are in areas that previously were identified as having elevated ground-water nitrate concentrations (Dillow and Greene, 1999).

Ground-water samples from well Fc 56, which came from an oxic, sandy environment, contained the highest concentrations of nitrate (15.5 mg/L as N) found during the study. In contrast, samples from wells Fc 57 and 58, located 0.9 mi west of well Fc 56, which have anoxic, silty environments, contained the highest concentrations of dissolved ammonia found in nonsaline ground water during the study (table 2). These data provide a good example of the effects of geologic materials and dissolved-oxygen concentration on the dominant form of nitrogen present in ground water.

Changes in the amount and composition of material dissolved in ground water occur as it travels along a flow path through the surficial aquifer. From recharge to the aquifer through discharge to a surface-water body, ground-water chemistry is affected by the dissolution of aquifer material and reactions with anthropogenically introduced chemicals. The chemical composition of much of the ground water in the study area reflects this transition.

It should be noted that the two wells with samples containing the highest nitrate levels recorded during the study, Fc 56 and Ee 25, are characterized by relatively young ground water (discussed in the following section). In addition, well Dg 25 had elevated sodium and chloride concentrations above background levels, indicating the effect of seawater from periodic overwash events.

Ground-Water Age

Ground-water age is the average length of time that a discrete water sample has resided in the saturated zone as ground water. One method for determining the age of relatively young ground water (less than 35 years old) involves measuring the concentration of SF_6 (sulfur hexafluoride) gas in the dissolved gas phase of the water sample (Busenberg and Plummer, 2000). SF_6 gas occurs naturally in the atmosphere at very low concentrations. Since about 1970, the atmospheric concentration of SF_6 gas has been increasing because of releases from anthropogenic sources. This method can provide ages of known accuracy for ground water that has been recharged since 1970.

Ground water recharged to the aquifer prior to 1970 retains SF_6 gas in concentrations that are not related to the time of recharge, so ground water recharged during this period cannot be dated using this technology. The atmospheric concentration of SF_6 gas from 1970 until 2001 has increased with time. Because the ground water being sampled has been out of contact with the atmosphere since it was recharged, the measured concentration of gas in a sample reflects that of the atmosphere at the time of recharge. Measuring this concentration and matching it with the known concentration curve allows the average age of the sample to be determined.

The ground-water ages obtained by measuring SF_6 gas concentrations also are considered to be relatively consistent with the results obtained using other methods to analyze ground water from the Atlantic Coastal Plain (L.N. Plummer, U.S. Geological Survey, written commun., 1999). This level of accuracy results, in part, because nonatmospheric sources of SF_6 gas, such as igneous rocks and some industrial activities commonly found in urban areas, are not present in the study area; therefore, there is little or no contamination of the samples with regard to the atmospheric concentration of SF_6 gas.

The SF_6 method used in this study was selected because ground-water-flow paths in the surficial aquifer were expected to contain little or no ground water that was recharged prior to 1970, and the field techniques used to collect the samples were easily applied. Results indicate that ground-water ages from the 25 wells sampled range from a minimum of 3 years to a maximum of more than 30 years (table 2).

As previously discussed, the SF_6 method may not be reliable in quantitative terms for water recharged to the saturated zone prior to 1970. As a result, ground water from this period cannot be assigned a specific average age on the basis of the SF_6 method, but may be interpreted as having an average age that is greater than 30 years. The accuracy of this method varies according to the number of environmental factors that can be reliably associated with the apparent age of the sample. The accuracy of the estimate for ground-water ages between 20 and 30 years is reported as +/-3.5 years; for ages between 10 and 20 years is reported as +/-1.5 years; and for ages between 0 and 10 years is reported as +3.5/-1 year. The accuracy range of the last age group is not symmetric because underestimation is less likely as the ground-water age approaches 0 years.

It also should be noted that the age of ground water with a high salinity usually is overestimated by this method because salinity decreases the solubility of SF_6 gas in water. The accuracy of age estimates for saline ground water has not yet been determined or correlated with specific salinity levels. Therefore,

ground-water age estimates for wells Ef 26 and Ef 27 may be higher than they would be if the wells contained freshwater.

The results of the ground-water age analyses generally are consistent with those reported for a similar hydrologic environment on the Delmarva Peninsula by Dunkle and others (1993), and support the assumption that ground water in the surficial aquifer in the study area generally is less than 30 years old. In addition, the ages presented generally increase with depth within each well cluster, which is consistent with the expectation that shallow ground water generally is younger than deep ground water. Possible flow paths that correspond to the reported ground-water ages will be discussed later in this report.

Stream Base-Flow Data

Measurements of stream base flow were made at 17 locations in the study area during January and February 1999 and February and March 2000 (fig. 2). One measurement was made at each location during each sampling period. Water-quality sampling allowed comparison of flow and water-quality conditions under winter base-flow conditions during 2 consecutive years. Additionally, sampling from January through March meant that the greatest number of streams could be sampled because many streams in the study area do not flow throughout the year. Selected water-quality parameters, including various nutrient species, were determined concurrently.

Discharge

During the first set of measurements, collected in January and February 1999, the measured base flows in the study area ranged from 0.01 to 1.49 ft^3/s (cubic feet per second) (table 3). A stream adjacent to the study area, measured during the same period to allow comparison of conditions in the study area with those in nearby drainage basins, had a base flow of 5.20 ft^3/s.

The second set of base-flow measurements, collected in February and March 2000, ranged from 0.15 to 1.62 ft^3/s (table 3). The drainage basins of the stream locations where discharge was measured ranged in size from 0.09 to 1.48 mi^2. The ratios of flow rate to basin area for the 17 measured streams varied by more than two orders of magnitude, indicating variability in the hydrogeologic and geomorphic environments among the streams in the study area. It also should be noted that table 3 contains data from five additional stream locations, sample sites 0148469995, 01484710, 01484714, 0148473510, and 0148474010, that are not located within the study area. These locations were sampled to compare water quality within the study area to that in nearby watersheds. The results are included in table 3 for reference purposes.

Water Quality

Water-quality conditions corresponding to the measured base flows were determined at each of the 17 streams. Field parameters measured included air and water temperature, pH, specific conductance, alkalinity, and dissolved oxygen. Water-quality samples were collected and sent to the USGS National Water-Quality Laboratory in Denver, Colorado, for analysis of major ions, nutrient species, and dissolved solids. Samples also were sent to the University of Maryland Center for Environmental Science Chesapeake Biological Laboratory for analysis of dissolved organic carbon using the method defined by Fishman and Friedman (1989).

Ionic composition of stream base flow is consistent throughout the study area. Four dominant cationsó magnesium, calcium, sodium, and potassiumó are present in comparable concentrations. Sulfate and chloride are the dominant anions in most waters (fig. 7, table 3).

Sampling sites were located in the upper part of each basin so that there would be no tidal effect on the flows and constituents measured (fig. 2). As a result, the water-quality information presented in table 3 reflects the characteristics of nontidal water. The lower fluvial and estuarine parts of the drainage basins tend to be more affected by the characteristics of brackish-water chemistry.

In the study area, ground water near the beginning of each flow path is in equilibrium with dissolved atmospheric gases including oxygen. In his discussion of shallow ground-water flow in Coastal Plain sediments in New Jersey, Modica (1999) showed that whereas base flow is an aggregation of water chemistry originating from both nearby and distant sources, flow paths generally become shorter and ground-water ages become younger in an upstream direction. As stated, surface-water sample sites (fig. 2) were chosen to avoid tidal effect and are located in the upper part of each basin. Base flow at these sites generally is more

likely to be derived from oxic ground water that has followed a short flow path from a nearby source than base flow at sites farther downstream.

The reaction of various compounds with dissolved oxygen within the surficial aquifer can result in the depletion of dissolved oxygen over time as ground water travels downgradient along the flow path. If all dissolved oxygen is depleted, reducing conditions are present in the aquifer. The selection of stream-sample sites near the upper part of each basin coupled with aquifer material composed of minimally reactive sands allows the assumptions that stream base flow is derived from oxic ground water, and that dissolved constituents in ground water supplying base flow to streams generally are not under reducing conditions while in the aquifer.

The average concentration of nitrate in 34 base-flow samples, 2 samples from each of the 17 sites in the study area, was 1.75 mg/L as N, and reflects water quality from predominantly short (less than 1,000 ft), local ground-water-flow paths during winter and early spring. The median nitrate concentration from this data set is 1.18 mg/L as N. Bachman and Phillips (1996) indicated that there is no discernible seasonal variation in base-flow nitrate concentrations on the Delmarva Peninsula. Dillow and Greene (1999) assumed an average annual base-flow nitrate concentration of 0.72 mg/L as N, based on the median value of nitrate concentrations in wells with depths predominantly ranging from 30 to 90 ft bls. This assumption by Dillow and Greene (1999) was weighted to reflect water quality in deeper parts of the surficial aquifer rather than water quality in the short, local ground-water-flow paths that supply most of stream base flow. When this apparent bias is taken into account, the use of either the average or the median base-flow nitrate concentration from data collected during this study may provide a more accurate estimate of the average annual base-flow nitrate load.

Reactions of concern in oxic ground water are the oxidation of ammonium (NH_4) applied as fertilizer to nitrite (NO_2), and the subsequent oxidation of nitrite to nitrate (NO_3), the stable form of nitrogen in the oxic ground-water environment in the study area. The data from table 3 indicate that the measured base flow at most sites in the study area has measurable nitrate concentrations, most of which are in excess of background concentrations (generally less than or equal to 0.4 mg/L as N), indicating anthropogenic influences on ground water. Base-flow samples in the study area also contained measurable concentrations of ammonia plus organic nitrogen in concentrations as high as 1.11 mg/L as N (table 3). It is not known if the concentrations of these species detected in this study are representative of the annual average for base flow, or if there is seasonal variability. Because these nitrogen species are available to plants for use as nutrients, their presence in base-flow samples may be an important factor in eutrophication of the coastal bays.

Relation of Land Use to Water Quality

Comparisons between stream base-flow water-quality data and land-use types within each drainage basin were made based on the assumption that land use outside a stream drainage basin has a negligible effect on base-flow water quality of the stream within the basin. The percentages of general land-use categories for each sampled stream and the entire study area are shown in table 4.

The land-use characteristics for the study area are similar to those calculated by Shedlock and others (1999) for the entire Delmarva Peninsula. There are some appreciable land-use differences, however. Proportionally, the study area has 11 percent more wetland and 5 percent more forest than the entire Delmarva Peninsula. This difference reflects the coastal lowland topography that characterizes the study area. The percentage of the study area characterized by urban and agricultural land uses is 5 and 11 percent less, respectively, than in the Delmarva as a whole.

Water-quality samples from 12 of 17 streams in the study area had base-flow nitrate concentrations above 0.4 mg/L as N (the level generally found in natural waters in the study area), indicating that base-flow water quality at most stream sites is being affected by anthropogenic activities (table 3). Four of the five streams that did not have nitrate concentrations above the threshold level had detectable nitrate levels, whereas the remaining stream had nitrate levels that were consistently below the analytical reporting limit of 0.05 mg/L as N.

The levels of nitrate present in most of the stream base-flow water-quality samples collected during this study are consistent with the assumption that most ground water supplied to base flow follows short, shallow flow paths, and that water following short flow paths through an oxic environment tends to transport nitrate (Shedlock and others, 1999). In addition,

Table 3. *Chemical characteristics of stream base flow at nontidal stream-sample sites in the Maryland Coastal Bays drainage area, JanuaryñFebruary 1999 and FebruaryñMarch 2000*

[All identification numbers are found in figure 2 with the exception of those numbers indicated with an *; the * indicates that the stream-sample sites are outside of the study area boundary; ft^3/s, cubic feet per second; mm, millimeters; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; ∝C, degrees Celsius; µg/L, micrograms per liter; <, less than; **E**, estimated; ñ, no data collected]

Station identification number	Date	Discharge, instantaneous (ft^3/s)	Barometric pressure (mm of Hg)	Oxygen, dissolved (mg/L)	pH, water, whole (standard units)	Specific conductance (µS/cm)	Temperature, air (∝C)	Temperature, water (∝C)
*0148469995	02/24/1999	0.89	771	11.0	6.6	324	1.5	3.7
*01484710	02/23/1999	5.20	771	12.6	7.1	241	.0	3.2
*01484714	02/23/1999	.61	771	13.8	6.7	190	1.0	1.8
01484716	01/27/1999	1.46	764	11.4	7.7	211	11.0	11.0
	02/08/2000	1.12	775	12.0	7.0	223	4.0	8.0
01484717	01/13/1999	.05	766	6.8	6.3	256	13.5	4.6
	02/09/2000	.23	768	11.0	5.8	220	-1.0	0.3
01484718	01/13/1999	.83	765	8.3	6.7	167	10.5	10.6
	02/09/2000	1.40	768	9.9	5.8	166	9.0	6.3
01484719	01/28/1999	1.49	760	9.8	6.0	173	12.0	8.1
	02/08/2000	1.62	ñ	10.6	6.0	149	4.5	3.9
01484720	01/28/1999	.85	760	8.4	6.5	215	20.0	10.2
	02/09/2000	.50	768	11.2	6.4	185	11.0	10.2
01484721	01/28/1999	.60	762	7.8	4.7	180	19.0	10.1
	02/09/2000	.92	768	10.4	5.5	104	13.5	3.7
01484722	01/27/1999	.55	ñ	6.9	6.3	145	9.0	8.5
	02/09/2000	.62	ñ	10.5	6.3	138	14.5	10.2
01484723	01/28/1999	.14	760	4.6	4.9	130	19.0	12.5
	02/09/2000	.16	768	9.2	4.7	117	13.5	9.1
01484725	02/11/1999	.10	771	12.4	5.3	159	12.5	10.5
	02/10/2000	.15	762	12.6	6.0	112	9.5	1.1
01484726	01/29/1999	.73	ñ	9.1	5.6	210	8.0	7.7
	02/09/2000	1.62	ñ	11.8	5.7	122	11.5	9.5
01484727	02/11/1999	.01	771	5.9	4.1	200	12.5	7.9
	02/10/2000	.28	762	7.6	4.5	102	14.0	4.9
01484728	01/29/1999	.13	769	5.2	4.9	158	11.0	8.8
	02/10/2000	.37	ñ	10.5	5.9	118	14.5	6.1
01484729	02/11/1999	.09	771	8.4	6.1	247	10.0	5.7
	02/10/2000	.30	ñ	10.3	5.9	140	14.0	10.0
01484730	02/10/1999	.44	766	11.7	5.7	195	12.0	8.6
	02/10/2000	1.00	ñ	12.2	6.3	127	11.5	9.9

Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Potassium, dissolved (mg/L as K)	Sodium, dissolved (mg/L as Na)	Alkalinity (mg/L as $CaCO_3$)	Bicarbonate (mg/L as HCO_3)	Chloride, dissolved (mg/L as Cl)	Station identification number
22	5.8	11	17	21	26	32	*0148469995
16	6.1	7.2	11	9	11	24	*01484710
7.4	4.8	3.4	15	ñ	ñ	27	*01484714
19	7.1	3.0	8.4	50	61	11	01484716
20	7.5	2.6	9.8	46	57	13	
11	7.9	2.5	20	6	7	35	01484717
9.9	8.4	2.1	14	12	15	32	
8.2	4.1	1.7	15	13	16	18	01484718
8.0	4.2	1.8	13	18	22	19	
8.5	7.0	3.6	9.3	4	4	17	01484719
6.5	5.6	2.3	8.5	1	1	18	
12	8.9	4.2	10	7	9	17	01484720
9.9	7.3	2.3	9.8	9	11	16	
8.2	5.6	2.4	13	<1	<1	13	01484721
4.0	2.6	1.6	8.4	<1	<1	13	
6.9	4.4	2.2	11	9	10	17	01484722
5.9	4.1	1.7	11	8	10	19	
6.9	4.2	3.8	8.1	<1	<1	ñ	01484723
4.4	3.2	1.8	7.7	<1	<1	16	
7.2	5.1	2.6	10	1	1	17	01484725
4.0	3.3	1.7	8.8	2	2	15	
12	7.1	4.8	9.7	2	2	21	01484726
5.8	3.5	2.2	8.0	2	3	17	
6.6	6.5	1.8	11	<1	<1	14	01484727
2.0	1.8	1.0	8.6	<1	<1	16	
7.4	4.7	2.4	11	<1	<1	15	01484728
4.8	2.9	2.6	9.4	6	7	18	
15	9.4	5.5	11	8	10	24	01484729
6.8	4.8	2.2	8.4	8	10	16	
13	6.0	2.6	9.6	2	2	15	01484730
7.3	3.8	1.9	7.8	4	6	13	

Table 3. *Chemical characteristics of stream base flow at nontidal stream-sample sites in the Maryland Coastal Bays drainage area, JanuaryñFebruary 1999 and FebruaryñMarch 2000ó* Continued

Station identification number	Date	Discharge, instantaneous (ft^3/s)	Barometric pressure (mm of Hg)	Oxygen, dissolved (mg/L)	pH, water, whole (standard units)	Specific conductance (µS/cm)	Temperature, air (∞C)	Temperature, water (∞C)
01484731	02/10/1999	0.06	766	9.8	6.9	410	12.0	7.7
	02/11/2000	.15	ñ	10.6	7.0	319	10.5	7.3
01484732	02/10/1999	.43	766	10.2	6.6	283	11.0	8.4
	02/11/2000	.87	ñ	9.6	6.4	204	13.0	8.8
01484733	02/10/1999	.46	766	10.8	5.1	257	12.0	9.1
	02/11/2000	.41	ñ	11.5	6.2	221	12.0	10.2
*0148473510	02/09/1999	.21	764	8.3	6.7	248	11.5	10.3
	03/02/2000	.24	758	8.4	6.5	233	12.5	12.5
*0148474010	02/10/1999	.17	766	8.9	5.9	157	14.0	7.4
	03/02/2000	.38	758	8.8	5.7	113	14.0	11.9

Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Potassium, dissolved (mg/L as K)	Sodium, dissolved (mg/L as Na)	Alkalinity (mg/L as $CaCO_3$)	Bicarbonate (mg/L as HCO_3)	Chloride, dissolved (mg/L as Cl)	Station identification number
32	12	7.2	22	28	34	41	01484731
23	9.5	4.1	16	30	37	30	
16	12	3.2	14	1	1	25	01484732
11	8.1	2.1	9.8	10	12	18	
19	8.1	5.2	8.7	2	2	20	01484733
15	6.7	4.3	8.2	7	9	18	
15	10	3.2	11	16	19	18	*0148473510
13	9.0	3.1	12	25	31	19	
6.9	5.1	1.7	11	6	7	20	*0148474010
4.3	3.0	1.5	9.6	10	12	16	

Table 3. *Chemical characteristics of stream base flow at nontidal stream-sample sites in the Maryland Coastal Bays drainage area, JanuaryñFebruary 1999 and FebruaryñMarch 2000ó* Continued

Station identification number	Date	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Sulfate, dissolved (mg/L as SO_4)	Nitrogen, ammonia, dissolved (mg/L as N)	Nitrogen, ammonia plus organic, dissolved (mg/L as N)	Nitrogen, ammonia plus organic, total (mg/L as N)	Nitrogen, nitrite plus nitrate, dissolved (mg/L as N)	Nitrogen, nitrite, dissolved (mg/L as N)
*0148469995	02/24/1999	<0.10	10.0	42	1.110	2.00	2.10	8.04	0.026
*01484710	02/23/1999	< .10	9.0	29	.065	.75	.73	6.28	.013
*01484714	02/23/1999	< .10	4.3	26	< .020	.30	.34	.67	< .010
01484716	01/27/1999	< .10	8.4	28	.036	.37	.61	.90	.013
	02/08/2000	< .10	12.0	29	.049	.32	.51	1.57	< .010
01484717	01/13/1999	< .10	11.0	47	.020	.26	.30	.20	< .010
	02/09/2000	< .10	11.0	33	.023	.26	.57	1.02	< .010
01484718	01/13/1999	< .10	20.7	11	.035	.11	.39	4.97	.013
	02/09/2000	< .10	20.0	11	.022	.15	.54	4.67	< .010
01484719	01/28/1999	< .10	10.6	32	.027	.67	.69	1.12	< .010
	02/08/2000	< .10	11.0	23	.030	.46	.53	1.18	< .010
01484720	01/28/1999	< .10	14.9	42	.025	.53	.54	3.70	.012
	02/09/2000	< .10	16.0	32	.035	.32	.44	2.62	< .010
01484721	01/28/1999	< .10	19.9	47	.023	.42	.42	.08	< .010
	02/09/2000	< .10	17.0	16	.029	.34	.43	.28	< .010
01484722	01/27/1999	< .10	14.7	24	.036	.48	.77	.23	.015
	02/09/2000	< .10	16.0	17	.022	.34	.45	.40	< .010
01484723	01/28/1999	< .10	12.2	ñ	.020	1.08	1.11	.22	.012
	02/09/2000	< .10	13.0	15	.253	.90	1.00	.21	< .010
01484725	02/11/1999	< .10	11.0	33	.024	.33	.50	.46	< .010
	02/10/2000	< .10	11.0	17	< .020	.30	.85	.43	< .010
01484726	01/29/1999	< .10	8.8	33	< .020	.54	.55	4.20	< .010
	02/09/2000	< .10	8.7	14	.020	.44	.53	1.17	< .010
01484727	02/11/1999	< .10	13.6	54	< .020	.16	.21	< .05	< .010
	02/10/2000	< .10	12.0	11	< .020	.37	.73	< .05	< .010
01484728	01/29/1999	< .10	12.1	36	< .020	.33	.32	< .05	.011
	02/10/2000	< .10	9.4	15	.028	.25	.39	.36	< .010
01484729	02/11/1999	< .10	12.4	54	.065	.51	.55	1.25	< .010
	02/10/2000	< .10	11.0	19	.029	.38	.49	1.34	< .010
01484730	02/10/1999	< .10	14.6	46	< .020	.33	.32	1.51	< .010
	02/10/2000	< .10	12.0	20	< .020	.31	.42	.80	< .010

Phosphorus, dissolved (mg/L as P)	Phosphorus, ortho, dissolved (mg/L as P)	Phosphorus, total (mg/L as P)	Solids residue at 180 ∝C, dissolved (mg/L)	Iron, dissolved (µg/L as Fe)	Manganese, dissolved (µg/L as Mn)	Carbon, organic, dissolved (mg/L as C)	Station identification number
0.021	0.013	0.050	206	400	86	9.8	*0148469995
.011	.012	.038	157	280	48	9.3	*01484710
.012	< .010	.020	112	54	11	5.7	*01484714
.057	.037	.131	131	118	35	6.0	01484716
.024	.022	.077	133	36	46	4.0	
.008	< .010	.016	164	76	42	6.4	01484717
.006	< .010	.074	131	260	47	6.6	
.017	.022	.040	114	37	16	1.7	01484718
.011	.014	.049	108	34	13	2.9	
.027	.015	.055	129	389	65	15.0	01484719
.013	.017	.031	105	370	46	12.8	
.082	.072	.114	148	138	89	11.0	01484720
.039	.035	.052	122	120	47	7.5	
.007	< .010	.021	138	329	32	11.0	01484721
.020	< .010	.014	89	300	19	11.2	
.026	.014	.077	119	441	43	15.0	01484722
.014	.012	.029	104	350	26	10.8	
.094	.068	.109	168	442	67	39.0	01484723
.027	.017	.056	117	650	33	22.1	
.025	.018	.055	110	129	74	8.7	01484725
.018	.013	.111	88	490	38	10.5	
.008	< .010	.017	126	56	44	8.5	01484726
.011	< .010	.019	88	150	26	11.9	
.005	< .010	.008	120	138	46	6.4	01484727
E .003	< .010	.045	86	380	17	15.3	
.016	.011	.028	110	212	49	9.4	01484728
.013	< .010	.036	82	260	27	8.4	
.029	.018	.045	161	164	35	7.1	01484729
.023	.016	.044	103	330	33	8.8	
.008	.016	.014	126	59	44	5.5	01484730
.020	.011	.033	99	280	33	6.3	

Table 3. *Chemical characteristics of stream base flow at nontidal stream-sample sites in the Maryland Coastal Bays drainage area, JanuaryñFebruary 1999 and FebruaryñMarch 2000ó* Continued

Station identification number	Date	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Sulfate, dissolved (mg/L as SO_4)	Nitrogen, ammonia, dissolved (mg/L as N)	Nitrogen, ammonia plus organic, dissolved (mg/L as N)	Nitrogen, ammonia plus organic, total (mg/L as N)	Nitrogen, nitrite plus nitrate, dissolved (mg/L as N)	Nitrogen, nitrite, dissolved (mg/L as N)
01484731	02/10/1999	<0.10	11.3	77	0.030	0.59	0.69	3.84	0.019
	02/11/2000	< .10	7.0	47	.093	.48	.52	4.09	.016
01484732	02/10/1999	< .10	13.4	56	< .020	.27	0.32	3.98	< .010
	02/11/2000	< .10	13.0	31	< .020	.35	.41	4.21	< .010
01484733	02/10/1999	< .10	10.8	52	.094	.56	.60	5.29	.011
	02/11/2000	< .10	12.0	43	.091	.54	.62	3.24	.013
*0148473510	02/09/1999	< .10	13.8	45	.030	.16	.31	4.57	.010
	03/02/2000	< .10	13.0	39	.595	.88	1.60	3.42	.013
*0148474010	02/10/1999	< .10	17.6	25	.022	.29	.32	.79	.015
	03/02/2000	< .10	14.0	11	.036	.36	.85	.65	< .010

Phosphorus, dissolved (mg/L as P)	Phosphorus, ortho, dissolved (mg/L as P)	Phosphorus, total (mg/L as P)	Solids residue at 180 ∝C, dissolved (mg/L)	Iron, dissolved (µg/L as Fe)	Manganese, dissolved (µg/L as Mn)	Carbon, organic, dissolved (mg/L as C)	Station identification number
0.094	0.097	0.134	260	48	30	6.7	01484731
.056	.044	.092	199	120	73	4.3	
.011	.019	.025	171	117	28	4.2	01484732
.022	.012	.042	139	170	25	6.0	
.005	.014	.034	145	192	69	5.7	01484733
.008	< .010	.035	147	330	60	6.9	
.013	.020	.024	144	66	34	2.9	*0148473510
.052	.037	.150	140	89	36	ñ	
.009	.018	.014	110	227	36	8.2	*0148474010
.011	< .010	.076	90	300	20	ñ	

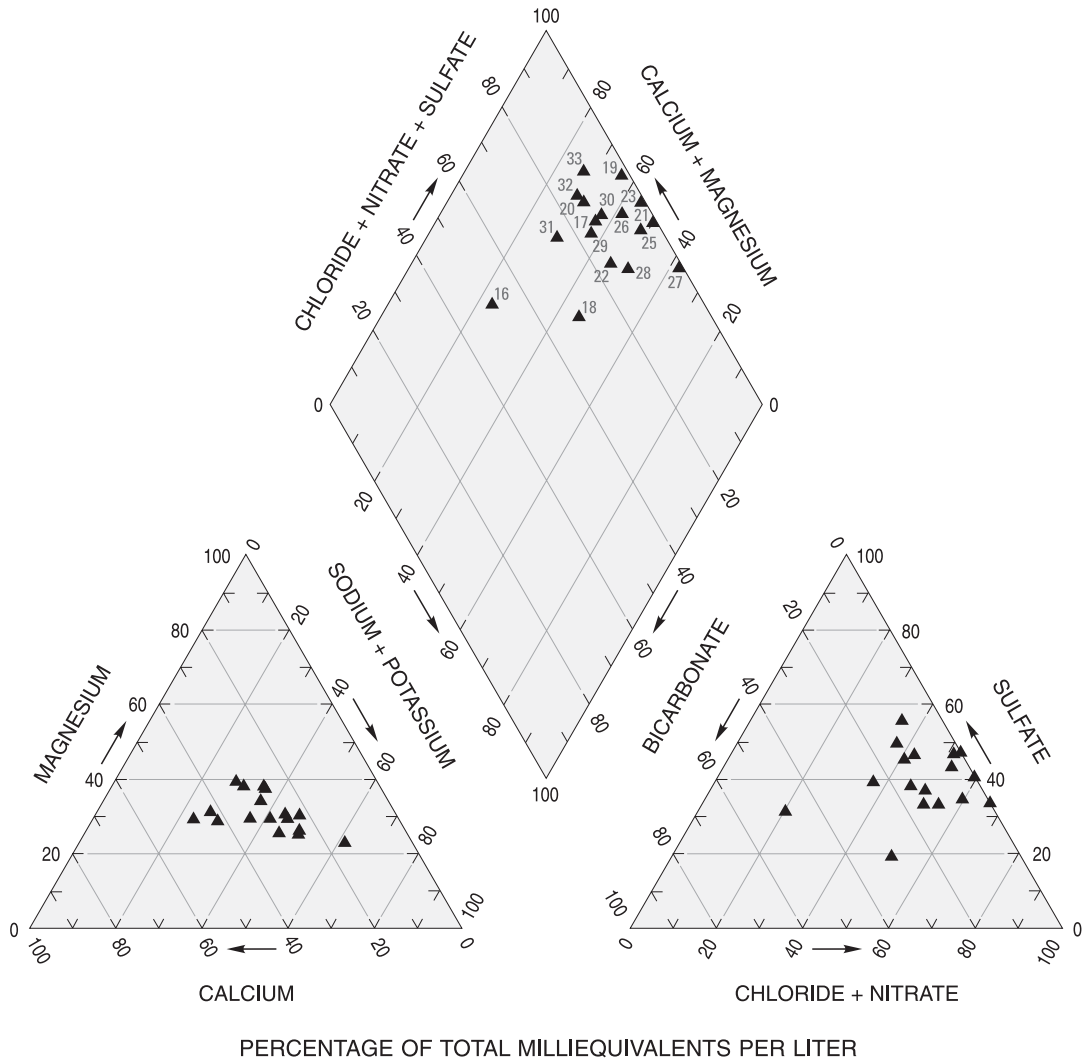


Figure 7. Chemical composition of stream base flow from sample sites in the study area, Worcester County, Maryland.

statistical analysis of the land-use data and average nitrate values collected during base-flow sampling indicate a significant, positive correlation (R^2=0.31, and p=0.0199) between nitrate concentration in base flow and the percentage of land area devoted to row crops within a stream drainage basin. The analyses also indicated a significant negative correlation (R^2=0.32, and p=0.0177) between average nitrate concentration in base flow and the percentage of land area characterized as deciduous forest. The development of precise relations between nitrate concentrations and land-use characteristics is not possible because of the limited amount of sampling done during this study, but the significance of the correlations indicates that further investigations in this area may be useful. The characterization of relations between water quality in wells and land use was not attempted because of a lack of hydraulic information that would allow the reliable delineation of areas of influence for wells used in the study.

GROUND-WATER DISCHARGE TO THE BAYS

A major factor in defining the effect of ground water on the water quality of Sinepuxent and Chincoteague Bays is the determination of the occurrence and distribution of ground-water discharge to the bays. The water-level data and water-quality data collected during this study indicate that in some areas direct ground-water discharge to the bays is minimal,

Table 4. *Land-use characteristics of sampled stream basins in the Maryland Coastal Bays drainage area, in percent*

[Data from Vogelmann, 1993]

Identification number (fig. 2)	Water	Low intensity residential	High intensity commercial/ residential	Pasture/ hay	Row crops	Evergreen forest	Mixed forest	Deciduous forest	Woody wetlands	Emergent wetlands	Barren
01484716	0.0	30.1	3.5	31.7	20.9	1.9	9.4	2.5	0.0	0.0	0.0
01484717	3.0	10.9	2.1	5.8	21.9	18.5	10.7	21.8	4.4	.9	0.0
01484718	.2	0.0	.1	23.3	47.0	6.3	8.2	7.5	7.2	.2	0.0
01484719	.4	.1	.3	6.5	48.4	19.6	10.0	11.5	3.1	.1	0.0
01484720	0.0	0.0	0.0	4.2	30.8	28.2	16.7	11.4	8.7	0.0	0.0
01484721	.5	6.4	1.0	15.8	20.6	21.6	14.1	12.7	7.1	.2	0.0
01484722	0.0	.1	0.0	12.5	36.0	9.7	13.8	23.4	4.5	0.0	0.0
01484723	0.0	0.0	0.0	1.1	44.7	8.4	20.4	25.4	0.0	0.0	0.0
01484725	.3	0.0	.1	8.5	21.5	3.6	22.2	23.6	2.5	1.2	16.5
01484726	0.0	0.0	.3	2.3	30.6	32.9	6.9	6.2	10.2	0.0	10.6
01484727	1.0	0.0	.6	1.2	41.6	24.9	11.8	6.6	9.9	.9	1.5
01484728	0.0	0.0	0.0	1.4	19.7	30.8	17.5	15.9	14.3	0.0	.4
01484729	0.0	0.0	0.0	.8	23.4	6.7	32.8	29.2	7.1	0.0	0.0
01484730	0.0	0.0	0.0	7.2	40.9	20.3	13.0	8.1	10.2	.3	0.0
01484731	0.0	8.5	.6	29.6	43.0	4.6	7.0	6.7	0.0	0.0	0.0
01484732	0.0	0.0	0.0	16.2	45.4	17.6	10.1	5.1	5.2	.4	0.0
01484733	.1	0.0	.3	3.4	85.0	6.4	1.2	3.2	.1	.3	0.0
Study area	**.1**	**1.4**	**0.0**	**9.2**	**27.5**	**16.1**	**9.8**	**10.7**	**5.1**	**18.8**	**1.3**

whereas other areas can receive substantial amounts of direct ground-water discharge. Subsurface resistivity surveys conducted in similar hydrogeologic environments indicate that there are appreciable variations in the geographic distribution of direct ground-water discharge through the bay-bed sediments in areas where such discharge occurs (D.E. Krantz, U.S. Geological Survey, oral commun., 2001). The data collected during this study were not sufficient to determine the geographic distribution of direct ground-water discharge to Sinepuxent and Chincoteague Bays, however.

Ground-Water Gradients

Ground-water hydraulic-head gradients were calculated using the water-level data shown in figures 5añc, along with the known geographic locations of each well cluster. Gradients were calculated in the horizontal direction between selected wells from different clusters, as well as in the vertical direction between wells within each cluster. Horizontal gradients are oriented northwest to southeast unless otherwise noted.

Transect AñA' (fig. 2) has three well clusters. The water-level elevation (head) generally decreases in a northwest-to-southeast direction along this transect, although there are instances where this is not the case. The head gradients between the deepest wells in each of the three clusters ranged from 0.0002 to 0.0005 ft/ft (foot per foot) over a distance of 3.4 mi between wells Cf 56 and Cg 84, and from 0.0003 (southeast to northwest) to 0.0002 ft/ft (northwest to southeast) over 1.7 mi between wells Cg 84 and Dg 23. Vertical head gradients within well clusters in the transect varied from 0.09 ft/ft downward between wells Cg 86 and Cg 85 to 0.02 ft/ft upward between wells Cf 57 and Cf 58.

Transect BñB' has four well clusters. As with transect AñA', water levels decrease in a northwest-to-southeast direction toward the estuary. The horizontal head gradient between wells Ee 23 and Ee 18, the deepest wells in each of their respective clusters, ranges from 0.010 to 0.011 ft/ft over a distance of 1.5 mi. Vertical head gradients within well clusters in the transect varied from 0.6 ft/ft downward between wells Ee 25 and Ee 24 to 0.08 ft/ft upward between wells Ee 19 and Ee 20.

At transect CñC', well clusters in the area are associated with multiple flow paths of varying flow direction; therefore, a discussion of horizontal head gradients is not useful. This complex flow-path pattern is caused by the proximity of Swans Gut Creek and its associated tributaries. Vertical head gradients within well clusters in the transect varied from 0.2 ft/ft downward between wells Fc 58 and Fc 57 to 0.0 ft/ft between wells Fc 52 and Fc 53.

Ground-Water-Flow Paths

Ground-water-flow paths were inferred from hydraulic gradients between wells, relative ground-water ages, geochemical similarities among wells within each transect, and well stratigraphy from gamma logs along the three well transects in the study area (figs. 8añc). In general, deep ground-water-flow paths that discharge to Chincoteague Bay or the Atlantic Ocean can be more than 5 mi long, whereas shallower flow paths that discharge to streams, drainage ditches, ponds, and tidal marshes can be less than 500 ft long. Major factors that affect flow paths in the study area include aquifer thickness and composition, and topography. In figures 8b and 8c, the drainage divide is coincident with the left end of the transect, whereas in figure 8a the drainage divide is approximately 2 mi west of the left end of the transect and is not shown.

Horizontal hydraulic gradients between adjacent well clusters along transects AñA' and BñB' (fig. 2) indicate that the regional flow paths in these parts of the surficial aquifer have a northwest-to-southeast alignment. This alignment is consistent with the flow paths projected by Dillow and Greene (1999). Horizontal gradients between well clusters along transect CñC' indicate that this alignment is not characteristic of the surficial aquifer in the southernmost part of the study area where the surficial aquifer is thinner and more silty. In this area, most flow paths probably discharge to the main-stem channel and deeply incised tributaries of Swans Gut Creek.

A graphic representation of the monthly water levels from each well used in the study grouped by well cluster is shown in figures 5añc. Comparison of these water-level data indicates both short (hundreds of feet) local, and longer (miles) regional flow paths along transects AñAí and BñBí, with short or moderate length local flow paths along transect CñC' (figs. 8añc).

At the upgradient well cluster along transect AñA', the upward hydraulic gradient between wells Cf 57 and Cf 58 indicates a local flow path discharging to

nearby Newport Creek (fig. 8a). However, the downward head gradient between wells Cf 56 and Cf 57 indicates that the lower part of the surficial aquifer at this site is part of an intermediate or regional flow path. Farther downgradient along transect AñA', the downward vertical head gradient between the shallow and intermediate, and intermediate and deep wells (wells Cg 84, Cg 85, and Cg 86) indicates that recharge in the area of this cluster also may infiltrate into the deeper parts of the surficial aquifer to join the regional flow.

The easternmost and most downgradient well cluster in the transect is located on Assateague Island, between Sinepuxent Bay and the Atlantic Ocean (fig. 2). Downward hydraulic gradients between wells within this well cluster (wells Dg 23, Dg 24, and Dg 25) indicate that the ground water may be flowing down into the surficial aquifer, as it does in the previous well cluster (wells Cg 84, Cg 85, and Cg 86). The slightly brackish (330 mg/L as chloride) nature of the water in well Dg 25 likely results from tidal overwash. The flow direction and the occurrence of freshwater in the deep part of the aquifer at this site indicate that the deep, regional flow path of fresh ground water along this transect passes under Assateague Island and discharges at some indeterminate distance offshore in the Atlantic Ocean. This conclusion is not consistent with the assumption used by Dillow and Greene (1999) that all ground water from the northern part of the study area follows flow paths that discharge in Sinepuxent Bay. As a result, the nitrate load to Sinepuxent Bay from direct ground-water discharge may be smaller than was estimated by Dillow and Greene (1999).

Transect BñB' is defined by four well clusters (fig. 2). The most upgradient well cluster consists of three wells, Ee 23, Ee 24, and Ee 25, located near the top of a scarp that defines the upgradient boundary of the local drainage system. The two deeper wells maintained identical water levels during the period when water-level measurements were collected, indicating no vertical head gradient between these two wells. Water from these wells apparently flows along a deep, regional flow path. In contrast, the shallowest well in the cluster is characterized by water levels that are approximately 15 ft higher than those of the two deeper wells, indicating a strong downward vertical head gradient in the shallow part of the aquifer at this site.

The next downgradient well cluster from wells Ee 23, Ee 24, and Ee 25 consists of two wells, Ee 21 and Ee 22, both of which had identical water levels (fig. 5b). As with the deeper two wells of the previous cluster, water levels at both wells of this cluster indicate no vertical head gradient at this site, with all horizontal flow moving toward the southeast along the regional flow path.

The third well cluster along the transect is located on the western shore of Chincoteague Bay and consists of three wells, Ee 18, Ee 19, and Ee 20 (fig. 2). As with the most upgradient cluster, the deeper two wells of this cluster essentially had identical water levels, indicating no vertical head gradient in the deeper part of the aquifer. In this cluster, however, the shallowest well had water levels approximately 2 ft lower than those of the deeper two wells (fig. 5b). This result indicates that there is an upward vertical head gradient from the central to the upper part of the aquifer, indicating probable discharge of ground water into the nearshore part of Chincoteague Bay. The lack of vertical head gradient in the deeper part of the aquifer indicates the presence of a regional flow path, trending southeastward below Chincoteague Bay.

The fourth and most downgradient well cluster in the transect consists of two wells, Ef 26 and Ef 27, located on the bay side of Assateague Island, approximately 6 mi east of the next upgradient well cluster (fig. 2). Water from these wells is saline (well Ef 26) to hypersaline (well Ef 27). Hypersaline conditions in well Ef 27 likely are caused by density-driven infiltration from the occasional inundation by and subsequent evaporation of seawater from overlying salt marshes. Well Ef 26 contains water with major ion concentrations that are comparable to those of seawater. The presence of saline waters in both wells indicates that the regional freshwater flow path terminates west of Assateague Island as direct discharge to Chincoteague Bay. A small upward vertical head gradient, possibly caused by density differences, is present between these wells.

Transect CñC' also is defined by four well clusters, with each cluster consisting of two wells (fig. 2). The surficial aquifer in this vicinity is approximately 50 ft thick, which is thinner than in the rest of the study area. As shown in figure 5c, three wells (Fc 52, Fc 55, and Fc 57) are screened in the confining bed composed of the Yorktown-Eastover Formations (undivided), because the exact thickness of the surficial aquifer in this area was not known at the time the wells were drilled. Well Fc 52 is screened in the upper confining bed that is the uppermost part of the Yorktown-

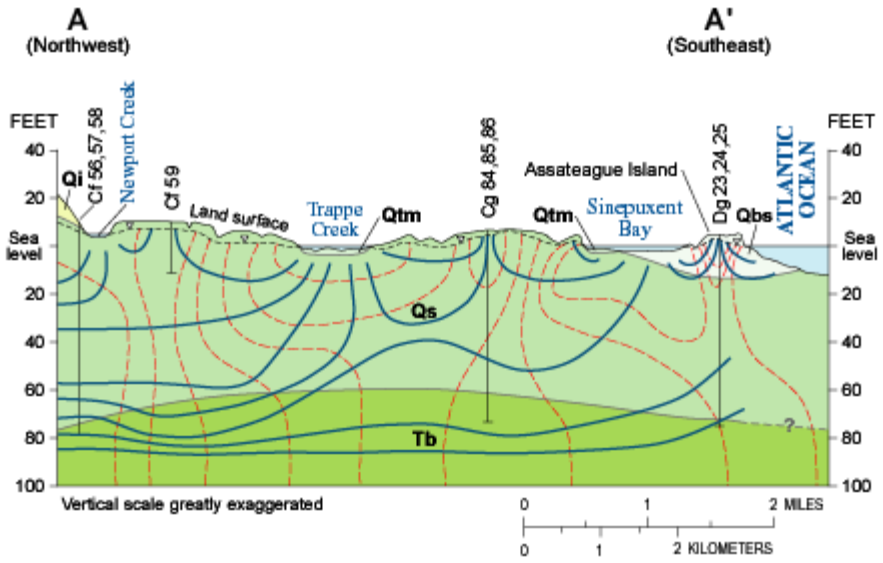


Figure 8a. Flow net for transect A-A', Worcester County, Maryland (shown in figure 2).

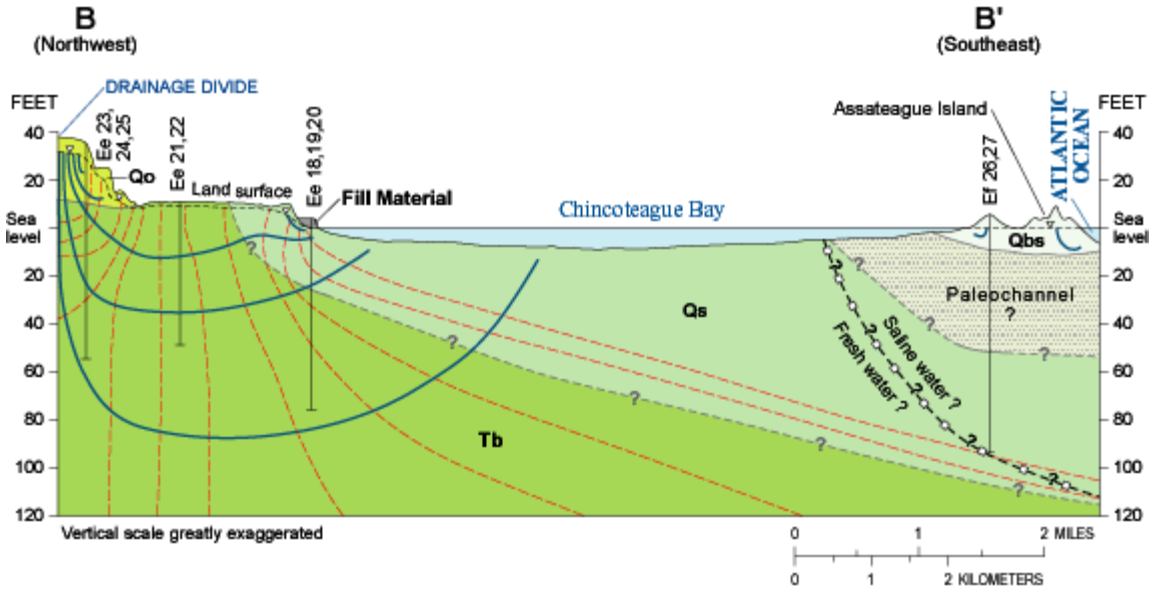


Figure 8b. Flow net for transect B-B', Worcester County, Maryland (shown in figure 2).

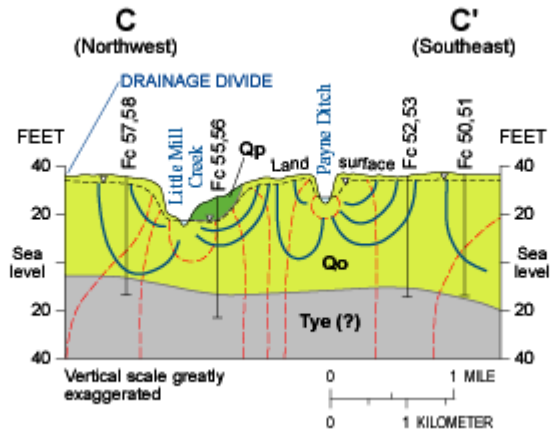
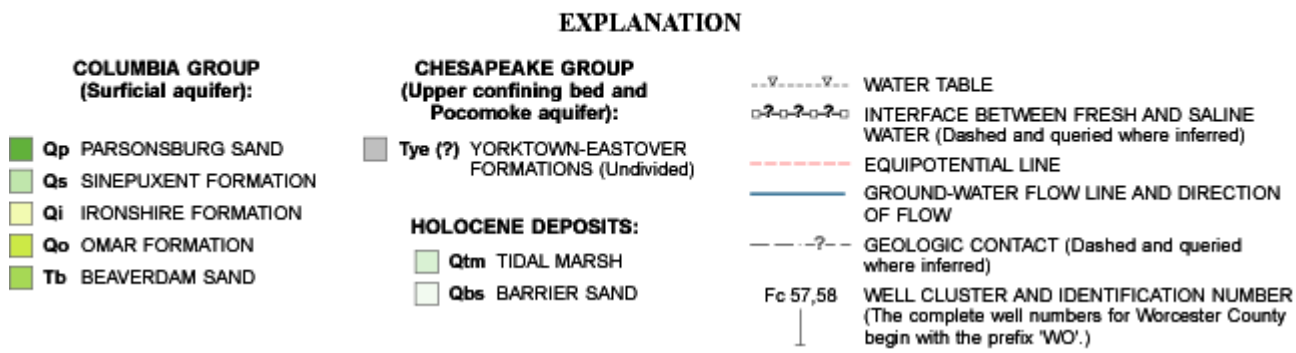


Figure 8c. Flow net for transect C-C', Worcester County, Maryland (shown in figure 2).



Eastover Formations (undivided). Wells Fc 55 and Fc 57 are screened in the Pocomoke aquifer, below the upper confining bed, in the Yorktown-Eastover Formations (undivided).

Unlike transects AñA' and BñB', the northwest-southeast trend of this transect does not parallel the dominant ground-water-flow direction in the vicinity. This difference in flow direction results from the topographic characteristics of the area, which is dominated by a radial drainage pattern associated with Swans Gut Creek and its tributaries, and aquifer material that generally is finer and less permeable than in the rest of the study area. The alignment of the four well clusters roughly parallels the main stem of the creek, with tributary streams interspersed between well clusters.

Three of the well clusters (Fc 50 and Fc 51, Fc 52 and Fc 53, and Fc 57 and Fc 58) are situated on topographic highs between tributary channels near the upgradient end of their respective ground-water-flow paths. The fourth well cluster, Fc 55 and Fc 56, is located somewhat farther downslope and nearer to the main stem of the creek.

All well clusters indicated downward vertical head gradients. The water levels at the two well clusters consisting of wells Fc 52 and Fc 53, and wells Fc 55 and Fc 56, respectively, indicated identical (less than 0.1 ft difference in fluctuation magnitudes) variations (fig. 5c). The variation in water levels between wells within each of the remaining two clusters (wells Fc 50 and Fc 51 and wells Fc 57 and Fc 58) were similar, generally following the same patterns of rise and fall, but with greater differences in water levels than the preceding two clusters, and more than a 1-ft difference in some fluctuation magnitudes. All flow paths that exist in the area of this transect terminate in discharge to the main stem or a tributary stream to Swans Gut Creek, with no deep, regional flow reaching Chincoteague Bay. It is likely that short, local flow paths located east of the transect, which do not provide discharge to the Swans Gut Creek Basin, deliver some direct discharge to Chincoteague Bay.

SUMMARY AND CONCLUSIONS

The mission of the National Park Service at Assateague Island National Seashore in Worcester County, Maryland, includes preserving and protecting

the natural resources of the Park and its adjacent estuaries. In support of this mission, the U.S. Geological Survey, in cooperation with National Park Service at Assateague Island National Seashore, conducted a study of the transport of nutrients in ground water in the surficial aquifer to the estuaries. The study area includes Assateague Island, Chincoteague and Sinepuxent Bays, and the surface-water drainage basins of the bays.

This study was designed to collect data that describe ground-water-flow paths in the surficial aquifer that carry freshwater to Chincoteague and Sinepuxent Bays and their tributary streams, and to collect water-quality data associated with these freshwater inputs, with particular regard to nutrient concentrations. In the study area, the surficial aquifer is mainly composed of the Beaverdam Sand and the Sinepuxent Formation, and ranges from less than 40 feet to more than 120 feet in thickness. Twenty-eight ground-water monitoring wells were installed in the surficial aquifer and the underlying confining bed in 12 clusters in the study area to collect water-level and water-quality data at various depths. In addition, base flow was measured and water-quality samples were collected at 17 sites on nontidal streams in the study area to define the concentrations and amounts of nutrients being contributed to Chincoteague Bay from base flow at each site. Analyses of the data from these wells and streams were used to characterize ground-water-flow paths in the study area and ground-water-nutrient contributions to Chincoteague and Sinepuxent Bays.

In the study area, the surficial aquifer is under water-table conditions. Water recharged to the surficial aquifer follows flow paths with lengths ranging from less than 500 feet to more than 5 miles. Many of the shorter flow paths end by discharging ground water as base flow to streams, whereas longer flow paths end by discharging ground water directly to Chincoteague Bay or the Atlantic Ocean. Ground-water age dating indicates that traveltimes for ground water following a shorter flow path through sandy aquifer material before discharging to a stream may range from less than 1 year to as long as 5 years. Traveltimes for ground water following shorter flow paths in silty sands, such as in the Omar Formation, are longer. Ground water flowing along longer flow paths may take 30 years or more to reach the discharge point at the end of the flow path. The volume of direct ground-water discharge to Sinepuxent Bay, following short flow paths discharging near the bay shoreline, probably is relatively small compared to the volume of ground water flowing beneath the bay to the Atlantic Ocean. Chincoteague Bay likely receives an appreciable amount of direct ground-water discharge that is not input near the bay shoreline. However, the data collected during this study are insufficient to show the geographic distribution of this type of ground-water discharge.

Based on the water-quality data collected from both wells and streams, dissolved ammonia and dissolved nitrate are the dominant nutrients in ground water in the study area. Ammonia concentrations as high as 23.4 milligrams per liter as nitrogen were detected in anoxic ground-water samples. Nitrate concentrations in ground-water samples ranged from below the analytical reporting limit for nitrate of 0.05 milligrams per liter as nitrogen to 15.5 milligrams per liter as nitrogen. Only 6 of 25 wells sampled had water with detectable nitrate concentrations.

In contrast, nitrate concentrations in stream base-flow samples were above the analytical reporting limit for all but 1 of 17 streams sampled. In addition, the majority of base-flow nitrate samples had concentrations above the background level that is found in surface water in the study area, 0.4 milligrams per liter as nitrogen, indicating that stream base-flow water quality at most stream sites is being affected by anthropogenic activities. Because the length of the flow paths supplying the majority of base flow to streams is short, the effects of anthropogenic nitrate can be seen in the aquatic environment of the bays within 5 years after entering the surficial aquifer. Dissolved nitrate concentrations in stream base-flow samples in this study ranged from below 0.05 milligrams per liter as nitrogen to 5.28 milligrams per liter as nitrogen, and showed a significant, positive correlation with the percentage of stream basin area used to cultivate row crops.

Data collected during this study may affect the validity of two assumptions used in a previous study of the area. Based on the base-flow nitrate concentrations seen in the current study, the assumption of average annual base-flow nitrate concentrations may be revised upward from 0.72 milligrams per liter as nitrogen to 1.75 milligrams per liter as nitrogen. Based on the flow-gradient and water-quality data collected during this study, the flow-path configuration used by previous studies may be revised to show that flow paths in the northern part of the study area discharge to the Atlantic Ocean, not to Sinepuxent Bay. This is incon-

sistent with the previous assumption that all ground water from the northern part of the study area follows flow paths that discharge in Sinepuxent Bay. As a result, the actual nitrate load to Sinepuxent Bay from direct ground-water discharge may be appreciably smaller than was previously estimated.

These results indicate that stream base flows with high nitrate concentrations can have a significant effect on water quality, particularly in the area near the western shores of Chincoteague and Sinepuxent Bays. Although high nitrate concentrations are not as prevalent in water samples from wells, the data indicate that appreciable nitrate concentrations can be present in deep flow paths that discharge directly to Chincoteague Bay. In addition, any dissolved ammonia that is transported by ground water and discharged to local streams or Chincoteague Bay could be oxidized to form nitrate. The data collected during this study are insufficient to indicate whether deep flow paths contribute direct ground-water discharge with appreciable concentrations of nitrate to the bay.

REFERENCES CITED

Achmad, Grufron, and Wilson, J.M., 1993, Hydrogeologic framework and the distribution and movement of brackish water in the Ocean City-Manokin Aquifer system at Ocean City, Maryland: Maryland Geological Survey Report of Investigations No. 57, 125 p.

Andres, A.S., 1987, Estimate of direct discharge of fresh ground water to Rehoboth and Indian River Bays: Delaware Geological Survey Report of Investigations No. 43, 37 p.

ó ó ó **1992**, Estimate of nitrate flux to Rehoboth and Indian River Bays, Delaware, through direct discharge of ground water: Delaware Geological Survey Open File Report No. 35, 36 p.

Bachman, L.J., 1984, Nitrate in the Columbia Aquifer, central Delmarva Peninsula, Maryland: U.S. Geological Survey Water-Resources Investigations Report 84ñ4322, 36 p.

Bachman, L.J., and Phillips, P.J., 1996, Hydrologic landscapes on the Delmarva Peninsula, part 2ó Estimates of base-flow nitrogen load to Chesapeake Bay: Water Resources Bulletin, v. 32, no. 4, p. 779ñ791.

Brady, N.C., 1974, The nature and properties of soils (8th ed.): New York, Macmillan Publishing Company, 639 p.

Busenberg, Eurybiades, and Plummer, L.N., 2000, Dating young groundwater with sulfur hexafluorideó natural and anthropogenic sources of sulfur hexafluoride: Water Resources Research, v. 36, no. 10, p. 3,011ñ3,030.

Chaillou, J.C., Weisberg, S.B., Kutz, F.W., DeMoss, T.E., Mangiaracina, Leonard, Magnien, Robert, Eskin, Richard, Maxted, John, Price, K.S., and Summers, J.K., 1996, Assessment of the ecological condition of the Delaware and Maryland Coastal Bays: Washington, D.C., U.S. Environmental Protection Agency, Office of Research and Development, EPA/620/Rñ96/004, 274 p.

Chapelle, F.H., 1993, Ground-water microbiology and geochemistry: New York, John Wiley and Sons, 424 p.

Denny, C.S., Owens, J.P., Sirkin, L.A., and Rubin, Meyer, 1979, The Parsonsburg Sand in the central Delmarva Peninsula, Maryland and Delaware: U.S. Geological Survey Professional Paper 1067ñB, 16 p.

Denver, J.M., 1986, Hydrogeology and geochemistry of the unconfined aquifer, west-central and southwestern Delaware: Delaware Geological Survey Report of Investigations No. 41, 100 p.

ó ó ó **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 No. 45, 66 p.

Dillow, J.J.A., and Greene, E.A., 1999, Ground-water discharge and nitrate loadings to the coastal bays of Maryland: U.S. Geological Survey Water-Resources Investigations Report 99ñ4167, 8 p.

Drever, J.I., 1988, The geochemistry of natural waters (2d ed.): Englewood Cliffs, N.J., Prentice Hall, 437 p.

Dunkle, S.A., Plummer, L.N., Busenberg, Eurybiades, Phillips, P.J., Denver, J.M., Hamilton, P.A., Michel, R.L., and Coplen, T.B., 1993, Chlorofluorocarbons (CCl_3F and CCl_2F_2) as dating tools and hydrologic tracers in shallow groundwater of the Delmarva Peninsula, Atlantic Coastal Plain, United States: Water Resources Research, v. 29, no. 12, p. 3,837ñ3,860.

Fishman, M.J., and Friedman, L.C., eds., 1989, Methods for determination of inorganic substances in water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A1, 545 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, N.J., Prentice Hall, 604 p.

Halsey, S.D., 1978, Late Quaternary geologic history and morphologic development of the barrier island system along the Delmarva Peninsula of the Mid-Atlantic Bight: Wilmington, University of Delaware, Ph.D. dissertation, 592 p.

ó ó ó **1979**, Nexusó New model of barrier island development, *in* Leatherman, S.P., ed., Barrier islands from the Gulf of St. Lawrence to the Gulf of Mexico: New York, Academic Press, p. 185ñ210.

Hamilton, P.A., Denver, J.M., Phillips, P.J., and Shedlock, R.J., 1993, Water-quality assessment of the Delmarva Peninsula, Delaware, Maryland, and Virginiaó Effect of agricultural activities on nitrate and inorganic constituents in the surficial aquifer: U.S. Geological Survey Open-File Report 93ñ40, 87 p.

Hansen, H.J., 1981, Stratigraphic discussion in support of a major unconformity separating the Columbia Group from the underlying upper Miocene aquifer complex in eastern Maryland: Southeastern Geology, v. 22, no. 3, p. 123ñ138.

ó ó ó **1983**, Maryland Atlantic Coast, *in* Jordan, R.R., and Smith, R.V., coordinators, American Association of Petroleum Geologistsó correlation of stratigraphic units in North Americaó Atlantic Coastal Plain Region correlation chart: Norman, Okla., American Association of Petroleum Geologists, 1 sheet.

Maryland Coastal Bays Program, 1997, Todayís treasures tomorrowó an environmental report on Marylandís coastal bays: Annapolis, Md., Maryland Department of Natural Resources, Maryland Coastal Bays Program 97ñ02.

Mixon, R.B., 1985, Stratigraphic and geomorphic framework of uppermost Cenozoic deposits in the southern Delmarva Peninsula, Virginia and Maryland: U.S. Geological Survey Professional Paper 1067ñG, 53 p.

Modica, Edward, 1999, Source and age of ground-water seepage to streams: U.S. Geological Survey Fact Sheet 063ñ99, 4 p.

National Oceanic and Atmospheric Administration, 1977, Climate of Maryland, *in* Climatography of the United States: Washington, D.C., Periodic summarization of climate, no. 60, Climates of the States, 19 p.

Owens, J.P., and Denny, C.S., 1978, Geologic map of Worcester County: Maryland Geological Survey, scale 1:62,500, 1 sheet.

ó ó ó **1979**, Upper Cenozoic deposits of the Central Delmarva Peninsula, Maryland and Delaware: U.S. Geological Survey Professional Paper 1067ñA, 28 p.

Rasmussen, W.C., and Slaughter, T.H., 1955, The ground-water resources of Somerset, Wicomico, and Worcester Counties: Maryland Geological Survey Bulletin No. 16, 533 p.

Richardson, D.L., 1994, Hydrogeology and analysis of the ground-water-flow system of the Eastern Shore, Virginia: U.S. Geological Survey Water-Supply Paper 2401, 108 p.

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 Virginiaó Results of investigations, 1987ñ91: U.S. Geological Survey Water-Supply Paper 2355ñA, 41 p.

Smigaj, M.J., Saffer, R.W., and Marchand E.H., 2001, Water resources data, Maryland and Delaware, water year 2000, volume 2ó Ground-water data: U.S. Geological Survey Water-Data Report MDñDEñ00ñ2, 551 p.

Speiran, G.K., 1996, Geohydrology and geochemistry near coastal ground-water-discharge areas of the Eastern Shore, Virginia: U.S. Geological Survey Water-Supply Paper 2479, 73 p.

Speiran, G.K., Hamilton, P.A., and Woodside, M.D., 1998, Natural processes for managing nitrate in ground water discharged to Chesapeake Bay and other surface watersó more than forest buffers: U.S. Geological Survey Fact Sheet 178ñ97, 6 p.

Vogelmann, James, 1993, Multi-resolution land characteristic (MRLC) grid of Pennsylvania, Maryland, Delaware, Virginia, and West Virginia: U.S. Geological Survey EROS Data Center, Sioux Falls, S. Dak. [data set].

Ward, L.W., and Powars, D.S, 1989, Tertiary stratigraphy and paleontology, Chesapeake Bay Region, Virginia and Maryland: Washington, D.C., American Geophysical Union 28th International Geological Congress Field Trip Guidebook T216, 64 p.

Weigle, J.M., and Achmad, Grufron, 1982, Geohydrology of the fresh-water aquifer system in the vicinity of Ocean City, Maryland, *with a section on* Simulated water-level changes: Maryland Geological Survey Report of Investigations No. 37, 55 p.

Wells, D.V., 2001, The Maryland coastal bays sediment mapping project synthesis report: Maryland Geological Survey data available on the World Wide Web, accessed April 13, 2001, at URL http://mgs.dnr.md.gov/coastal/vmap/czmatlas/czmseddistr.html

Wilde, F.D., Radtke, D.B., Gibs, Jacob, and Iwatsubo, R.T., eds., 1999, National field manual for the collection of water-quality dataó Collection of water samples: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chap. A4, 156 p.