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**EFFECTS OF INCREASED WITHDRAWALS FROM THE
AQUIA AQUIFER ON THE MAYO PENINSULA,
ANNE ARUNDEL COUNTY, MARYLAND
WITH AN EVALUATION OF WATER QUALITY**

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ABBREVIATIONS USED IN THIS REPORT

AAHD	Anne Arundel County Health Department
ALS	ALS Environmental
CDP	Census Designated Place
Cl:Br	Chloride:Bromide mass ratio
DNR	Maryland Department of Natural Resources
MCL	Maximum Contaminant Level
MDDH	Maryland Department of Health
MGS	Maryland Geological Survey
NWIS	National Water Information System (database)
QA/QC	Quality Assurance/Quality Control
SMCL	Secondary Maximum Contaminant Level
TDS	Total Dissolved Solids
USEPA	United State Environmental Protection Agency
USGS	United States Geological Survey
bsl	Below sea level
ft	Feet
ft/day	Feet per day
ft ² /day	Feet squared per day
ft ³ /day	Cubic feet per day
gal/capita/day	Gallons per capita per day
gal/day	Gallons per day
gal/min/ft	Gallons per minute per foot
gal/year	Gallons per year
in.	Inches
in./yr	Inches per year
meq/L	Milliequivalents per liter
mi	Miles
Mgal/d	Million gallons per day
mg/L	Milligrams per liter
pCi/L	Picocuries per liter
μS/cm	Microsiemens per centimeter at 25 degrees Celsius
°C	Degrees Celsius
±	Plus/minus

EFFECTS OF INCREASED WITHDRAWALS FROM THE AQUIA AQUIFER ON THE MAYO PENINSULA, ANNE ARUNDEL COUNTY, MARYLAND WITH AN EVALUATION OF WATER QUALITY

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KEY RESULTS

The Mayo Peninsula in east-central Anne Arundel County, Maryland relies primarily on the Aquia aquifer for drinking-water supply. The deeper Magothy aquifer is also utilized but to a much lesser extent. The lifting of a building moratorium in 2017 on the peninsula associated with increased capacity for treating sewage effluent may result in the construction of up to approximately 630 homes (an approximate 20 percent increase over the number of housing units in 2010). The potential effects of increased domestic water withdrawals to support the possible growth on water levels and on the brackish-water interface in the Aquia aquifer were evaluated. In addition, water quality of the Aquia aquifer, both natural and affected by anthropogenic contaminants, that might constrain the use of the aquifer for domestic potable supply was also evaluated.

EFFECTS OF INCREASED WITHDRAWALS FROM THE AQUIA AQUIFER

The potential increase of between 0.093 and 0.158 million gallons per day resulting from the possible new development on the Mayo Peninsula was evaluated using a one-layer numerical groundwater-flow model (MODFLOW) to estimate the effects on water levels in the Aquia aquifer and on the brackish-water/freshwater interface. The two rates are based on estimated household water-use rates of 147 and 250 gallons per day, respectively.

- Additional withdrawal from the Aquia aquifer resulting from new development will likely result in drawdown (lowering of the water table) of less than 0.25 feet for most of the peninsula.
- Potential drawdown from new development on the peninsula is greatest near Glebe Bay, where drawdown could reach approximately 2 feet.
- Where potential drawdown is greatest, the brackish-water/freshwater interface could rise by approximately 55 feet to more than 65 feet and pose a risk for existing wells near the shoreline.
- The effects of the potential increased withdrawals from the Aquia aquifer could be reduced by shifting pumpage to the deeper Magothy aquifer in areas of greatest drawdown.

EVALUATION OF AQUIA AQUIFER WATER QUALITY

Water quality of the Aquia aquifer on the Mayo Peninsula is generally good; however, in areas near the shoreline (less than 600 feet), chloride concentrations are commonly elevated resulting from brackish-water intrusion. Additionally, anthropogenic contamination from the surface may affect the potability of water from the Aquia. A total of 24 wells were sampled during this study to characterize the water quality of the Aquia aquifer; one well screened in the Magothy aquifer was also sampled for comparison.

- Three wells with chloride concentrations between 284 and 436 milligrams per liter and chloride/bromide mass ratios between 249 and 393 were determined to be affected by brackish-water intrusion. All of these wells are located near the shoreline (less than 600 feet).
- Eight wells with chloride concentrations between 81 and 221 milligrams per liter and a chloride/bromide mass ratio greater than 400 were determined to be affected by surface-based chloride sources.
- One well exceeded the U.S. Environmental Protection Agency Maximum Contaminant Level for arsenic (0.01 milligrams per liter) and three wells exceeded the Maximum Contaminant Level for cadmium (0.005 milligrams per liter). Three wells exceeded Secondary Maximum Contaminant Level for chloride (250 milligrams per liter); seven wells exceeded the Secondary Maximum Contaminant Level for manganese (0.05 milligrams per liter); 17 wells exceeded the Secondary Maximum Contaminant Level for iron (0.3 milligrams per liter); and seven wells were outside the acceptable range for pH (6.5-8.5). Nine wells exceeded the Drinking Water Advisory for sodium (20 milligrams per liter).
- The uppermost portion of the Aquia aquifer is weathered (maximum depth of approximately 75 feet below land surface) and produces water that may be acidic (pH less than 6.5). Cadmium and chloride concentrations tend to be greatest in that portion of the aquifer.
- The deeper Magothy aquifer, an alternative drinking water supply on the peninsula, is less susceptible to surface contamination and brackish-water intrusion; however, iron concentrations can range from 14.0 – 26.0 milligrams per liter, requiring treatment for domestic supply.

INTRODUCTION

Withdrawals from the Aquia aquifer may increase on the peninsula as a result of potential new home construction (infilling of existing lots and new subdivision development) resulting from the lifting of a moratorium imposed on new sewer connections. A maximum of approximately 630 domestic wells could be constructed, resulting in an increase of groundwater withdrawals of approximately 0.158 million gallons per day (Mgal/day). The increase in withdrawals, if supplied by the Aquia aquifer, may adversely impact existing domestic wells and potentially induce the landward migration of brackish water from the surrounding estuary.

Drinking water for the Mayo Peninsula is supplied solely by domestic wells, almost all tapping the shallow, unconfined (water table) Aquia aquifer. Since the Aquia aquifer is mostly exposed at the surface on the peninsula, it is recharged relatively quickly by direct infiltration from precipitation; however, its relatively shallow depth makes it vulnerable to contamination from the surface. As an unconfined aquifer adjacent to brackish water bodies (South, Rhode, and West Rivers, and Chesapeake Bay), the Aquia aquifer is also subject to brackish-water intrusion. Typically, the extent of the brackish-water intrusion is limited to near shore (less than approximately 600 feet [ft]). The deeper, confined Magothy aquifer is also utilized for domestic supply within the study area, although to a much lesser amount. The Magothy aquifer, while capable of supplying significant quantities of water to wells, contains iron concentrations at levels requiring treatment for domestic supply.

Many wells on the peninsula in Anne Arundel County have elevated chloride levels, including wells that are located in the interior of the peninsula where high chloride concentrations would not be expected due to brackish-water intrusion. Other potential chloride sources include road salt, water-softener backwash, sewage effluent (legacy septic systems and leaky sewer lines), and overtopping of wells with brackish water during storm events. Different sources of high-chloride water can often be distinguished from one another using chloride/bromide mass ratios (Cl:Br) (Andreasen and Fleck, 1997; Davis and others, 1998; Mullaney and others, 2009). By distinguishing different chloride sources, County officials would be able to identify appropriate management strategies to guide future use of the groundwater resource for potable water supply.

PURPOSE AND SCOPE

The purpose of this study is to (1) assess the potential effects (drawdown and brackish-water intrusion) of projected increases in groundwater withdrawals from domestic wells in the Aquia aquifer on the Mayo Peninsula, and (2) evaluate the water chemistry of the Aquia aquifer on the peninsula with an emphasis on identifying sources of chloride contamination.

LOCATION OF STUDY AREA

The study area is focused on the Mayo Peninsula, a roughly 4 miles (mi) long by 2 mi wide neck of land bordered by the South River to the north, Chesapeake Bay to the east, and West River and Rhode River to the south (fig. 1). The peninsula has a very irregularly-shaped shoreline with many small inlets and coves. Approximately half of the peninsula lies less than 5 ft above mean sea level. Land use is a mixture of densely-populated residential housing centered around what were historically seasonal beach communities, newer developed communities, and several relatively large forested park lands. To simulate groundwater flow in the Aquia aquifer, a somewhat larger area was included in the study area to the west and south of the peninsula (fig. 1).

PREVIOUS INVESTIGATIONS

In 2002, the Maryland Geological Survey (MGS) conducted a study regarding the water-supply potential of Aquia and Magothy aquifers in southern Anne Arundel County (Andreasen, 2002). The study evaluated the potential effects on groundwater levels from projected pumping scenarios. Although the Mayo Peninsula was included in that study, it was not the focus and therefore lacked the detail needed to address the current specific problem. An earlier study, conducted in the late 1980s by MGS and the U.S. Geological Survey (USGS), did investigate groundwater-supply and groundwater-quality (brackish-water intrusion) issues on the Mayo and Annapolis Neck Peninsula (Fleck and others, 1996). That study specifically included a groundwater-flow model (MODFLOW) and a two-dimensional (cross sectional), solute-transport model (SUTRA)

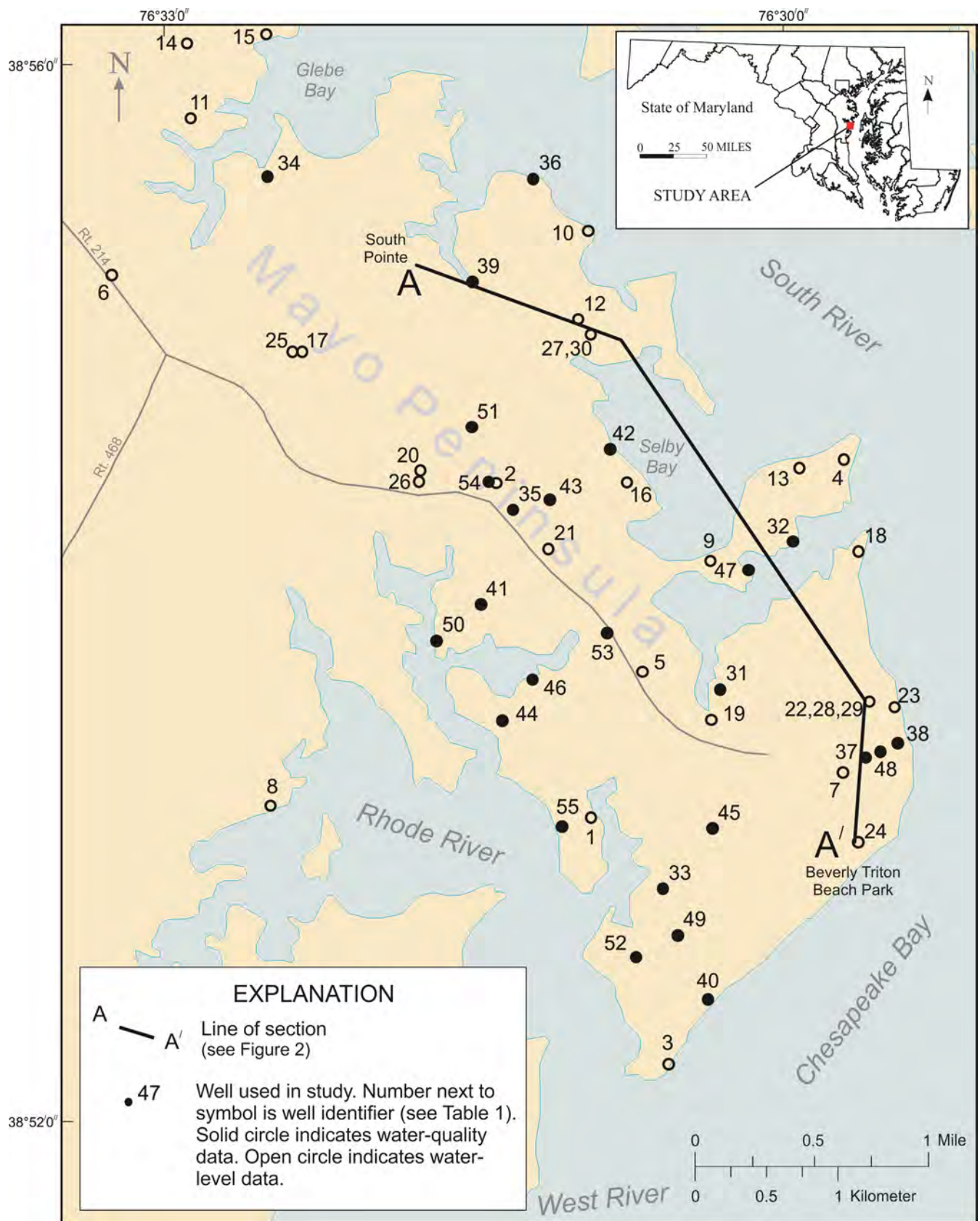


Figure 1. Location of study area.

representing the brackish-water/freshwater interface at a test-well transect along the southern shore of the Annapolis Neck Peninsula.

Water quality of the Aquia aquifer on the peninsula was examined in previous studies by MGS and the USGS. Fleck and others (1996) mapped the extent of chloride from brackish-water intrusion on both the Mayo and Annapolis Neck Peninsula, differentiated between sources of chloride (anthropogenic versus brackish-water intrusion), characterized the major water types and developed a conceptual model of the geochemistry from bay-bottom sediments through the brackish-water/freshwater interface to the freshwater portion of the aquifer. Andreasen (2002) determined the natural water quality of the Aquia and Magothy aquifers in southern Anne Arundel County including the distribution of iron. Bolton (2006) investigated cadmium concentrations in the upper weathered zone of the Aquia aquifer which extends to a maximum depth of 50 ft below land surface. Elevated cadmium concentrations were observed at pH less than 5.5 and were associated with elevated chloride concentrations (chloride greater than 50 milligrams per liter [mg/L]).

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BACKGROUND

HYDROGEOLOGY OF THE MAYO PENINSULA

The Mayo Peninsula is underlain by unconsolidated sediments of Maryland's Coastal Plain Physiographic Province. The sediments, consisting of Cretaceous to Quaternary-age sand, silt and clay, total approximately 2,050 ft in depth on the peninsula (Andreasen and others, 2016). The major aquifers occurring beneath the peninsula include, from shallowest to deepest, the Aquia, Magothy, Patapsco (Upper and Lower), and Patuxent. On the peninsula, only the Aquia and Magothy aquifers are utilized for water supply. A cross section oriented in a northwest-southeast direction from South Pointe to Beverly Triton Beach Park is shown in figure 2.

Geologic formations exposed at the surface of the peninsula include the Tertiary-age Aquia-Brightseat (undifferentiated), Marlboro Clay, Nanjemoy, and Calvert Formations, the Quaternary-age Lowland and Terrace Deposits, and sporadic deposits of Holocene-age alluvium (Glaser, 2002)

(fig. 3). The Tertiary-age formations occur in areas of higher topographic relief and the Quaternary Lowland deposits generally blanket the low-lying areas bordering the Chesapeake Bay. The Aquia Formation is exposed in two areas, one in the southern and one in the northern part of the peninsula. In the low-lying areas, the Aquia Formation is overlain by the Lowland Deposit which generally consists of a silty or clayey sand grading downward to a gravel and pebbly sand (Glaser, 2002). The silty clay of the Lowland Deposit often results in poor drainage and swampy conditions. An exceptional exposure of the Lowland Deposit occurs along the shoreline of Beverly Triton Beach Park at the southern end of the peninsula. At that location the Lowland consists of an olive green silty clay extending from sea level to about 8 ft above sea level and overlain by approximately 4 ft of light-buff silty clay.

The Aquia aquifer is composed chiefly of the Aquia Formation (a marine deposit). In Anne Arundel County, the underlying Severn Formation, a silty-sand layer, is hydraulically connected to the

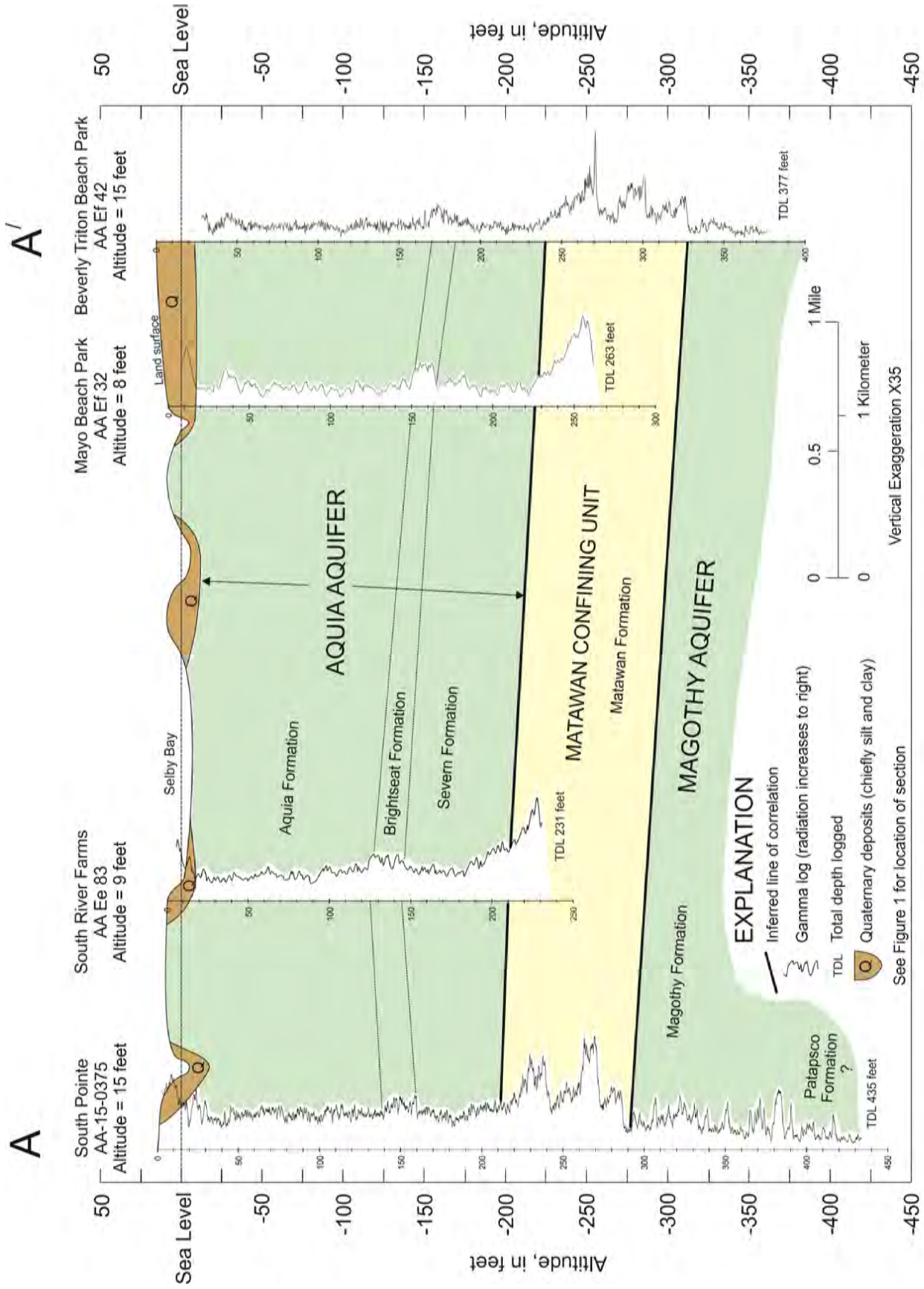


Figure 2. Hydrogeologic cross section A-A' on the Mayo Peninsula.

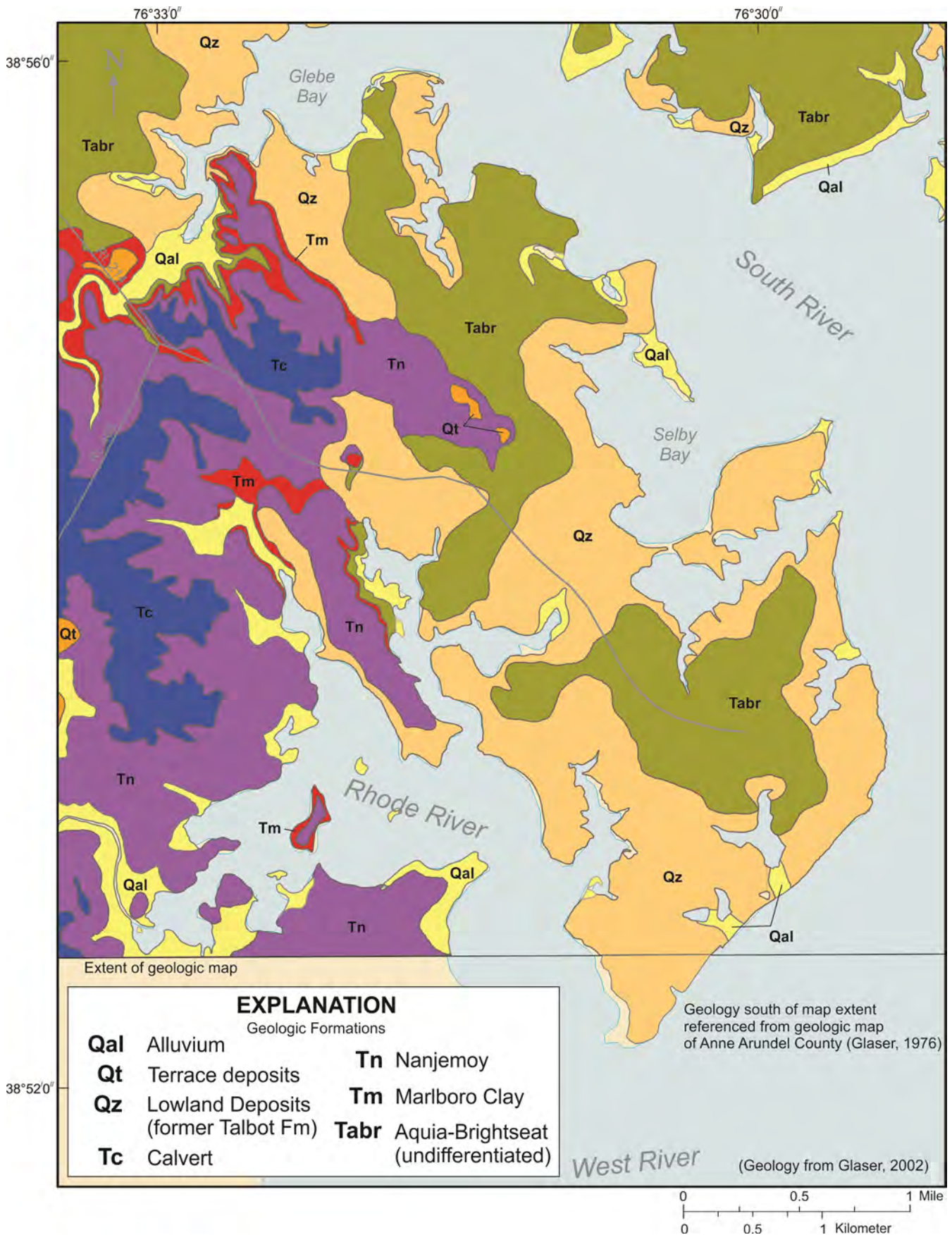


Figure 3. Geologic formations on the Mayo Peninsula.

Aquia through the silty Brightseat Formation, and therefore functions as part of the Aquia aquifer (Fleck and others, 1996). The Aquia aquifer consists of medium to coarse, clear and white quartz sand with moderate amounts of dark-green, brown, and black glauconite (Andreasen, 2002). Shell is common in the Aquia aquifer; however, on the Annapolis Neck and Mayo Peninsulas the shell has often been leached out by acidic recharge water from precipitation forming a white, chalky calcareous silt (Fleck and others, 1996). In less weathered portions of the aquifer, the sediment may appear dark green to black and take on the appearance of “salt and pepper” where glauconite is unaltered by oxidation and quartz grains are free of iron-oxide coatings. In more weathered zones the sediment appears brown with glauconite having been altered to goethite(?), limonite, and iron hydroxide minerals. In those sediments, quartz grains are commonly iron-stained and shell material leached to form sporadic beds of calcareous sandstone. The altitude of the bottom of the Aquia aquifer ranges from about 200 ft below sea level at South Pointe to 225 ft below sea level at Beverly Triton Beach Park (fig. 2). The thickness of the Aquia aquifer ranges on the peninsula ranges from approximately 210 to 225 ft.

The transmissivity of the Aquia aquifer ranges from approximately 930 to 3,420 feet squared per day (ft^2/day) in the confined portion of the aquifer in southern Anne Arundel County (Andreasen, 2002). On the Annapolis Neck Peninsula, aquifer-test analyses indicate the transmissivity of the unconfined Aquia aquifer ranges from 1,120 to 5,600 ft^2/day (Fleck and others, 1996). Given the aquifer thickness at the sites tested, the horizontal hydraulic conductivity ranges from about 4 to 43 feet per day (ft/day). No aquifer-test data are available for the Aquia aquifer on the Mayo Peninsula.

In the higher topographic elevations on the western portion of the peninsula the Aquia aquifer is overlain by (from deepest to shallowest) the Marlboro Clay, Nanjemoy, and Calvert Formations (fig. 3). The Marlboro Clay, consisting of approximately 20 ft of dull gray to reddish-pink, dense, low permeability clay, forms a confining unit overlying the Aquia aquifer. In areas where the Marlboro Clay is present, infiltrating precipitation to the Aquia aquifer is likely reduced compared to areas where the aquifer is directly exposed at the surface. The Nanjemoy and Calvert Formations both consist of silt to fine sand intermixed with clay, and therefore are generally poor water-bearing units.

The silt and clay layers in those formations likely further act to reduce infiltrating precipitation to the Aquia aquifer.

Underlying the Aquia aquifer is the Matawan confining unit, composed chiefly of the Matawan Formation (a marine deposit) and possibly silt or clay beds of the Severn and Magothy Formations (Andreasen and others, 2016) (fig. 2). The Matawan confining unit hydraulically separates the Aquia aquifer from the underlying Magothy aquifer. The confining unit typically consists of dark-green to black, glauconitic and slightly micaceous clay. At many locations, the clay is divided into two distinct layers by a sandy zone composed predominantly of fine- to coarse-grained quartz and black glauconite (Andreasen, 2002). Total thickness of the Matawan generally ranges from 70 to 130 ft in Anne Arundel County (Fleck and others, 1996) and about 80 to 90 ft on the peninsula (fig. 2).

The Matawan confining unit has relatively low permeability with reported vertical hydraulic conductivity ranging from 2.7×10^{-6} to 4.3×10^{-3} ft/day (Mack, 1974; Mack and Mandl, 1977). The relatively thick clay beds of the Matawan unit combined with the low vertical hydraulic conductivity likely results in an effective confining unit. However, reported occurrences of elevated chloride in the underlying Magothy wells near the brackish South River suggests that the unit may be leaky (Bill Dehn, Anne Arundel County Department of Health, personal communication, 2017). Alternatively, the presence of elevated chloride in the confined Magothy aquifer could potentially be a result of movement of brackish water from the overlying Aquia aquifer through insufficiently grouted wells.

The Magothy aquifer is composed chiefly of the sandy portions of the Magothy Formation (a fluvio-marine deposit). The aquifer typically consists of medium- to coarse-grained, light gray to white quartzose sands and gravels, interbedded with layers of white, gray and black clay. Lignite is very common in the Magothy Formation along with the associated mineral pyrite. The deeper portion of the aquifer may include sands of the Patapsco Formation (a fluvio-deltaic deposit) where sand-on-sand contact between the two formations occur (Andreasen, and others, 2016; Fleck and others, 1996). The altitude of the top of the aquifer ranges from about 275 to 315 ft below sea level on the peninsula (fig. 2). The thickness of the Magothy aquifer ranges from approximately 80 ft to as much as 200 ft in some areas (Fleck and others, 1996) and consists of an upper and lower sand in southern

Anne Arundel County (Andreasen, 2002). On the peninsula, total thickness is about 150 ft; however, few wells fully penetrate the unit.

The Magothy aquifer, as a result of its relatively massive, permeable sand beds, is a highly productive aquifer, with transmissivity values ranging from about 1,000 to 12,000 ft²/day (Andreasen and others, 2016). In some instances, transmissivity may be as great as 24,000 ft²/day (Fleck and others, 1996). Owing to its high-yield characteristics, the aquifer is often utilized for larger-scale municipal and institutional withdrawals. No aquifer-test data are available for the Magothy aquifer on the peninsula; however, specific capacity values calculated from pumping-rate and drawdown data reported on well completion reports for 142 wells drilled on the peninsula range from 0.1 to 20 gallons per minute per foot of drawdown (gal/min/ft) with a mean of 3.7 gal/min/ft.

GROUNDWATER WITHDRAWALS

The drinking-water supply on the Mayo Peninsula is supplied entirely by individual domestic wells. The majority of those wells are screened in the Aquia aquifer with less than about 5 percent screened in the deeper Magothy aquifer. Depth of wells is typically less than about 100 ft for the Aquia aquifer and about 380 ft for the Magothy aquifer. The distribution of domestic wells is estimated in figure 4. The map, showing the locations of lots with homes, assumes that each home has one well. The greatest densities of wells occur in the communities of Beverly Beach, Glebe Heights, Loch Haven, Selby-On-The-Bay, Shoreham Beach, Turkey Point, and West Shoreham. The approximately 3,200 wells screened in the Aquia aquifer on the peninsula pump a total of about 0.47 Mgal/day assuming that each well pumps on average 147 gallons per day (gal/day) based on an average household size of 2.45 people and per capita water-use rate of 60 gal/day. If a higher per household water-use rate of 250 gal/day is used, the total withdrawals are about 0.8 Mgal/day. Given the relatively small number of Magothy wells, the amount pumped from that aquifer is negligible.

WATER-LEVEL TRENDS AND WATER TABLE

Long-term observation-well data for the Aquia aquifer on and around the Mayo Peninsula indicate that water levels change little over time. A similar observation was made of Aquia water levels by

Bennion and Brookhart (1949, p. 52), referencing, in part, an observation well on the peninsula (AA Ee 14, located approximately 0.5 mi west of Selby Bay). Water-level trends in the unconfined part of the Aquia aquifer in the vicinity of the peninsula have been fairly stable over the past several decades (fig. 5). In observation well AA De 102, water levels show a very gradual decline since 1970 of about four feet. The Aquia aquifer at that location is overlain by the Marlboro Clay and Terrace Deposit which lie above the water table. Infiltration from precipitation is likely inhibited by the presence of the overlying low-permeability clays. The dampening of seasonal variations in water levels after about 2005 may be attributed to excavation and grading associated with construction of a nearby housing subdivision, which could have altered drainage and infiltration rates. Observation wells AA De 195, AA Ee 83, and AA Ef 34, also located in the unconfined part of the Aquia aquifer, show little change in water levels since 1989 (fig. 5). The Aquia aquifer at those locations is overlain by less than 10 ft of Lowland Deposit. The presence of the generally silty and clayey Lowland Deposit likely reduces infiltration of precipitation; however, the continuous water-level record indicates a direct head response to precipitation events in those wells (Fleck and others, 1996). Observation well AA Ee 67 screened in the confined (artesian) part of the Aquia aquifer shows declining water levels from 1976 to the early 2000s reflecting regional declines (Staley and others, 2016). Since then, water levels have been stable. The stabilization is directly related to a reduction of withdrawals from the Aquia aquifer in St. Mary's County as some pumpage has shifted to the deeper Upper Patapsco aquifer to avoid elevated arsenic concentrations in the Aquia aquifer. In general, withdrawals from the confined portion of coastal plain aquifers do not cause significant declines in water levels in the unconfined portion (outcrop area).

The approximate water-table elevation of the Aquia aquifer is shown in figure 6. The map was drawn using water levels measured over a wide time period extending from 1945 to 2017 (tabs. 1 and 2). The use of water levels from different time periods is justified since heads in the water table, other than varying seasonally, have changed very little over time. The water table generally is a subdued reflection of topography. Water levels are highest (9 ft above sea level) in the west-central portion of the peninsula in areas of higher topographic relief and decrease to sea level toward the shoreline. The direction of groundwater flow is generally to the

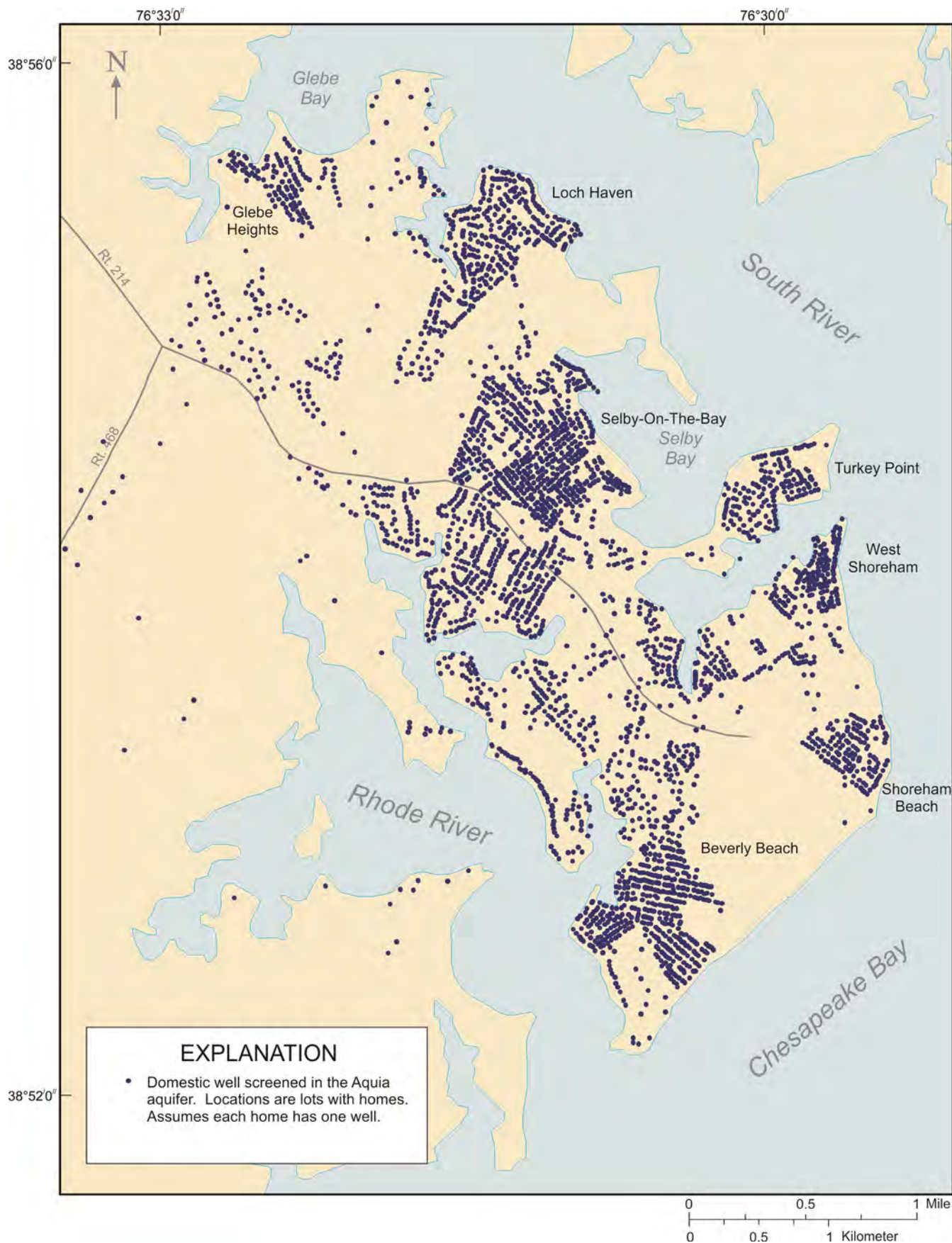


Figure 4. Distribution of domestic wells screened in the Aquia aquifer on the Mayo Peninsula.

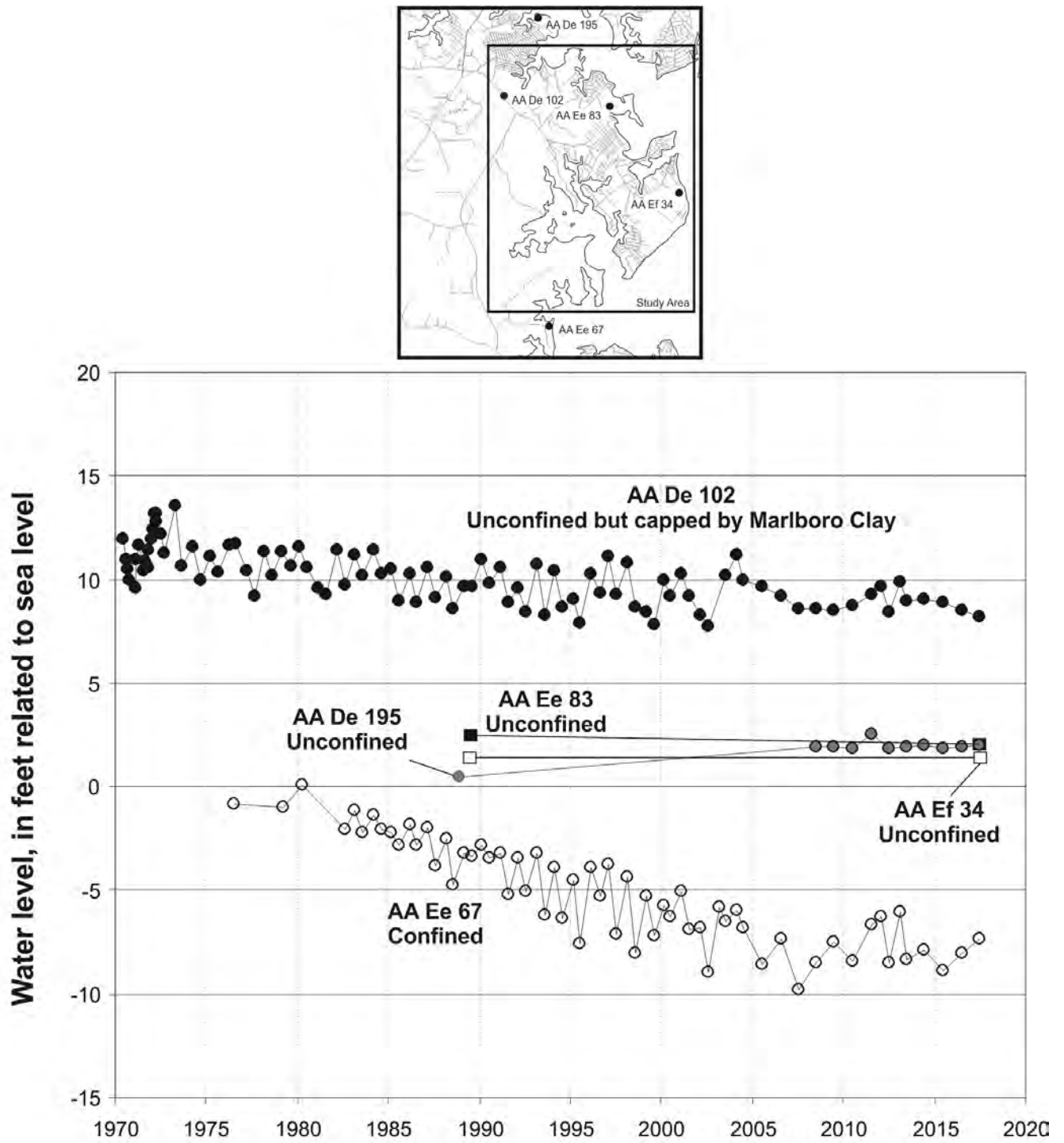


Figure 5. Hydrograph showing water-level trends in the Aquia aquifer.

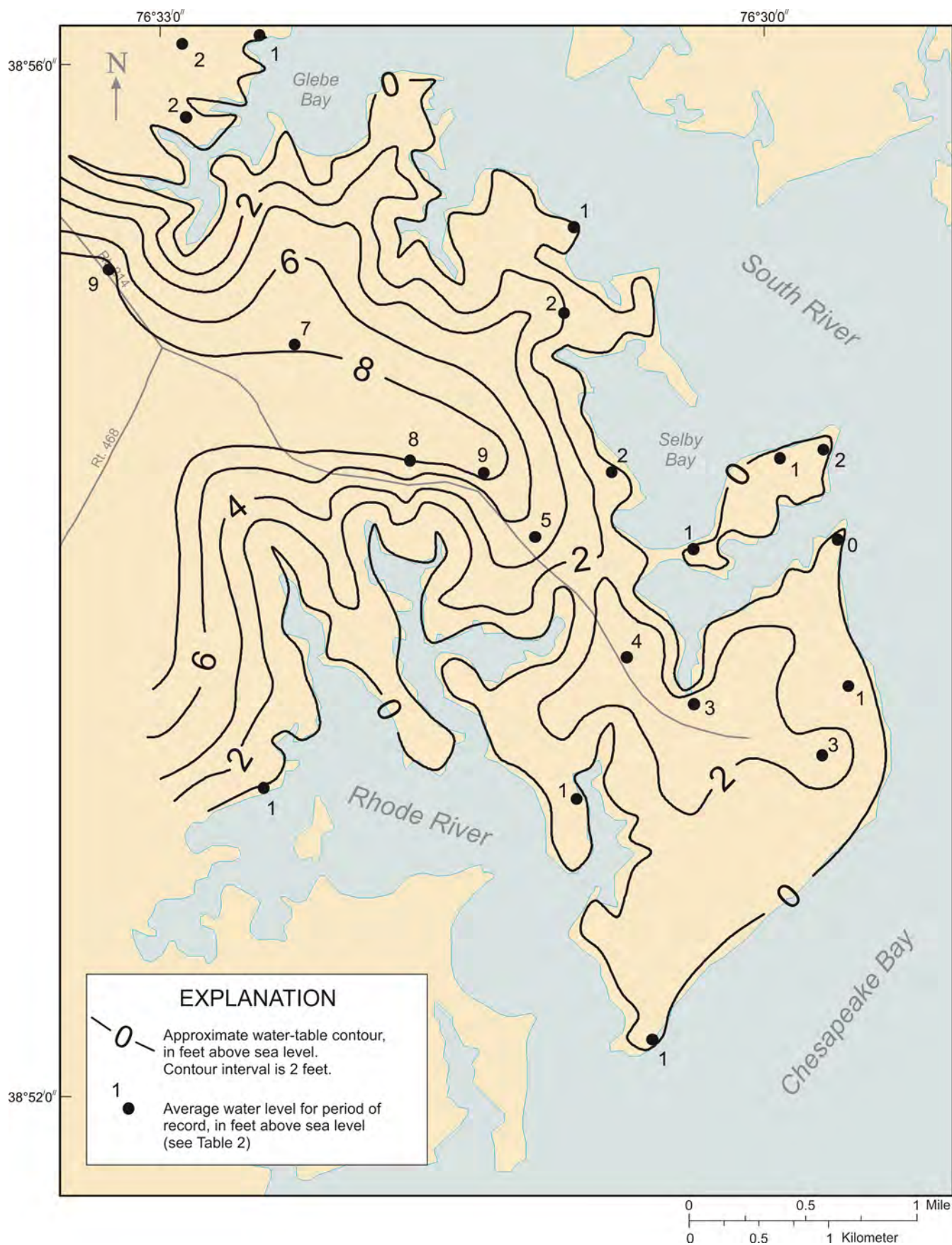


Figure 6. Water table of the Aquia aquifer.

Table 1. Construction records of wells used in this study. All wells are screened in the Aquia aquifer with the exception of AA-95-5706, which is screened in the Magothy aquifer.

[ft, feet; in., inch; QW, water quality; WL, water level]

Map ID (see Figure 1)	Well permit	Well name	Completion year	Depth of well, ft	Depth to top of well screen, ft	Length of well screen, ft	Screen diameter, in.	Type of data (QW,WL)
1	-	AA Ee 3	1946	110	95	5	-	WL
2	-	AA Ee 14	1941	101	-	-	-	WL
3	-	AA Ee 21	1941	95	-	-	-	WL
4	-	AA Ef 5	-	44	-	-	48	WL
5	AA-03-6921	AA Ee 56	1959	70	60	10	2	WL
6	AA-69-0332	AA De 102	1968	96	70	26	-	WL
7	AA-71-0808	AA Ef 17	1971	41	37	4	2	WL
8	AA-73-0208	AA Ee 70	1972	70	65	5	4	WL
9	AA-73-2504	AA Ee 76	1974	60	55	5	4	WL
10	AA-73-5289	AA De 187	1975	40	35	5	4	WL
11	AA-73-6741	AA De 190	1977	58	53	5	2	WL
12	AA-73-8941	AA De 186	1978	45	38	7	2	WL
13	AA-74-2996	AA Ef 24	1981	66	59	7	2	WL
14	AA-74-3436	AA De 183	1981	100	93	7	2	WL
15	AA-81-1925	AA De 182	1983	60	55	5	2	WL
16	AA-81-3780	AA Ee 73	1984	95	90	5	2	WL
17	AA-81-5707	AA Ee 75	1985	125	110	15	6	WL
18	AA-81-7977	AA Ef 27	1987	41	35	6	2	WL
19	AA-81-9887	AA Ee 71	1988	59	52	7	2	WL
20	AA-88-1069	AA Ee 78	1988	98	88	10	3	WL
21	AA-88-1207	AA Ee 80	1988	46	36	10	2	WL
22	AA-88-1492	AA Ef 34	1989	80	70	10	4	WL
23	AA-74-1831	AA Ef 21	1980	75	61	14	2	WL
24	AA-81-7681	AA Ef 26	1986	50	40	10	4	WL
25	AA-81-8050	AA Ee 74	1987	223	203	20	4	WL
26	AA-88-1071	AA Ee 79	1988	50	43	7	3.5	WL
27	AA-88-1416	AA Ee 83	1989	191	176	10	4	WL
28	AA-88-1493	AA Ef 33	1989	137	122	10	4	WL
29	AA-88-1494	AA Ef 32	1989	225	210	10	4	WL
30	-	AA Ee 81	1989	191				WL
31	AA-88-5997	-	1991	70	60	10	2	QW
32 ¹	AA-95-5706	-	2011	347	320	6	2.5	QW
33	AA-92-0557	-	1994	115	108	7	2	QW
34	AA-93-1307	-	1996	42	35	7	2	QW
35	AA-94-0129	-	1996	77	70	7	2	QW

Table 1, Continued

Map ID (see Figure 1)	Well permit	Well name	Completion year	Depth of well, ft	Depth to top of well screen, ft	Length of well screen, ft	Screen diameter, in.	Type of data (QW,WL)
36	AA-94-0336	-	1996	40	35	5	2	QW
37	AA-94-0338	-	1996	50	43	7	2	QW
38	AA-94-0535	-	1996	50	43	7	2	QW
39	AA-94-1712	-	1997	42	35	7	2	QW
40	AA-94-3321	-	1998	78	68	10	2	QW
41	AA-94-9923	-	2004	90	85	15	2	QW
42	AA-95-0213	-	2004	40	33	7	2	QW
43	AA-95-0341	-	2004	90	83	7	2	QW
44	AA-95-0710	AA Ee 109	2004	90	80	10	2	QW
45	AA-95-1410	-	2005	110	90	10	2	QW
46	AA-95-1682	-	2005	70	50	10	2	QW
47	AA-95-2129	-	2006	48	38	10	2	QW
48	AA-95-2513	-	2006	50	43	7	2	QW
49	AA-95-3423	-	2007	110	90	20	2	QW
50	AA-95-5638	-	2011	105	95	10	4	QW
51	AA-11-0220	-	2012	110	100	10	2	QW
52	AA-11-0249	-	2012	125	118	7	2	QW
53	AA-11-0566	-	2012	95	80	15	2	QW
54	AA-11-0704	-	2012	121	111	10	4	QW
55	AA-11-0765	-	2013	120	110	10	3	QW

Table 2. Water levels in the Aquia aquifer.

Map ID (see Figure 1)	Well name	Date(s) of measurement	Water level, in feet above sea level
6	AA De 102	6/9/1970-9/7/2017	9 ¹
15	AA De 182	8/17/1983	1
14	AA De 183	7/20/1981	2
12	AA De 186	9/5/1978	3
10	AA De 187	11/21/1975	1
11	AA De 190	2/3/1977	2
8	AA Ee 70	9/6/1972	1
19	AA Ee 71	1/16/1988	3
16	AA Ee 73	9/12/1988	2
17	AA Ee 75	12/24/1985	7
2	AA Ee 14	6/1/1946-12/9/1948	9 ¹
3	AA Ee 21	7/1/1946	1
1	AA Ee 3	2/1/1946	1
5	AA Ee 56	5/1/1960	4
9	AA Ee 76	2/14/1976	1
20	AA Ee 78	11/2/1988-5/14/1989	8 ¹
21	AA Ee 80	11/17/1988-5/14/1989	5 ¹
13	AA Ef 24	4/6/1981	1
7	AA Ef 17	5/3/1971-4/15/2003	3 ¹
18	AA Ef 27	2/6/1987	0
22	AA Ef 34	1/31/1989-7/13/2017	1 ¹
4	AA Ef 5	6/1/1945	2

¹ Water level is an average over period of measurement.

north, east, and south from the area of high elevation and ultimately terminates at the tidal rivers and inlets. In the southeastern portion of the peninsula, a relatively small area of slightly elevated head occurs

corresponding to both a slight topographic high and an area of exposed Aquia Formation, which likely results in increased recharge (infiltration from precipitation).

EFFECTS OF INCREASED WITHDRAWALS FROM THE AQUIA AQUIFER

GROUNDWATER-FLOW MODEL

A steady-state, three-dimensional groundwater-flow model was developed to simulate flow in the shallow, water-table Aquia aquifer on the Mayo Peninsula. The model, calibrated to observed groundwater levels, was used to predict potential effects of increased withdrawals from domestic wells on groundwater levels in the area. The USGS MODFLOW code (McDonald and Harbaugh, 1988) was used to simulate flow in a one-layer model representing the Aquia aquifer.

Conceptual Model

The groundwater-flow model was based on a conceptual model of the groundwater-flow system of the Aquia aquifer on the Mayo Peninsula (fig. 7). The conceptual model generally describes the factors influencing the flow of groundwater, as well as the direction of flow. Factors influencing the flow of groundwater include the geometry of the system, sources of recharge and discharge, and flow boundaries.

The geometry of the groundwater-flow system represented in the conceptual model is a generalized version of the hydrogeologic framework of the study area discussed earlier in this report. For this study, the hydrogeologic units of concern are the Aquia aquifer and the Matawan confining unit, as well as the Quaternary-age Lowland Deposit and the Tertiary-age Marlboro Clay, Nanjemoy, and Calvert confining units that overlie the Aquia aquifer in places on the peninsula. The Aquia aquifer, which consists of the Aquia Formation as well as the Severn and Brightseat Formations (Andreasen and others, 2013) outcrops in two areas on the peninsula (Glaser, 2002). Since water levels in the Aquia aquifer generally occur at elevations below any overlying clay layers, the aquifer is considered unconfined. The underlying Matawan confining unit has a relatively low vertical hydraulic conductivity compared to the Aquia and deeper Magothy aquifers, and therefore inhibits flow

between the two. In the conceptual model, it is assumed to hydraulically separate the two aquifers and form a no-flow boundary at the base of the Aquia aquifer. The underlying Magothy aquifer is thus not included in the groundwater-flow model. The Lowland Deposit, Marlboro Clay, Nanjemoy, and Calvert confining units that overlie the Aquia aquifer in much of the peninsula also are likely to have relatively low vertical hydraulic conductivities. In the conceptual model, they function to reduce recharge to the Aquia aquifer.

Recharge in the study area is derived from precipitation. The average annual precipitation at the Baltimore-Washington International Airport located at approximately 20 mi from the peninsula is 42.03 inches (in.) (National Weather Service, 2018). Much of this precipitation is removed by surface runoff or evapotranspiration, and therefore does not contribute to aquifer recharge. Recharge to the Aquia aquifer in the conceptual model is higher where the Aquia aquifer outcrops (exposed at the surface), and lower where it underlies confining units. Groundwater leaves the model (Aquia aquifer) through discharge to surrounding bodies of surface water and through pumping of wells. Additionally, groundwater enters the model (Aquia aquifer) from the west and exits to the south as a result of the regional groundwater flow in the Aquia aquifer.

The South River, Rhode River, and Chesapeake Bay form natural constant-head boundaries at the northern, southern and eastern edges, respectively, of the peninsula. Glebe Bay, at the northwestern edge, forms a natural groundwater divide separating the Aquia aquifer flow system on the peninsula from the flow system northwest of Glebe Bay.

In a more regional sense, groundwater in the Aquia aquifer generally flows toward the southeast in Anne Arundel County (Andreasen, 2002). On the peninsula, groundwater in the Aquia aquifer flows from high topographic areas near the center of the peninsula to low topographic areas near the surrounding bodies of water (fig. 6) (Fleck and others, 1996).

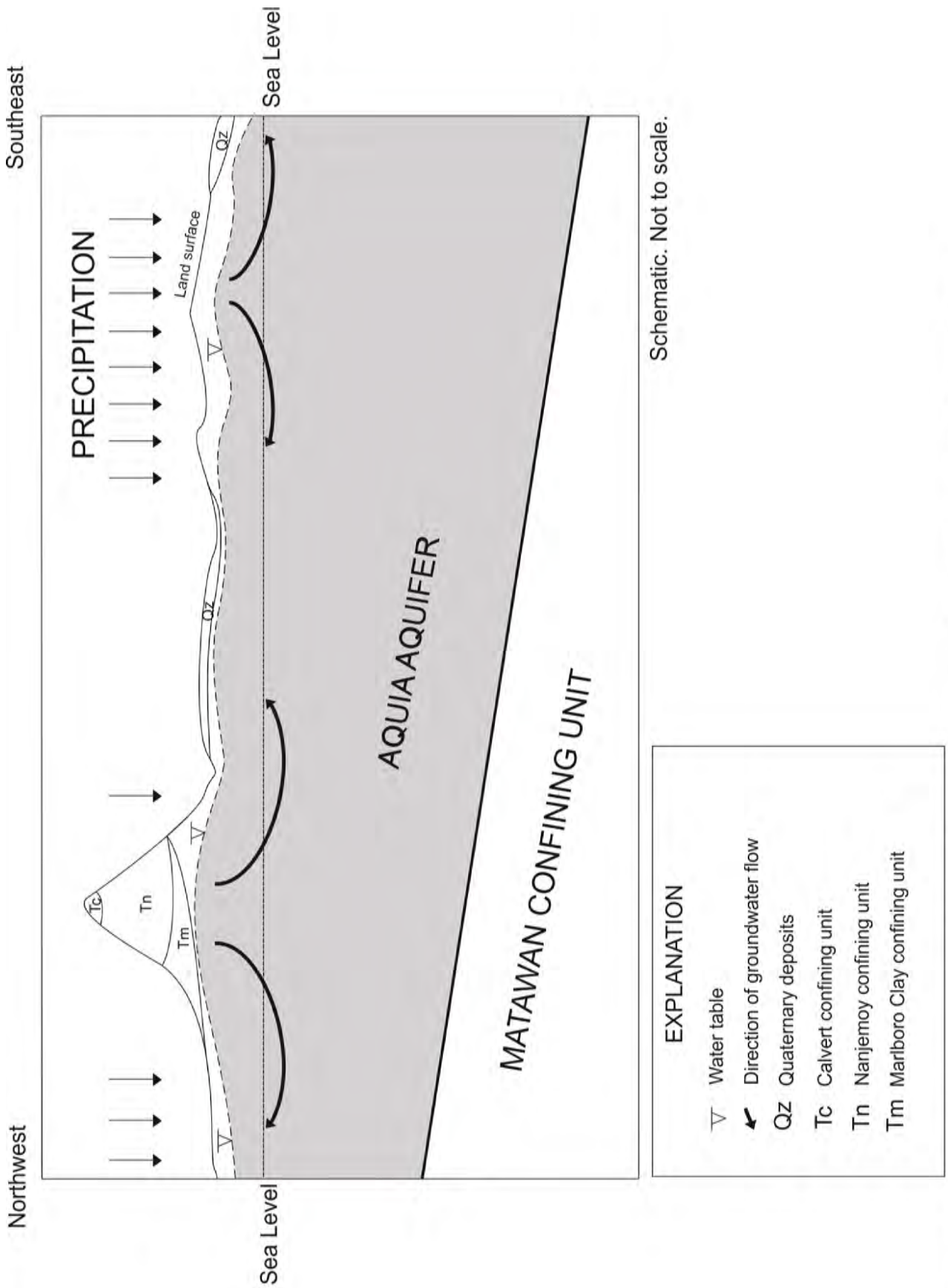


Figure 7. Conceptual model of the groundwater-flow system (Aquia aquifer) along the length of the Mayo Peninsula.

Model Grid, Layers, and Boundary Conditions

The numerical model grid has 110 rows, oriented east-west, and 84 columns, oriented north-south. Each cell is 250 ft by 250 ft, resulting in a modeled area of 20.7 square miles. This area includes all of the Mayo Peninsula and extends beyond the peninsula (south and west) to minimize potentially unrealistic boundary effects on the modeled groundwater-flow system (fig. 8).

The model contains one layer representing the Aquia aquifer, which is modeled as an unconfined aquifer. The elevation of the bottom of the model is set to the top of the Matawan confining unit as defined by Andreasen and others (2013). As the layer is modeled as unconfined, the elevation of the top of the layer is the active water table. Thickness of the layer is therefore the saturated thickness of the Aquia aquifer.

Recharge was added to the top of the model as a linear rate applied to each active model cell. In areas where the Aquia aquifer underlies other units, recharge rates were reduced to represent the relatively low vertical conductivity of those units.

Where possible, boundary conditions were specified based on natural flow boundaries. The South and Rhode Rivers, along with the Chesapeake Bay, are treated as constant-head boundaries set at mean sea level. Glebe Bay, on the South River, is a natural groundwater divide. Groundwater-flow northwest of Glebe Bay is therefore separate from groundwater-flow on the peninsula, and these cells are inactive in the model.

Natural flow boundaries of the Aquia aquifer to the west and south of the model area are too distant to be included within the model area. Therefore, the southern and western edges of the model are represented by a general-head boundary. A general-head boundary allows flow across the boundary to vary as a function of the head gradient. Flow into or out of a cell containing the boundary is proportional to: (1) the difference between the simulated head in the cell and the head assigned to an external specified-head source, and (2) the hydraulic conductance between the head and the source (McDonald and Harbaugh, 1988). The general-head boundary in this model assumes a fixed hydraulic head located at a distance from the boundary of the model and representing a regional head.

Pumpage

The numerical model simulates pumpage from wells by removing groundwater from individual active model cells. Pumping on the peninsula is primarily from domestic wells. The locations of existing wells were estimated in the model area through the examination of aerial imagery. One well was assumed for every house visible on the imagery for a total of 3,215 wells, the vast majority of which were located on the Mayo Peninsula. Two wells mapped on the general-head boundary of the model were removed, leaving 3,213 wells. This compares well to the 3,393 housing units located by the 2010 U.S. Census for the Mayo Census Designated Place (CDP) (U.S. Census Bureau, 2012), which has boundaries closely matching the peninsula. The total number of estimated existing wells located in each model cell was tallied and used as an input to the numerical model (fig. 9a). Any wells mapped on constant head cells were added to adjacent active cells.

Estimates for the rate of water use vary from 60 gallons per person per day (gal/capita/day) (Andreasen, 2002) to 100 gal/capita/day (U.S. Geological Survey, 2016). A recent study of residential water use in the United States found that household water use averaged 88,000 gallons per year (gal/year), or approximately 241 gal/day (Mayer, 2016). The nearest water utility to the peninsula participating in that study, the Philadelphia Water Department, had an average household usage of 57,000 gal/year, or 156 gal/day. Water usage had decreased since 1999 with future reductions likely as a result of further improvements in water conservation. The U.S. Census Bureau (2012) indicated a 2010 population of the Mayo CPD of 8,298 people and 3,393 housing units, resulting in an average of approximately 2.45 people per housing unit. At 60 gal/capita/day with each housing unit having one well, each well is estimated to pump approximately 147 gal/day (approximately 19.6 cubic feet per day [ft³/day]). At approximately 3,215 wells in the study area, the total withdrawals are about 0.47 Mgal/d. To provide for a more conservative estimate of domestic well-withdrawal rate, an upper limit of approximately 250 gal/day (or approximately 33.4 ft³/day) was used for comparison in the model.

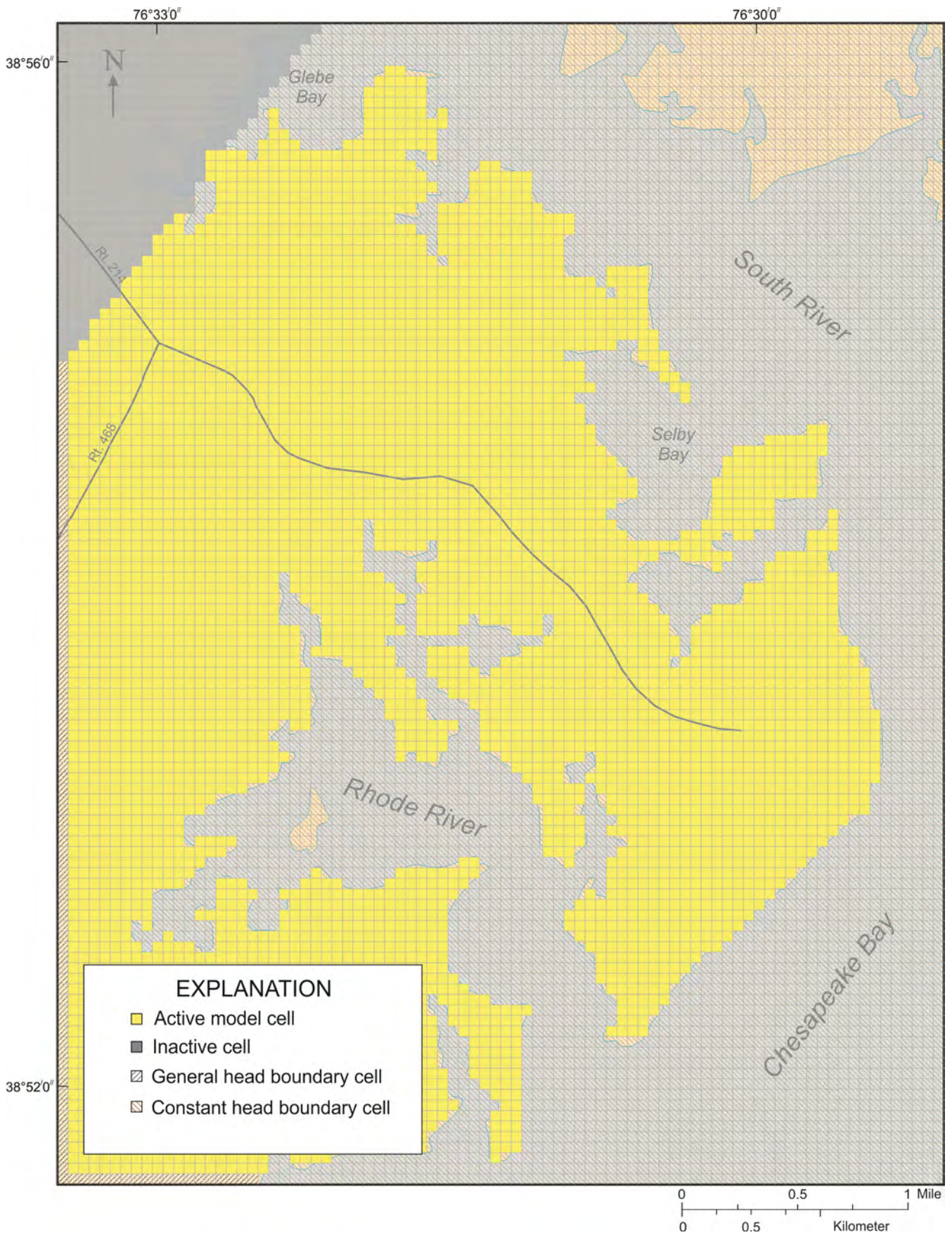


Figure 8. Finite-difference grid and boundary conditions of the groundwater-flow model.

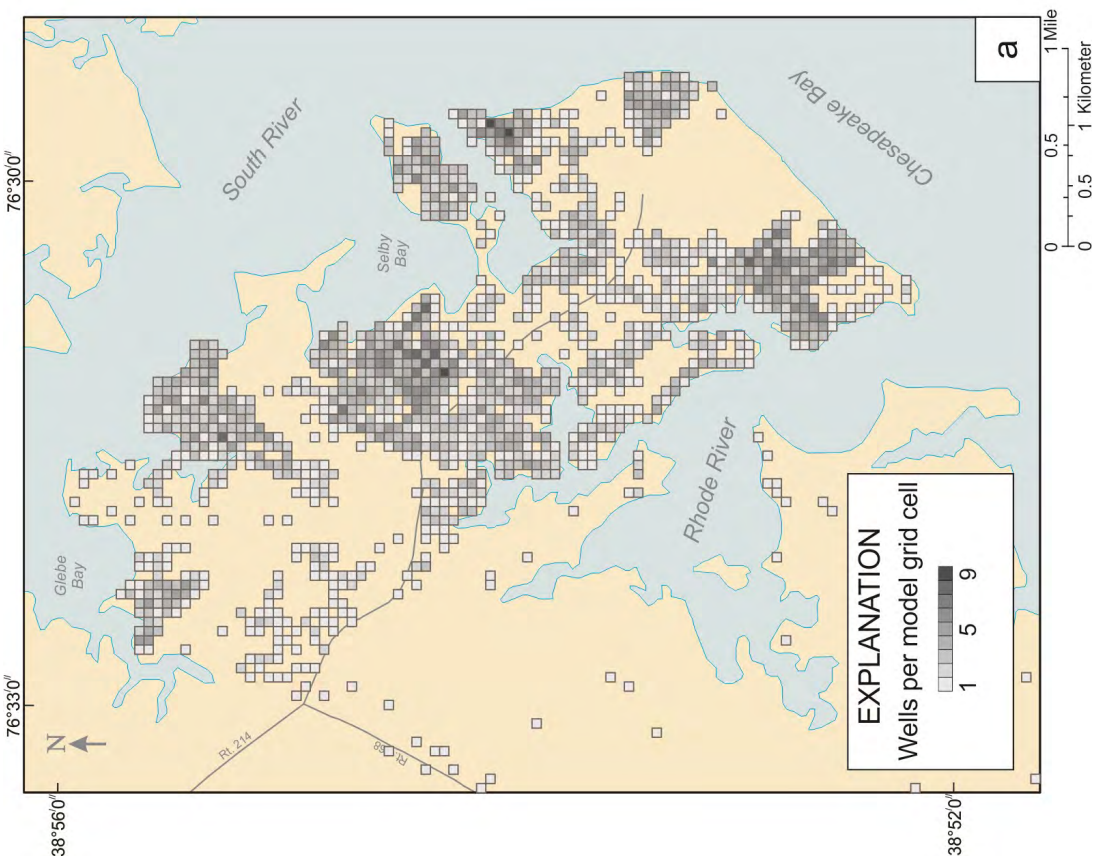
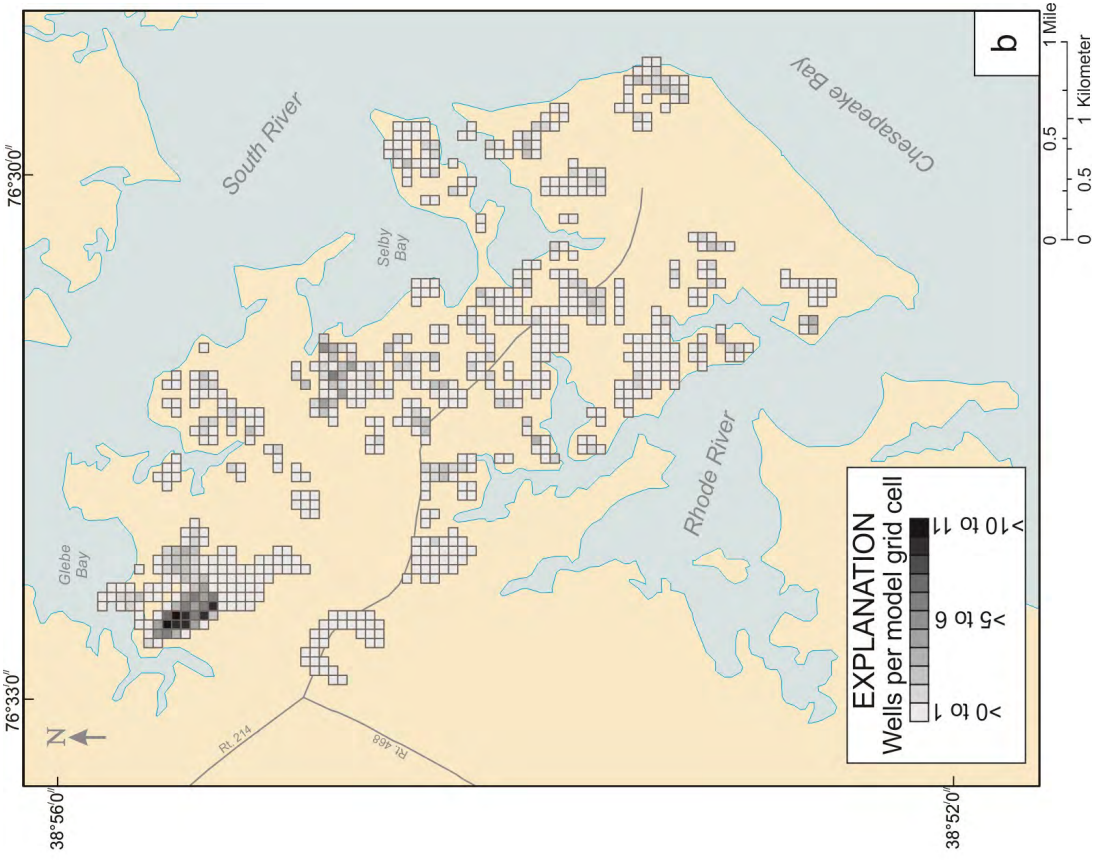


Figure 9. Distribution of (a) existing wells and (b) potential wells screened in the Aquia aquifer with respect to the finite-difference grid.

Model Calibration and Analysis

Prior to simulating the effects of increased domestic well withdrawals resulting from new development, the numerical model was calibrated using existing pumpage at 147 gallons per well per day. A steady-state flow simulation was run using estimated current well withdrawals and the resulting head output was compared to observed heads in observation wells (tab. 3). While few of the observation wells have been measured over long periods of time, those that have show either little change or lack a discernible trend, indicating that a steady-state simulation is appropriate (fig. 5). Additionally, a moratorium was placed on development in 2008, and the 1990 U.S. Census shows that the population of the Mayo and Selby-on-the-Bay CDPs (later combined in the Mayo CDP) was already by that point greater than two-thirds the population measured in 2010 (U.S. Census Bureau, 1992; 2012). As such, water levels have had decades to stabilize, again indicating that a steady-state simulation is appropriate. The model was calibrated by adjusting recharge and horizontal hydraulic conductivity within ranges deemed reasonable, until the differences between simulated and observed heads at observations wells were low and the general shape of the water-table surface in the model was similar to that indicated by observation wells (fig. 6). While the resulting model solution is non-unique, and other combinations of values of input parameters could potentially produce similar results, the set of parameter values assigned during model calibration seemed the most reasonable.

Groundwater Levels Used in Calibration

The model was calibrated to the groundwater levels in sixteen wells at ten sites (fig. 10). All wells used for calibration are screened in the Aquia aquifer and are within the model area. Wells that are within approximately 250 ft of a shoreline were not used, as the constant head boundary conditions would force the calculated groundwater levels of these wells to be near zero regardless of changes in input parameters. Groundwater levels known to be from drillers' logs were not used, as the process of drilling may affect groundwater levels measured at the time of drilling. Three wells with anomalously high readings relative to nearby wells and the shoreline were not used. Groundwater levels were

taken from the U.S. Geological Survey's National Water Information System (NWIS), and from field notes of MGS personnel.

The 16 wells used in calibration had between 1 to 42 groundwater-level measurements each, with most having fewer than five. The oldest measurement used occurred in 1946, while the most recent were in 2017. Because the timeframe in which wells were measured is so broad, the composite potentiometric surface should be viewed in a general sense, rather than as a snapshot of groundwater levels at a specific time. All measurements for a given well were averaged to produce a single groundwater level for model calibration. At four sites, the measurements of multiple wells that were in close proximity to each other were averaged to produce a single value.

Calibration Parameters

In order to calibrate the model, input parameters were varied over ranges considered reasonable based on available field data and general knowledge of the Aquia aquifer until a solution was found that most closely matched simulated and observed groundwater levels. During calibration, the amount of recharge over several regions of the active model area, as well as the horizontal hydraulic conductivity associated with the Aquia aquifer, both within the model area and surrounding the model area (represented in the general head boundary), were adjusted.

Recharge was adjusted for three regions in the model area (fig. 11). The first region corresponds to the outcrops, one large and several smaller, of the Aquia Formation in the northwestern part of the peninsula, as mapped by Glaser (2002). The second region corresponds to the large outcrop area of the Aquia Formation in the southeastern part of the Mayo Peninsula on the same map. The third region is the rest of the model area, where the Aquia Formation is covered by overlying silt and clay layers and recharge is presumably less. The average annual precipitation is approximately 42.0 in. (0.01 ft/day) (National Weather Service, 2018). Accounting for the loss of runoff and evapotranspiration, initial estimates for recharge in the outcrop areas were one quarter to one third of total precipitation. Recharge in areas where the Aquia did not outcrop was initially estimated to be approximately one order of magnitude smaller.

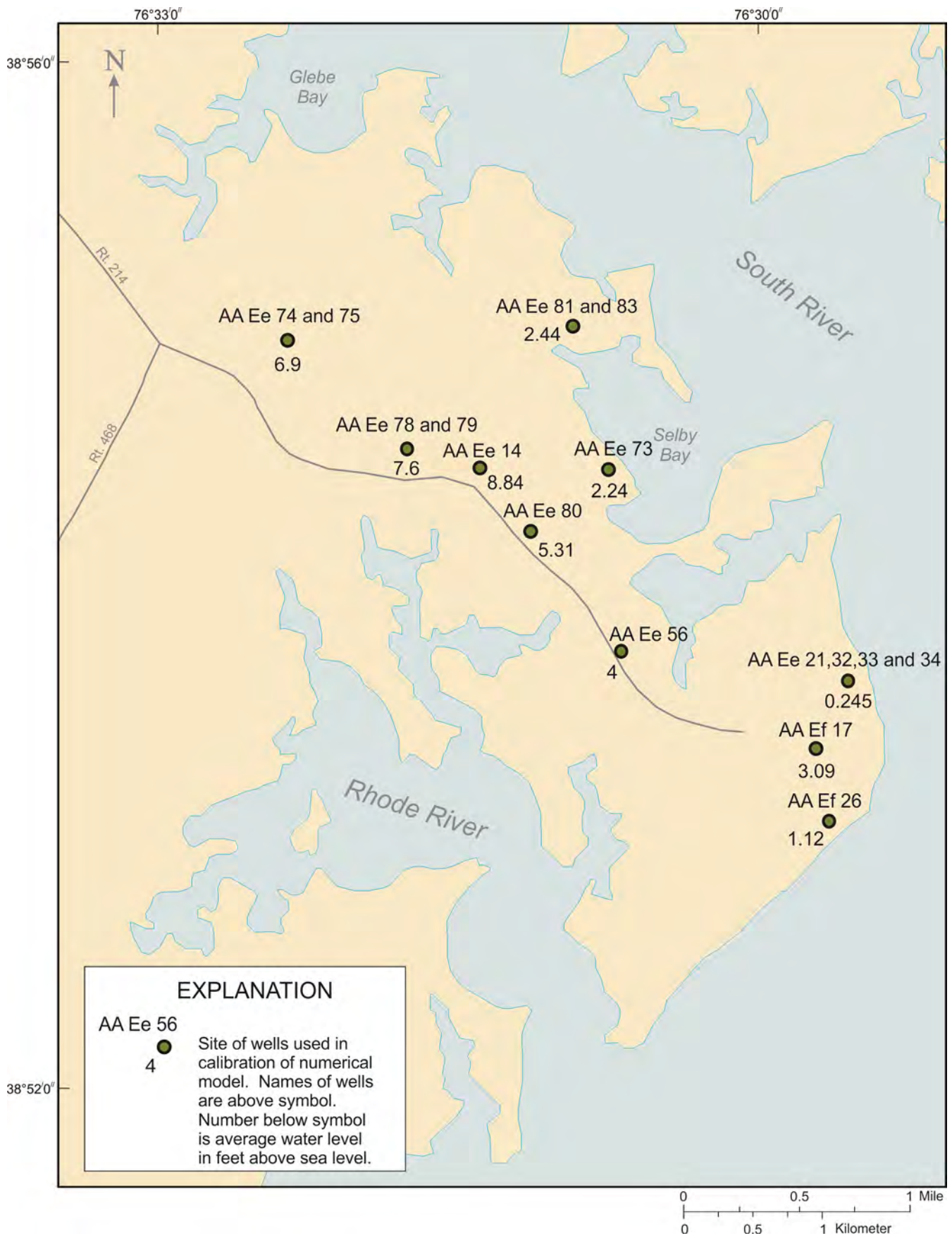


Figure 10. Wells used in the calibration of the groundwater-flow model. Where multiple wells are in close proximity, the average location and water level defines a single calibration point.

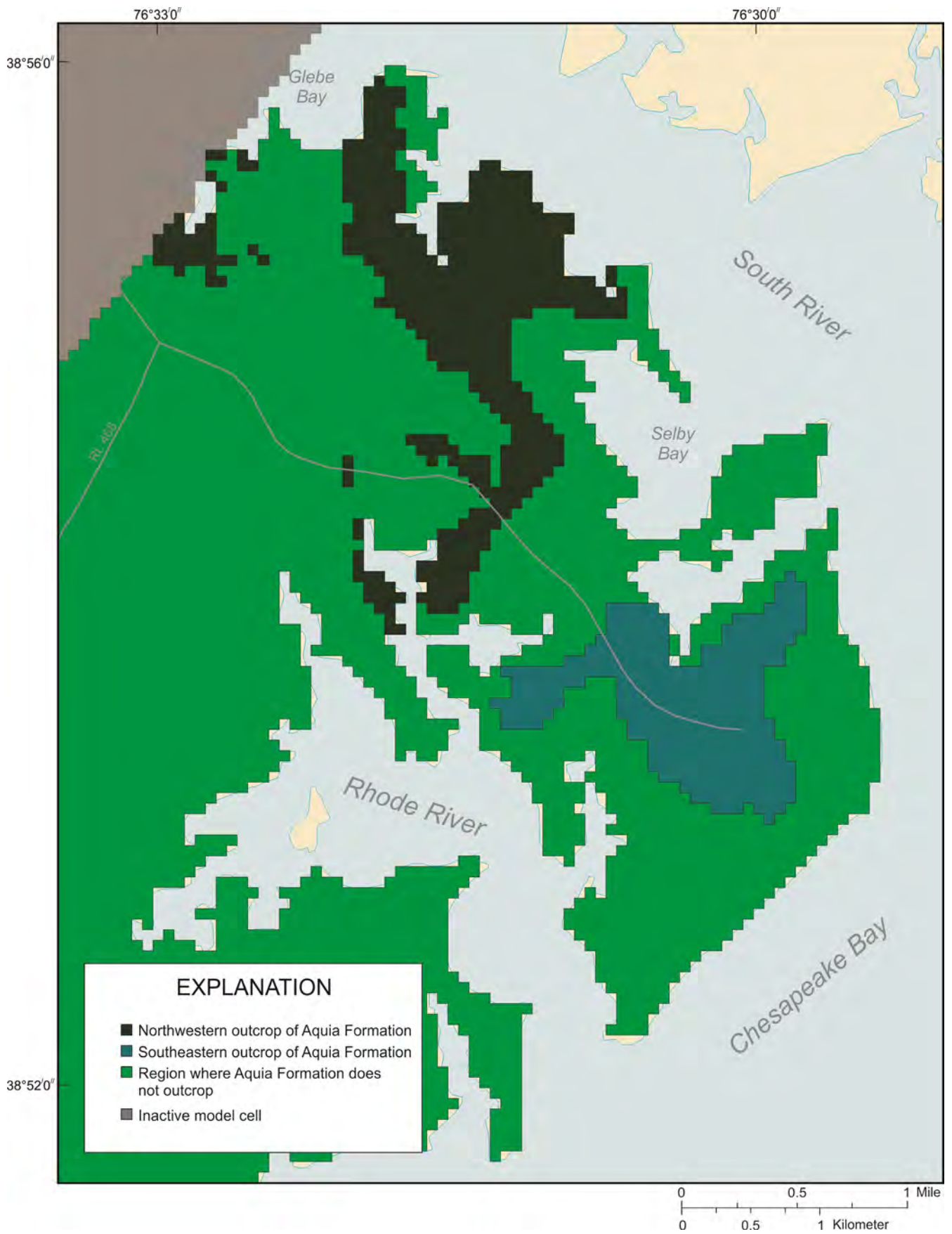


Figure 11. Distribution of recharge zones used in the groundwater-flow model.

Table 3. Simulated versus observed water levels after model calibration.

Site Identifier (see Figure 13)	Well names at observation site	Water level, observed ¹ , in feet above sea level	Water level, simulated, in feet above sea level	Difference between observed and simulated water levels, ft
1	AA Ee 14	8.84	6.59	-2.25
2	AA Ee 56	4.00	2.69	-1.31
3	AA Ee 73	2.24	0.52	-1.72
4	AA Ee 74 and AA Ee 75	6.90	11.18	+4.28
5	AA Ee 78 and AA Ee 79	7.60	8.09	+0.49
6	AA Ee 80	5.31	3.00	-2.31
7	AA Ee 81 and AA Ee 83	2.44	2.47	+0.03
8	AA Ef 17	3.09	2.45	-0.64
9	AA Ef 21, AA Ef 32, AA Ef 33, and AA Ef 34	0.25	0.96	+0.71
10	AA Ef 26	1.12	0.91	-0.21

¹ Observed water level is an average over period of measurement. All water levels are reported to nearest 0.01 feet. Different sites have different numbers of measurement, and measurement accuracy varies.

The final recharge rates used in the model were approximately 17.5 inches per year (in./yr) in the northwestern outcrop areas, approximately 13.1 in./yr in the southeastern outcrop area, and approximately 3.1 in./yr where the Aquia Formation is covered. The difference between recharge rates in the two outcrop areas suggests that there may be uncertainty in mapping exposures of the Aquia Formation. There may also be variability in the permeability of the Aquia Formation.

Initial estimates of horizontal hydraulic conductivity in the model area were calculated from transmissivity values from previous studies (Fleck and others, 1996; Andreasen, 2002) and a saturated thickness of approximately 200 ft for Aquia aquifer on the peninsula. Initial estimates of horizontal hydraulic conductivity in the Aquia aquifer ranged from approximately 4 to 50 ft/day. Horizontal hydraulic conductivity used in the calibrated model was 5 ft/day.

The general-head boundary in the model represents regional flow in the Aquia aquifer across the western and southern model boundaries. Inputs for the general-head boundary include hydraulic conductance and head elevations at some distant (regional) point outside the model domain. Regional heads were estimated from a regional potentiometric surface map (Staley and others, 2016) at a distance

of approximately 15,000 ft from the general-head boundary. The hydraulic conductance is dependent on the effective hydraulic conductivity between the external head and the boundary cell, the saturated area on the face of the boundary cell, and the distance to the external head. The saturated area was estimated using the regional potentiometric surface (Staley and others, 2016) and the elevation of the top of the Matawan confining unit (Andreasen and others, 2013). The effective hydraulic conductivity for the general-head boundary was varied during calibration. Initial estimates were in the same range as the hydraulic conductivity of the model area (4 to 50 ft/day). As the model showed little sensitivity to the effective hydraulic conductivity for the general-head boundary, it was eventually set equal to the horizontal hydraulic conductivity of the model area and was therefore also 5 ft/day in the calibrated model.

Pumpage values of 19.6 and 33.4 ft³/day per well (or 147 and 250 gal/day per well, respectively) were tested during calibration. The simulated water tables from the calibrated model using both pumpage rates are shown in figure 12. The simulated water tables capture the general pattern of the measured water table (fig. 6). Areas where the simulated water table is slightly below sea level are likely artifacts of the modeling process, resulting

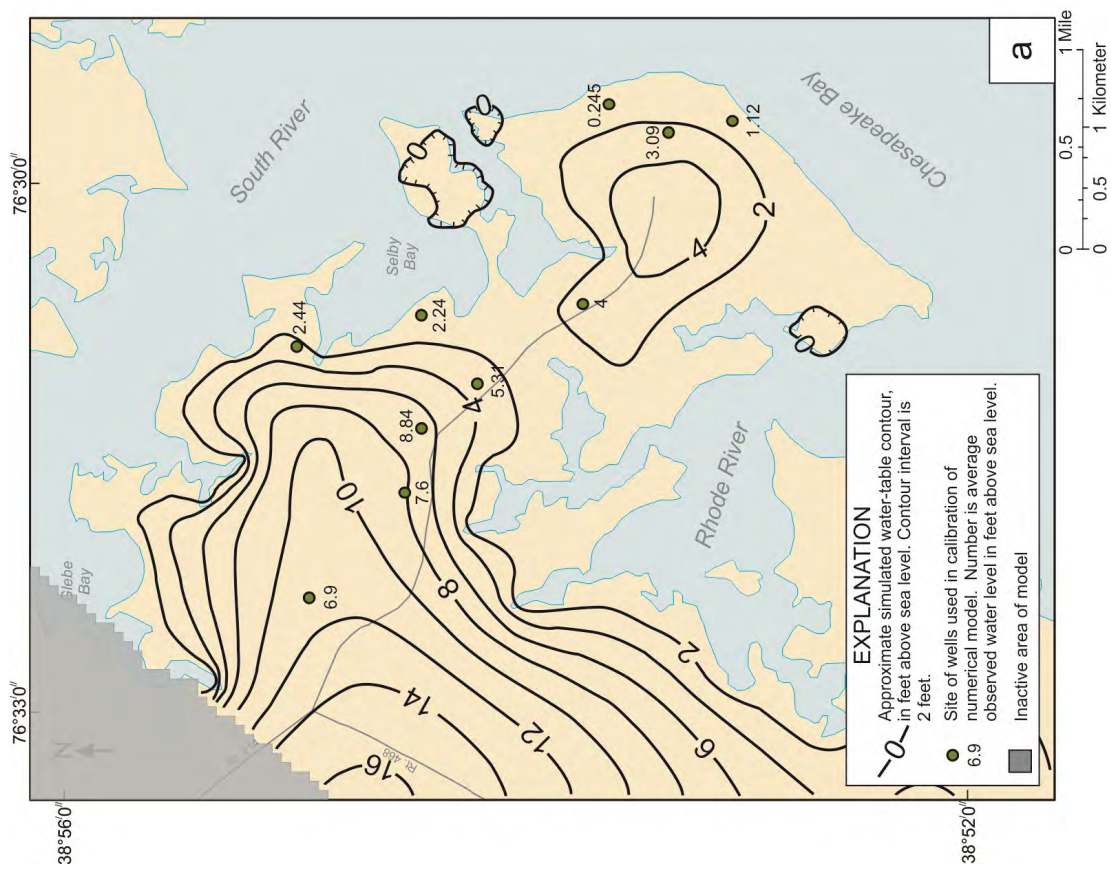
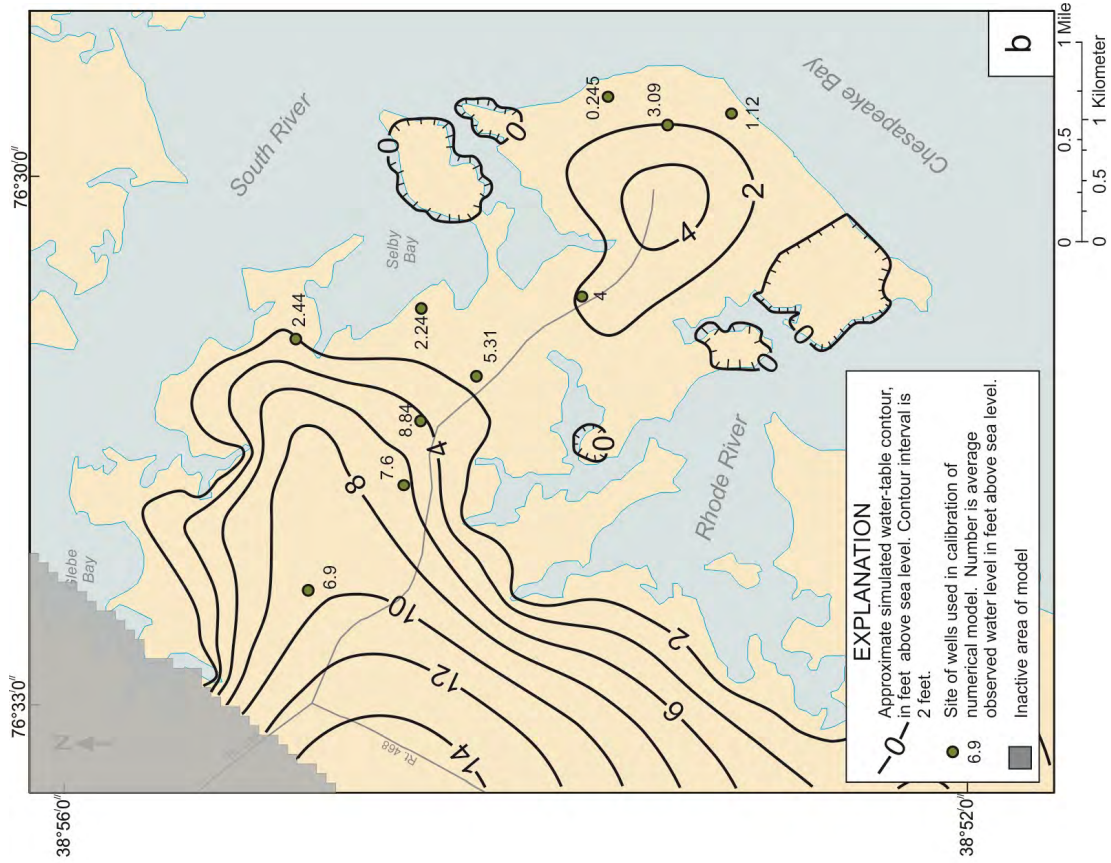


Figure 12. Simulated water table of the Aquia aquifer during model calibration assuming a pumping rate of (a) 147 gallons per day per well and (b) 250 gallons per day per well.

from uncertainty in modeled water levels. Several wells in those areas have observed water levels above sea level (tab. 2).

A comparison of observed and simulated water levels from the calibrated model using a domestic well withdrawal rate of 147 gal/day (approximately 19.6 ft³/day) is shown in figure 13 and table 3. The absolute differences between observed and simulated heads average about 1.4 ft. Overall, the simulated heads tend to be less than observed heads. The root-mean-square error calculated using observed water levels from 10 sites was about 1.9 ft. The differences between observed and simulated heads may in part be attributed to heterogeneities in the aquifer system not captured in the field data, conceptual model, and/or numerical model.

Sensitivity Analysis

After model calibration, a series of simulations was made to illustrate the sensitivity of the model to changes in the input parameters. In each simulation, one parameter was either increased or decreased by a factor of two or ten compared to the calibrated value, while all other parameters were held at their calibrated values. The parameters tested were recharge in the northwestern outcrop of the Aquia Formation, recharge in the southeastern outcrop of the Aquia Formation, recharge where the Aquia Formation does not outcrop, horizontal hydraulic conductivity of the model layer, and horizontal hydraulic conductivity of the general-head boundary. Results using a domestic well pumpage rate of 147 gal/day (approximately 19.6 ft³/day) are shown in figure 14.

The model shows very little sensitivity to the horizontal hydraulic conductivity of the general-head boundary. For this reason, during model calibration, the horizontal hydraulic conductivity of the general-head boundary was set to equal the horizontal hydraulic conductivity of the model layer. The model shows little sensitivity to decreases in recharge values, as well as to doubling of recharge values. The model is very sensitive to increasing the recharge values by an order of magnitude, especially in the northwestern outcrop and where there is no outcrop. It should be noted that increasing the recharge values by a factor of 2 or 10 represents unrealistic values for recharge. The model is moderately sensitive to increases in horizontal hydraulic conductivity of the model layer, and more sensitive to decreases, especially to a decrease of an order of magnitude. Using a pumpage rate of 33.4 ft³/day generally results in a slightly worse fit, but

the patterns of sensitivity to other parameters are similar.

Volumetric Budget

The volumetric budget for the model was calculated at the end of the steady-state calibration simulation. Results using a pumpage rate of 19.6 ft³/day are shown in table 4. Total inflow to the model enters through recharge (98.3 percent), the general-head boundary (regional flow) (1.5 percent), and the constant-head boundary (South and Rhode Rivers) (0.2 percent). Inflow was balanced by outflow. Total outflow from the model exited through the constant-head boundary (rivers and Chesapeake Bay: 80.8 percent), wells (17.3 percent), and the general-head boundary (regional flow) (1.9 percent).

PREDICTIVE MODEL SIMULATION OF INCREASED WITHDRAWALS

The recent (2017) lifting of a building moratorium on the Mayo Peninsula enacted in 2008 could potentially result in the construction of up to approximately 630 housing units (an approximate 20 percent increase over the number of housing units in 2010). The wells that could be drilled due to the lifting of the moratorium were located in the model based on a map of developable lots produced by the Anne Arundel County Office of Planning and Zoning (Bridget Nadolny, Anne Arundel County Office of Planning and Zoning, written communication, 2018). Future pumpage was calculated by assuming that each developable lot would result in a new well drilled into the Aquia aquifer. The pumpage from lots that spanned multiple model cells in the model was split among those model cells in proportion to the area of the lot within each cell. The number of potential wells located in each grid cell was tallied (fig. 9b). Any wells mapped on constant head cells were added to adjacent active cells.

To assess the potential effects the increased population would have on water levels in the Aquia aquifer, predictive simulations were run using the calibrated groundwater-flow model. As with the calibration simulation, the predictive simulations were run as steady-state. This was done, in part, to provide the total, worst-case drawdown resulting from increased pumpage. The predictive model simulations include current pumpage as well as estimated future pumpage. Two simulations were run, one assuming a pumping rate of 147 gal/day per well for all wells, and one assuming a rate of 250

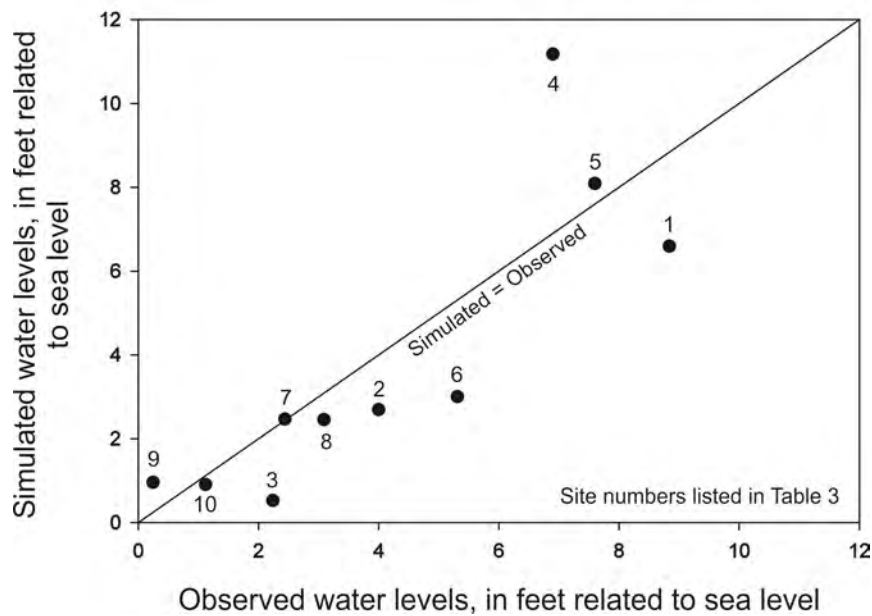
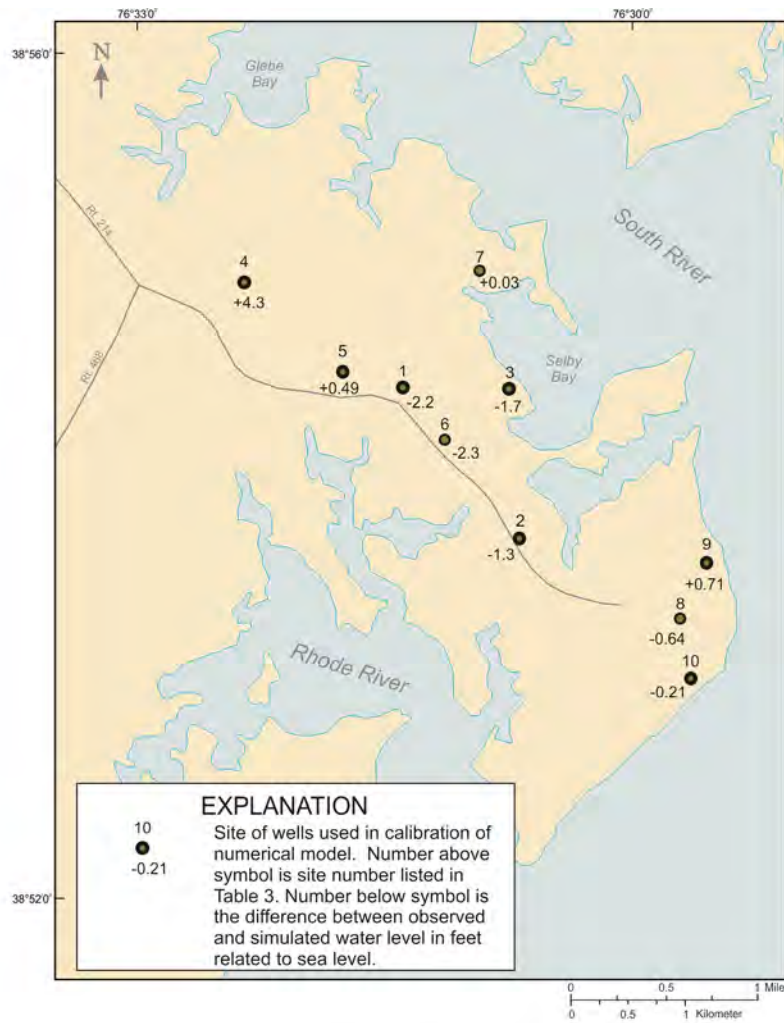


Figure 13. Observed versus simulated groundwater levels. See Table 3 for observed and simulated water levels.

Table 4. Simulated volumetric groundwater budget for calibrated groundwater-flow model.

Source	Volume in, gallons per day	Percentage of total volume in	Volume out, gallons per day	Percentage of total volume out
Constant head boundary	5,875	0.22	2,207,889	80.84
General head boundary	40,014	1.47	52,096	1.91
Recharge	2,685,179	98.32	0	0
Wells	0	0	471,084	17.25
<i>Total¹</i>	<i>2,731,069</i>	<i>100</i>	<i>2,731,069</i>	<i>100</i>

¹ May not sum to total due to rounding

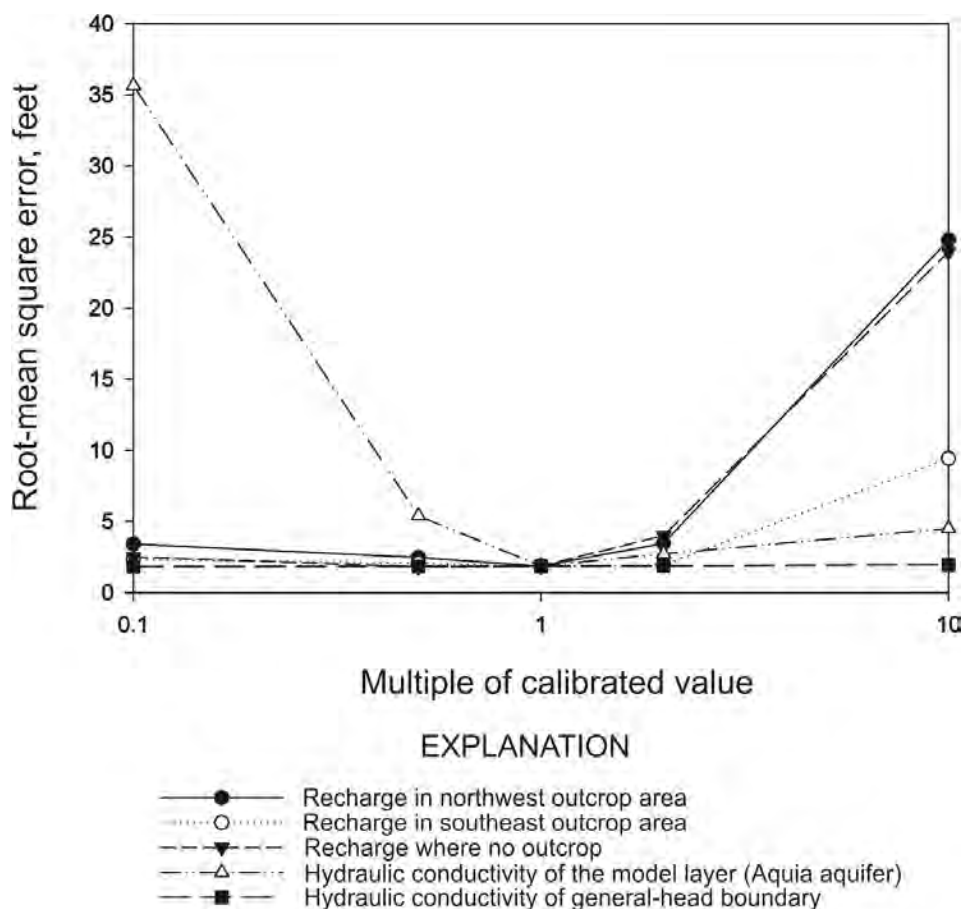


Figure 14. Sensitivity of groundwater-flow model to variations in calibrated model parameters.

gal/day per well for all wells. The resulting simulated water tables are shown in figure 15.

Simulated withdrawals from the potential new wells estimated using household water-use rates of 147 and 250 gal/day per well total approximately 0.093 and 0.158 Mgal/day, respectively. Current withdrawals from the Aquia aquifer are approximately 0.47 to 0.8 Mgal/day at household water-use rates of 147 and 250 gal/day, respectively; therefore, the simulated new withdrawals represent a 20 percent increase over current withdrawals.

Drawdown resulting from the potential increase in pumpage due to the development of new lots is shown in figure 16. The drawdown is the difference between the simulated water-table with only current withdrawals calculated and with current and potential withdrawals both calculated. In both scenarios (147 gal/day and 250 gal/day), drawdown is less than 0.25 ft in most of the model area, including the southeastern portion of the peninsula. The greatest drawdown occurs on the south-eastern side of Glebe Bay, where there is potential for dense development accounting for approximately one-quarter of the new wells (fig. 9b). For the simulation assuming 147 gal/day per well, the greatest drawdown is approximately 1.2 ft (fig. 16a), while for the simulation assuming 250 gal/day per well, the greatest drawdown is approximately 2.1 ft (fig. 16b). Both simulations also show a smaller cone of depression near the western side of Selby Bay, where there is potential for moderate development accounting for approximately one-eighth of the new wells. The drawdown in the smaller cone of depression is about half of the maximum drawdown in the model area.

Both pumping scenarios indicate that the Aquia aquifer is capable of supplying the estimated future demand of up to 630 additional housing units on the peninsula while only causing minimal declines in groundwater-levels.

POTENTIAL EFFECTS OF SIMULATED DRAWDOWN ON BRACKISH-WATER/ FRESHWATER INTERFACE

While drawdown resulting from simulated increases in pumpage suggests adequate water supply in the Aquia aquifer to meet projected demand, the higher levels of drawdown in certain areas may result in an increased risk of intrusion of brackish water from the Chesapeake Bay and South and Rhode Rivers. While the numerical simulation of brackish-water intrusion is beyond the scope of

this study, a previous study is used to estimate potential impacts. Fleck and others (1996) constructed a two-dimensional (cross-sectional) solute-transport model to study the effects of lowered groundwater levels in the Aquia aquifer on the movement of the brackish-water/freshwater interface at Quiet Waters Park, located just north of the Mayo Peninsula across the South River. In that model, the location and movement of the interface were calculated based on the densities and concentrations of dissolved solids in freshwater and seawater (fig. 17). Inflows of freshwater from above (recharge) and from the landward boundary (regional flow) were specified. General groundwater-level declines in the Aquia aquifer were simulated in two scenarios by either removing or reversing groundwater inflow from the landward model boundary, approximately 300 ft inland. These scenarios resulted in head decreases of 0.3 ft and 0.7 ft at the landward boundary, respectively. The decrease of 0.3 ft at the landward boundary resulted in a rise of the brackish-water/freshwater interface of approximately 55 ft at the landward boundary, and a rise of approximately 20 ft at the shoreward boundary over the course of 100 years. A decrease of 0.7 ft resulted in rises of the brackish-water/freshwater interface of approximately 65 ft and 30 ft at the landward and shoreward boundaries, respectively. The location of the brackish-water/freshwater interface varies between locations. As measured by Fleck and others (1996), the interface in a well near Historic London Town and Gardens, north of the study area along the South River, was shallower than at Quiet Waters Park. A well at South River Farms Park, on the northern edge of Selby Bay, did not encounter the interface at all. As the Magothy aquifer is separated from the Chesapeake Bay by the Matawan confining unit, it is not affected by the brackish-water/freshwater interface.

For the predictive numerical model scenarios discussed in the previous section, drawdown resulting from increased pumpage for most of the peninsula is less than 0.3 ft, indicating that the brackish-water/freshwater interface is likely to rise by less than that modeled at Quiet Waters Park. However, in the areas near Glebe Bay and Selby Bay where the density of potential development is relatively high, when the simulated pumping rate of a well is assumed to be 250 gal/day, simulated drawdown within a few hundred feet of the shore reach 1.2 ft and 0.6 ft, respectively (fig. 16). Using a pumping rate of 147 gal/day per well, simulated drawdown near the shore of Glebe Bay may reach

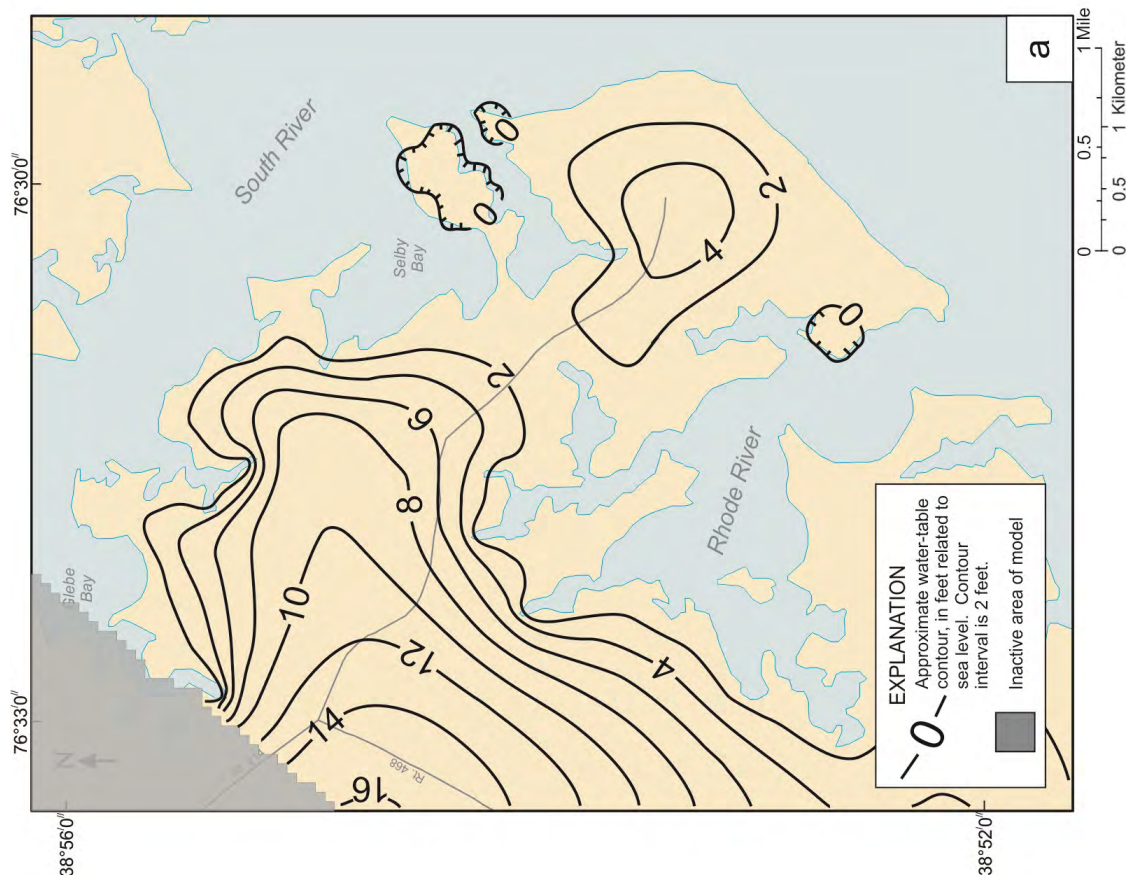
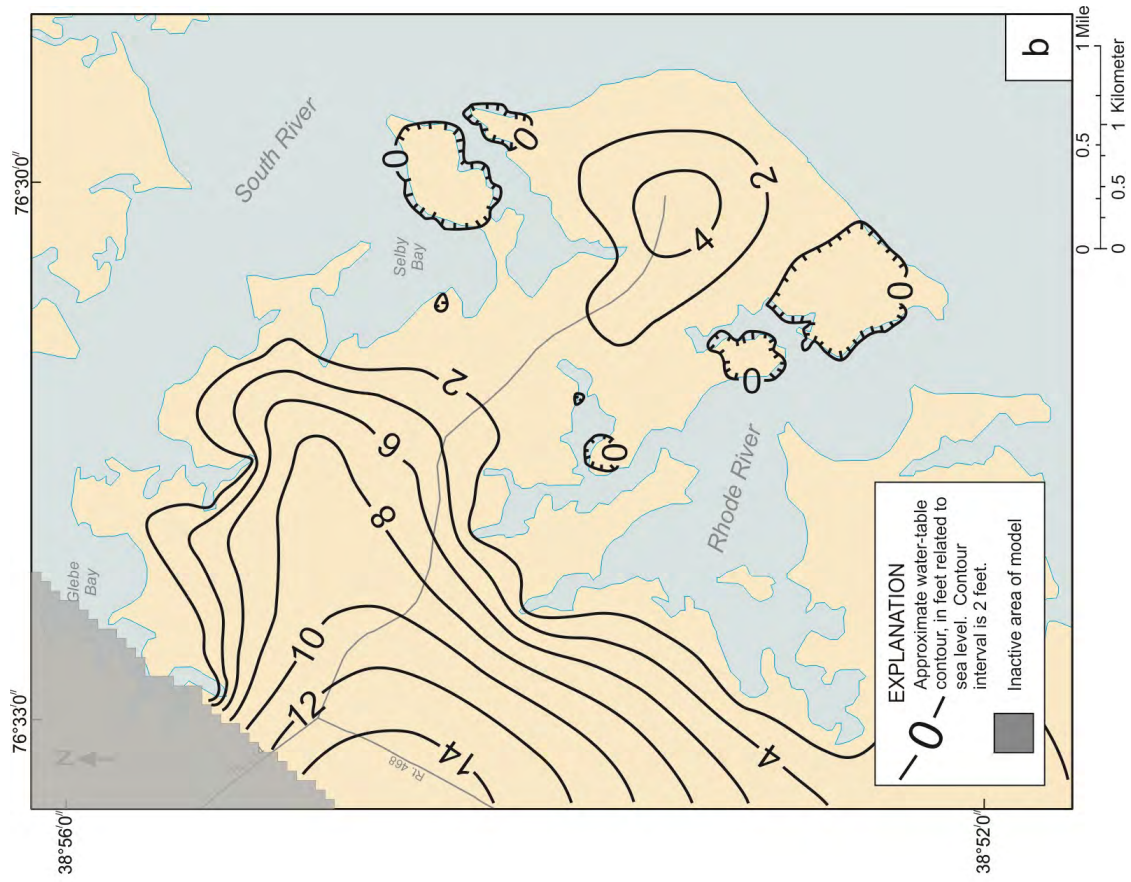


Figure 15. Simulated water table of the Aquia aquifer under increased domestic withdrawals assuming a pumping rate of (a) 147 gallons per day per well and (b) 250 gallons per day per well.

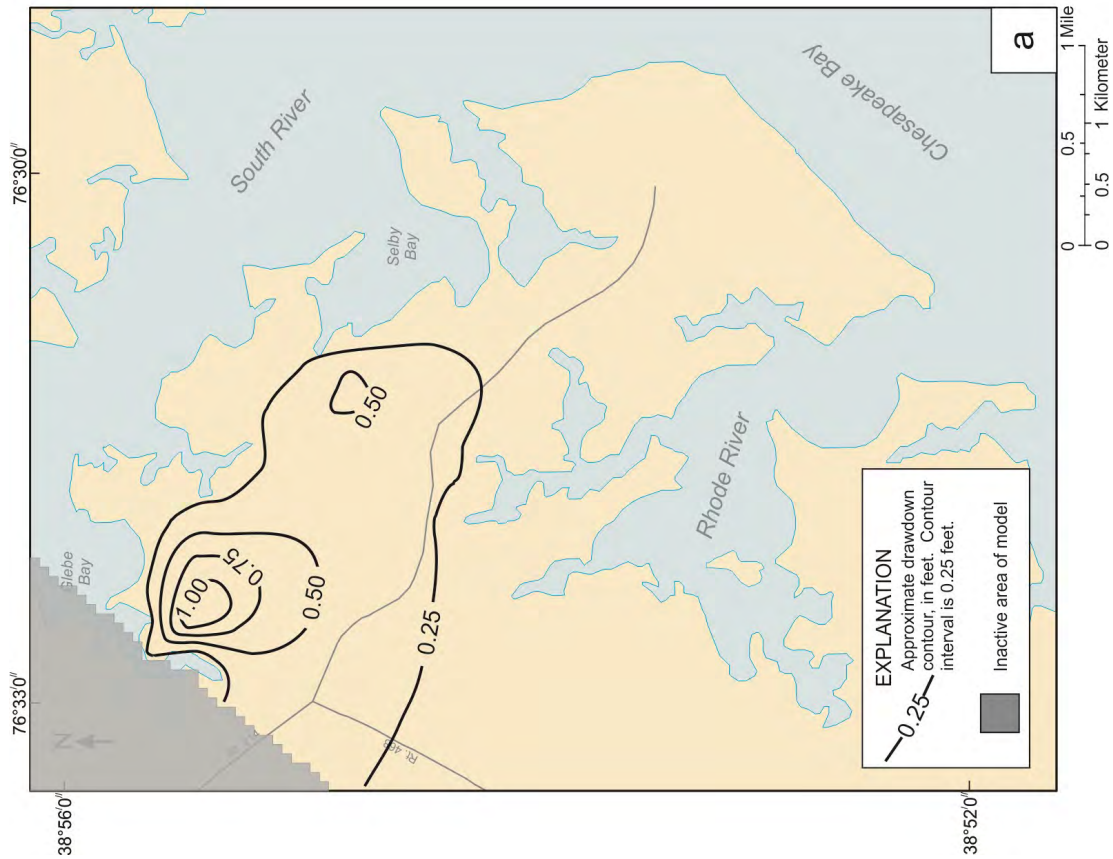
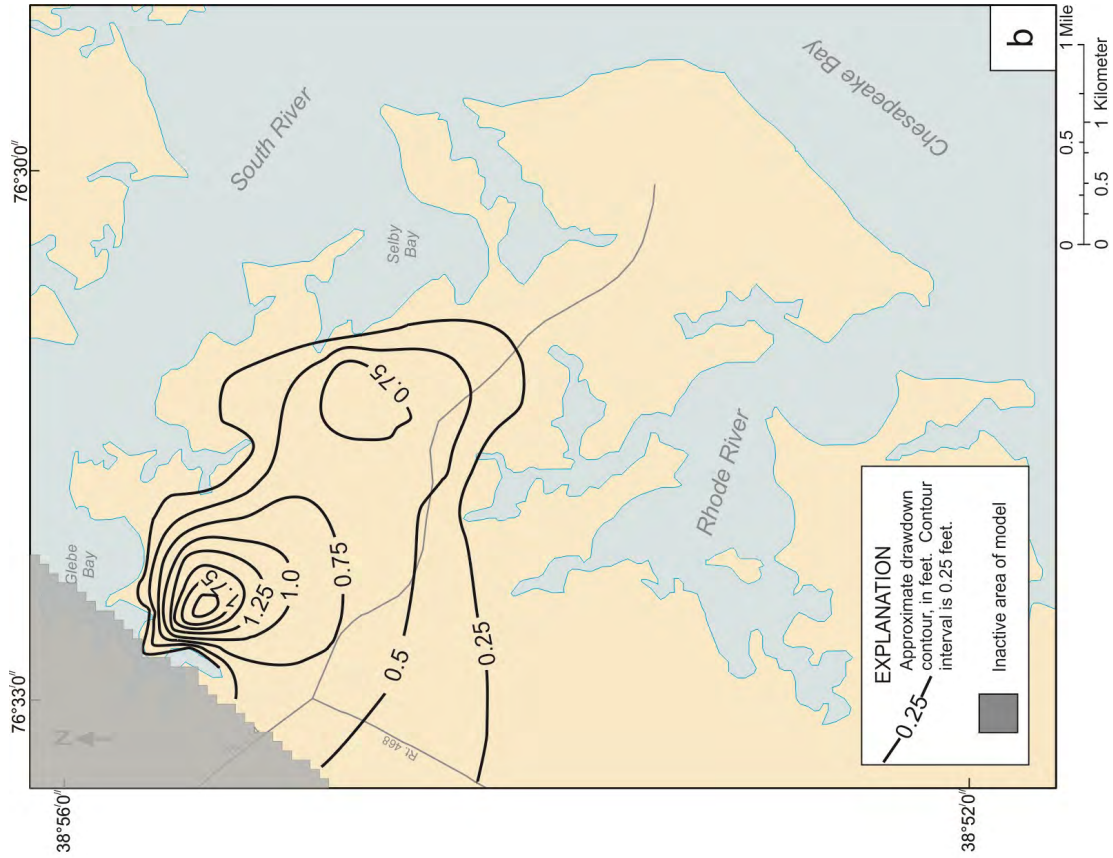
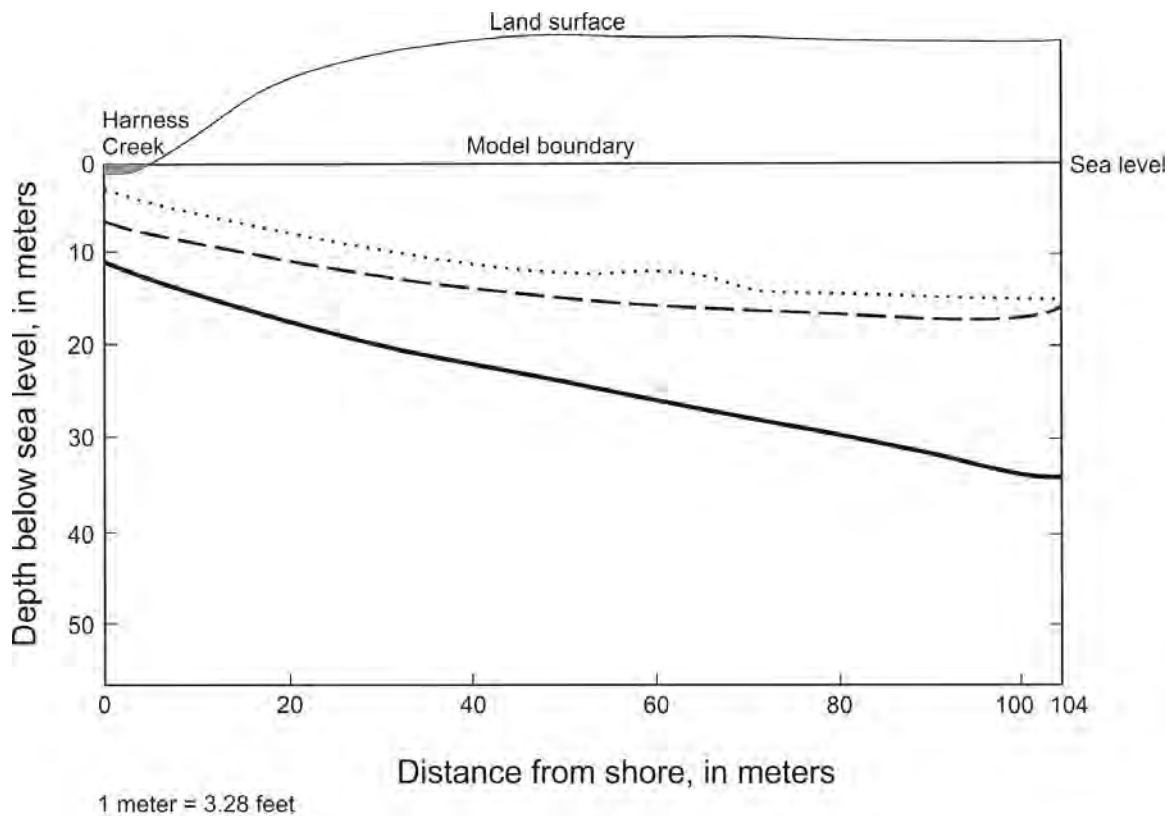


Figure 16. Simulated drawdown resulting from increased domestic withdrawals assuming a pumping rate of (a) 147 gallons per day per well and (b) 250 gallons per day per well.



- EXPLANATION**
- Initial calibrated brackish-water/fresh water interface
 - - - - - Brackish-water/fresh water interface after 100 years in scenario with a drop of 0.3 feet at landward boundary
 - Brackish-water/fresh water interface after 100 years in scenario with a drop of 0.7 feet at landward boundary

Figure 17. Simulated movement of the brackish-water/freshwater interface at Quiet Waters Park. Modified from Fleck and others (1996).

0.9 ft, while drawdown near Selby Bay may reach 0.3 ft. The greater drawdown in these areas suggests that the brackish-water/freshwater interface could potentially rise by approximately 55 ft to more than 65 ft and pose a risk for existing wells located near the shoreline.

FACTORS POTENTIALLY AFFECTING FUTURE WATER SUPPLY AND BRACKISH-WATER INTRUSION

While not within the scope of this project, other factors could affect future groundwater supply and brackish-water intrusion on the Mayo Peninsula. In

the Northeast United States, precipitation trends and climate models suggest that the frequency and intensity of heavy downpours will increase in the future (Georgakakos, 2014; Karl and others, 2009). Additionally, evapotranspiration may change resulting from increased development and warmer temperatures. These changes may affect the amount of groundwater infiltration (recharge) and alter groundwater levels. A possible relative sea-level rise in Maryland of 0.6 to 1.3 ft by mid-century (Boesch, 2008) punctuated by periodic storm events (tidal flooding) would result in greater brackish-water intrusion near the shoreline. These factors may increase the uncertainty of the groundwater-flow model simulations.

EVALUATION OF AQUIA AQUIFER WATER QUALITY

Samples were collected from 24 wells completed in the Aquia aquifer (tab. 1) on the peninsula and analyzed for major ions, trace metals, nutrients, gross alpha-particle activity, and bromide (app. A). Eight samples were also analyzed for total coliforms and *e. coli*. Well-construction records for the sampled wells, including well-screen intervals to determine depth zone of aquifer screened, were compiled (tab. 1). Additional samples were collected from the Magothy aquifer, Rhode River, South River, and Chesapeake Bay to compare against the water chemistry of the Aquia aquifer. Using Quality Assurance and Quality Control (QA/QC) procedures (see data collection and methods section), the data collected in this study were determined to be of good quality.

DATA COLLECTION AND METHODS

Three groups of domestic wells were sampled during this study: (1) wells with elevated chloride that are located adjacent to the shoreline (less than 300 ft from shoreline [n=9]; (2) wells with elevated chloride that are located on the interior of the Mayo Peninsula (more than 300 ft from shoreline [n=6]; and (3) wells with no detected chloride that are located throughout the peninsula [n=9] (fig. 18). The purpose of these groups was to target areas of potential chloride contamination from brackish water (adjacent to the shoreline) and surface-based sources (interior of peninsula) as well as areas with no historically detected chlorides.

A multi-meter was calibrated for dissolved oxygen, pH, and specific conductance in accordance with the manufacturer's instructions every morning before sample collection. The multi-meter was calibrated using solutions supplied by a commercial laboratory supply company at concentration ranges that bracketed the expected values of the sampled groundwater.

Prior to sample collection the well was purged to remove water stored in the well casing or pressure tank. Water was purged at an approximate rate of 2-4 gallons per minute, for at least 20 minutes. Purge water flowed into a bucket, where pH, specific conductance, dissolved oxygen, and temperature were monitored. Readings were taken at 5-minute intervals until the following stabilization criteria were met: pH, ± 0.05 pH units; specific conductance, ± 5 percent (if specific conductance was greater than 100 microsiemens per centimeter [$\mu\text{S}/\text{cm}$]) or ± 5 $\mu\text{S}/$

cm (if specific conductance was less than 100 $\mu\text{S}/\text{cm}$); and temperature, ± 0.5 $^{\circ}\text{C}$.

After stabilization criteria were met, samples were collected. Unfiltered samples were collected first and were collected directly from the spigot. Filtered samples were passed through a 0.45 micron disposable capsule filter using a peristaltic pump. The filter was rinsed with deionized water first, followed by a rinse of the sample water, where samples were collected. After all samples were collected, alkalinity was titrated. Alkalinity was determined by digital titration with sulfuric acid for filtered samples. One sample (well AA-94-3321) was too acidic (pH less than 4.5) for field alkalinity titration and therefore no field titration was completed for that sample.

All field measurements were recorded in a field notebook and sample collection sheets. All sample equipment was cleaned onsite while still wet. The tubing was rinsed with a 10% hydrochloric acid solution followed by a rinse of deionized water. Metal fittings were rinsed in deionized water.

Anne Arundel County Health Department transported all samples to the Maryland Department of Health (MDDH) laboratory with the exception of bromide, which was sent via courier to ALS Environmental (ALS) by MGS. All samples requiring preservation were acidified before transport and samples requiring a maximum temperature of 4 $^{\circ}\text{C}$ (U. S. Environmental Protection Agency, 2016a) during transport were packed in ice. Chain of custody procedures were not used for samples sent to MDDH, but were used for bromide samples sent to ALS. A variety of laboratory methods were used to analyze each constituent and reporting levels varied by constituent and method (app. B).

QA/QC procedures were observed, which include collection of reference samples, duplicate samples, matrix spike and matrix spike duplicate, and blank samples. Duplicate samples, matrix spike and matrix spike duplicate samples were within the acceptable range (80-120 percent for duplicate samples; 75-125 percent for matrix spike and matrix spike duplicate samples) and blank contamination was not observed in any sample (U. S. Environmental Protection Agency, 2017). An additional sample was collected from well AA-95-0710 and analyzed by the USGS to ensure MDDH laboratory accuracy. The percent difference between the USGS analyzed sample and the MDDH analyzed

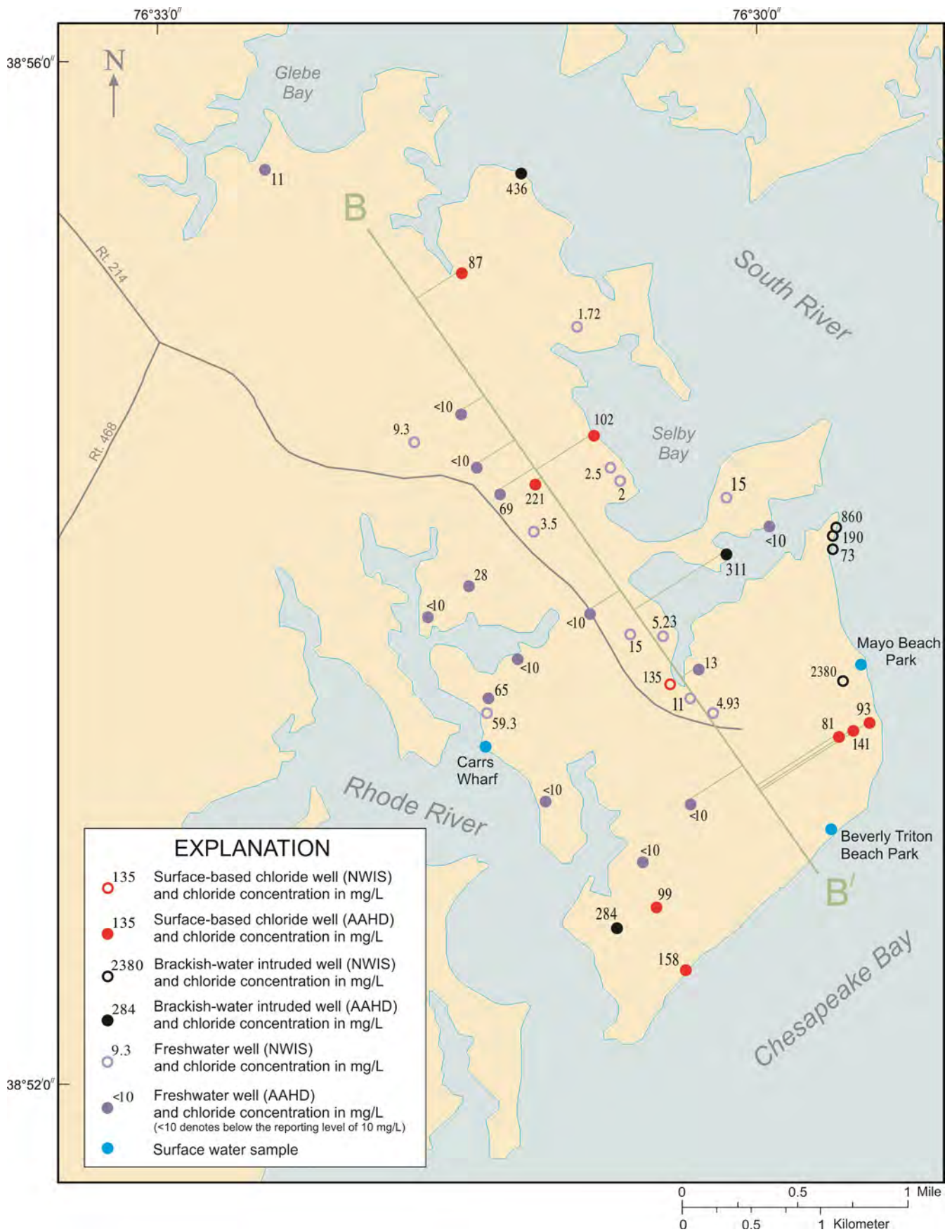


Figure 18. Well locations, chloride concentrations, and likely source of chloride in the Aquia aquifer on the Mayo Peninsula. Line of section shown on Figure 21.

sample for each constituent was below 15 percent. The accuracy of major ions dissolved in water can be determined using the charge balance between cations and anions, expressed as milliequivalents per liter (meq/L). If ion concentrations have been measured correctly, the cations (meq/L) will equal the anions (meq/L). The percent difference between cations and anions for all samples was below 6 percent.

AMBIENT WATER QUALITY UNAFFECTED BY BRACKISH-WATER INTRUSION

From the 24 samples that were collected from the Aquia aquifer, freshwater on the Mayo Peninsula is neutral (median pH = 7.16), reduced (median dissolved oxygen = 0.07 mg/L), with a median alkalinity of 213 mg CaCO₃/L, median total dissolved solids (TDS) of 305 mg/L, and median specific conductance of 442 µS/cm at 25° C. The term “freshwater” in this report identifies samples that have chloride concentrations less than 70 mg/L and is an operational term defined for this study. Most freshwater samples have chloride concentrations less than 10 mg/L. Water chemistry data are plotted on a Piper diagram, which is a tri-linear diagram that graphically represents water chemistry (fig. 19). Freshwater wells were determined to be calcium-magnesium bicarbonate dominated.

WATER QUALITY IN RELATION TO DRINKING WATER STANDARDS

The U.S. Environmental Protection Agency (USEPA) has established drinking water standards for various chemical constituents (U.S. Environmental Protection Agency 2012; 2016b). Maximum Contaminant Levels (MCLs) are health-related standards, above which adverse health effects may occur. These are enforceable standards for public water-supply systems but may not be enforceable for domestic water wells. Testing is required for new wells for contaminants known to be present in an area, such as radium, arsenic, and cadmium in parts of Anne Arundel County. The arsenic MCL (0.01 mg/L) was exceeded in one well and the cadmium MCL (0.005 mg/L) was exceeded in three wells. Secondary Maximum Contaminant Levels (SMCLs) are standards that are established for aesthetic reasons (such as taste or odor) rather than for potential adverse health effects. Several wells exceeded various SMCLs including chloride (250 mg/L) in three wells, manganese (0.05 mg/L)

in seven wells, iron (0.3 mg/L) in 17 wells, and seven wells were outside the acceptable range for pH (6.5-8.5). Nine wells exceeded the 20 mg/L Drinking Water Advisory for sodium (a non-enforceable level recommended for individuals on a 500 milligrams-per-day restricted sodium diet [U.S. Environmental Protection Agency, 2012]).

Nitrate greater than 3 mg/L (as N) can be indicative of anthropogenic surface contamination (particularly sewage contamination) (Fleck and Andreasen, 1996). Two wells had nitrate+nitrite concentrations greater than 3 mg/L, but lower than the MCL of 10 mg/L (AA-88-5997 had a nitrate+nitrite concentration of 3.11 mg/L and AA-94-0336 had a nitrate+nitrite concentration of 3.48 mg/L). Both high nitrate+nitrite wells are located in the unconfined (Glaser, 2002) portion of the aquifer, and are likely more susceptible to surface contamination.

CHLORIDE

Elevated chloride concentrations have been historically observed in the Aquia aquifer in Anne Arundel County (Fleck and others, 1996). As an unconfined aquifer adjacent to brackish water bodies (South River, Rhode River and Chesapeake Bay), the Aquia aquifer may be subject to brackish-water intrusion. Typically, brackish-water intrusion is limited to areas near the shore (less than approximately 600 ft). The deeper Magothy aquifer is also utilized for domestic supply within the study area, although to a much lesser amount. Many domestic wells screened in the Aquia aquifer on the Mayo Peninsula have elevated chloride concentrations, including wells that are located in the interior of the peninsula where high chloride concentrations would not be expected from brackish-water intrusion, but rather from anthropogenic sources.

Potential anthropogenic sources of chloride include road deicing salts, agricultural amendments, landfills, water softener backwash, and septic effluent (Mullaney and others, 2009). On the peninsula, there are no landfills and very little agricultural activities; therefore, any chlorides detected in groundwater would likely not be derived from these sources. On the peninsula, sewer lines are utilized by most homes; however, aging sewer lines (which may contain water softener effluent) have the potential to leak, thus allowing effluent to enter groundwater. Overtopping of wells during storm surges is not likely a major source of chlorides as the effects on the aquifer would likely be short-term

EXPLANATION - Total Dissolved Solids (TDS)

- 0-400 milligrams per liter
- 401-900 milligrams per liter
- >900 milligrams per liter
- Magothy well
- Brackish-water well
- Surface-based chloride well
- Freshwater well

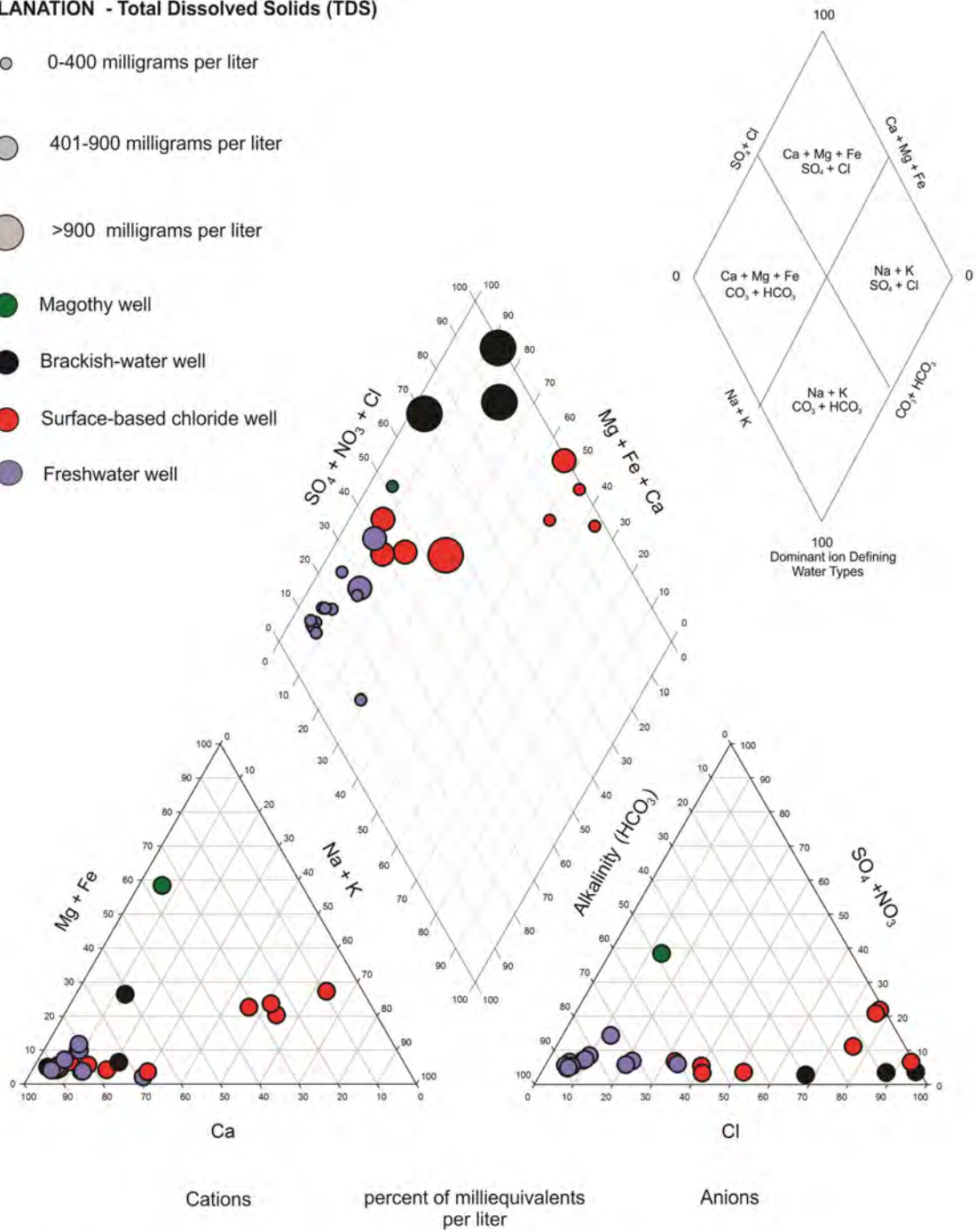


Figure 19. Piper diagram of Aquia aquifer water quality on the Mayo Peninsula.

(Tomaszewski and Lovelace, 2007).

To identify potential chloride sources, the mass ratio between chloride and bromide (Cl:Br ratio) can be used as an investigative tool. Chloride and bromide are relatively unreactive in groundwater, are not easily sorbed by geological materials, and are not involved in oxidation-reduction reactions, and therefore can be useful as indicators of chloride sources to groundwater (Andreasen and Fleck, 1997; Davis and others, 1998; Mullaney and others, 2009). Every well sampled in this study was classified according to the most likely source of chlorides based on their Cl:Br ratio, with the exception of freshwater samples which were identified by having chloride concentrations less than 70 mg/L. Because of the low chloride concentrations and variation in bromide concentrations in freshwater samples, the Cl:Br ratio was not calculated for freshwater samples. Cl:Br ratios around approximately 290 are generally sourced from brackish water and ratios greater than 400 are generally from surface-based sources. Cl:Br ratios for sewage range from 300 to 600 and Cl:Br ratios for road salt are usually greater than 1,000 (Davis and others, 1998). Based on Cl:Br ratios, three wells were likely impacted from brackish water, eight wells (33 percent of sampled wells) were likely impacted from surface-based chloride sources, and 13 wells were determined to be freshwater (fig. 20). Chloride concentrations were generally higher in brackish water (284 to 436 mg/L) than water impacted from surface-based chlorides (81 to 221 mg/L) (tab. 5).

Brackish-Water Intrusion

Brackish-water intrusion identified from wells in

this study (Cl:Br ratio around 290) was generally observed in wells located less than 600 ft from the shoreline. Typically, groundwater affected by brackish-water intrusion is characterized by an increase in concentrations of chloride, calcium, magnesium, sodium, potassium, and sulfate (Fleck and others, 1996). From the Piper diagram (fig. 19), brackish water wells were dominated by calcium, magnesium, sulfate, and chloride. It is possible that increasing trends of calcium, magnesium and sodium could be affected by cation exchange. TDS was the highest in brackish water wells, ranging from 962 to 1,143 mg/L compared to 171 to 573 mg/L for freshwater wells and 200 to 933 mg/L for wells impacted by surface-based chloride sources (tab. 5).

NWIS was accessed to obtain additional chloride and bromide data for 16 NWIS wells that had been previously sampled on the Mayo Peninsula (fig. 18). An evaluation of the Cl:Br ratio in those wells suggested that four of the wells were likely affected by brackish-water intrusion. Chloride concentrations in those wells were greater than 70 mg/L and the Cl:Br ratio ranged from 304-384. The location of these additional wells is consistent with the near-shore extent of brackish-water intrusion mapped in the wells sampled in this study.

Three surface water samples were collected from the Rhode River (Carrs Wharf), Severn River (Mayo Beach Park), and Chesapeake Bay (Beverly Triton Beach Park) (fig. 18) and analyzed for major ions, bromide, and trace metals as a comparison to brackish aquifer water (tab. 6). These surface water samples have similar Cl:Br ratios (282-322) to those of brackish aquifer samples (248-393). It is important to note that geology and redox conditions can affect various constituents (pH, dissolved oxygen, etc.) of aquifer water and therefore these constituents may vary greatly in comparison to

Table 5. Ranges of selected constituents based on water classification.

Water Type (number of samples)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	TDS (mg/L)	Bromide (mg/L)	Chloride (mg/L)	Cl:Br
Freshwater (13)	44.9 – 156.1	<1 – 7.2	1.65 – 35.13	171 – 573	<0.01-0.202	<70	- ¹
Brackish (3)	101.5 – 192.9	6.4 – 26.6	4.77 – 56.3	962 – 1,143	1.05-1.25	284 – 436	249-393
Surface-based chloride source (8)	5.43 – 146	2.4 – 11.8	8.95 – 70.67	200 – 933	0.0545-0.163	81 - 221	>529

¹Because of the low chloride concentrations and variation in bromide concentrations in freshwater samples, the Cl:Br ratio would not be meaningful.

Table 6. Water quality results from surface water sampled in the study area.

Location	Sample Date	pH (field)	Specific Conductance (us/cm @25 °C) - field	Dissolved Oxygen (mg/L) - field	Alkalinity (mg/L as CaCO ₃) - field	Alkalinity (mg/L as CaCO ₃) - lab
South River	12/12/2017	7.9	23,280	11.45	76	92
Rhode River	12/12/2017	8.21	21,950	10.12	73	113
Chesapeake Bay	12/12/2017	7.87	23,740	10.93	77	77

Location	Ammonium (mg/L)	Antimony (mg/L)	Arsenic (mg/L)	Barium (mg/L)	Beryllium (mg/L)	Bromide (mg/L)	Cadmium (mg/L)
South River	<0.2	<0.0025	0.03	<0.1	<0.001	28.1	<0.0025
Rhode River	<0.2	<0.0025	0.028	<0.1	<0.001	24.8	<0.0025
Chesapeake Bay	<0.2	<0.0025	0.029	<0.1	<0.001	29.5	<0.0025

Location	Calcium (mg/L)	Chloride - lab (mg/L)	Chromium (mg/L)	Fluoride (mg/L)	Iron (mg/L)	Lead (mg/L)	Magnesium (mg/L)
South River	176.4	8,430	<0.01	0.49	<0.1	<0.005	517.6
Rhode River	176.9	8,010	<0.01	0.46	<0.1	<0.005	515.3
Chesapeake Bay	183.7	8,330	<0.01	0.49	<0.1	<0.005	537.5

Location	Manganese (mg/L)	Nitrate+Nitrite (mg/L as N)	Potassium (mg/L)	Selenium (mg/L)	Sodium (mg/L)	Sulfate (mg/L)*
South River	<0.05	<0.2	159.2	<0.025	4178	601
Rhode River	<0.05	<0.2	155.6	<0.025	4080	618
Chesapeake Bay	<0.05	<0.2	163.6	<0.025	4364	620

Location	TDS (mg/L)	Thallium (mg/L)	Uranium (mg/L)
South River	14,578	<0.001	0.0013
Rhode River	13,902	<0.001	0.0012
Chesapeake Bay	14,637	<0.001	0.0012

*The MDDH analyzed sulfate for the surface water samples, however noticeable interference was observed. Only after dilution with deionized water were reported results achieved.

surface water samples (see section on weathered zone).

Surface-Based Chloride Sources

Salt has been used as a deicing method for roads for many decades as it provides safe travel during winter precipitation events. The application of deicing salt on Anne Arundel County roads is described below (Alexander Baquie, Chief, Road Operations, Anne Arundel Department of Public Works, written commun., 2018):

On main roads, those that carry the most traffic and are generally classified as “arterial” roads, liquid salt brine is applied prior to the onset of frozen precipitation (subject to certain weather conditions). Calcium chloride is used as a pre-wetting agent for use during very cold temperatures. Following precipitation, sodium chloride is applied to roads in solid form from a dump truck equipped with a salt spreader and plow. Particulates are generally in the size range of 0.125 to 0.25 in. and are comprised of no less than 95 percent sodium chloride where moisture content upon delivery does not exceed 3 percent by weight. Road salt application rates can range from 100 to 500 pounds per lane mile. Typically, 2-4 salting applications are made every 24-hour period in conjunction with plowing operations. The majority of storm events are concluded within 24-36 hours.

Salt usage will likely increase in the future as wider roads are constructed and population increases. Impacts to groundwater from road salt can be derived from improper construction of road salt storage facilities and direct application on roads. Generally, groundwater affected by road salt shows increased concentrations of sodium and chloride relative to other constituents that may be observed in brackish water. From the Piper Diagram (fig. 19) surface-based chloride-impacted wells were dominated by either sodium, chloride, and sulfate or calcium, magnesium and bicarbonate. Wells that have been impacted by surface-based chloride sources may be dominated by sodium and chloride; however, in this study anthropogenic impacts are thought to be minimal and water type is still likely dominated by aquifer chemistry. Wells impacted by surface-based chloride sources on the Mayo Peninsula were identified as having chloride concentrations greater than 70 mg/L and a Cl:Br

ratio greater than 400 (fig. 20). A salt storage facility is located to the west of the peninsula, but given its distance (approximately two miles), it is not likely to impact groundwater quality in the study area. Surface-based chlorides have contaminated approximately 33 percent of wells sampled in this study.

WEATHERED AQUIA ZONE

A weathered zone in the uppermost portion of the Aquia aquifer has been identified in parts of Anne Arundel County in previous studies (Glaser, 1971; Hansen, 1977; Mack and Andreasen, 1991; Bolton, 2006). This “weathered zone” is characterized by acidic pH, elevated cadmium concentrations, sometimes elevated chloride concentrations, and is restricted to 50 ft below sea level (bsl) (Bolton, 2006). From this study, the weathered zone was observed to extend up to 75 ft bsl. While sediments in this area are generally oxidized, groundwater throughout the Aquia aquifer tends to have very little dissolved oxygen; however, of all the wells sampled, those completed in the weathered zone contained the highest dissolved oxygen concentrations. The approximate contact between the weathered zone and unweathered zone is indicated in a cross section (fig. 21) where groundwater pH helps delineate the extent of the weathered zone. A transition between reddish-brown sediments to the characteristic unweathered “salt and pepper” colored sediments of the Aquia Formation is observed in driller’s logs throughout the peninsula at depths ranging from 40 to 70 ft below land surface. This wide range of depths may result from variations in surface elevation.

The weathered zone has been re-interpreted after Bolton (2006) to generally mimic surface topography and extend further towards the end of the Mayo Peninsula. The sediments in this weathered zone may be oxidized due to variations in the water-table elevation. As previously noted by Fleck and others (1996), acidic pH in the uppermost portion of the Aquia aquifer may also be due to recharge from slightly acidic precipitation. As they noted, carbonate material was noticeably absent in drill cuttings from a shallow well, which also may contribute to the acidic pH. The vertical extent of the weathered Aquia zone can be delineated using various chemical constituents (fig. 22). At approximately 65-70 feet bsl, nitrate/nitrite and dissolved oxygen concentrations rapidly decrease, indicating that is no longer oxidized below those

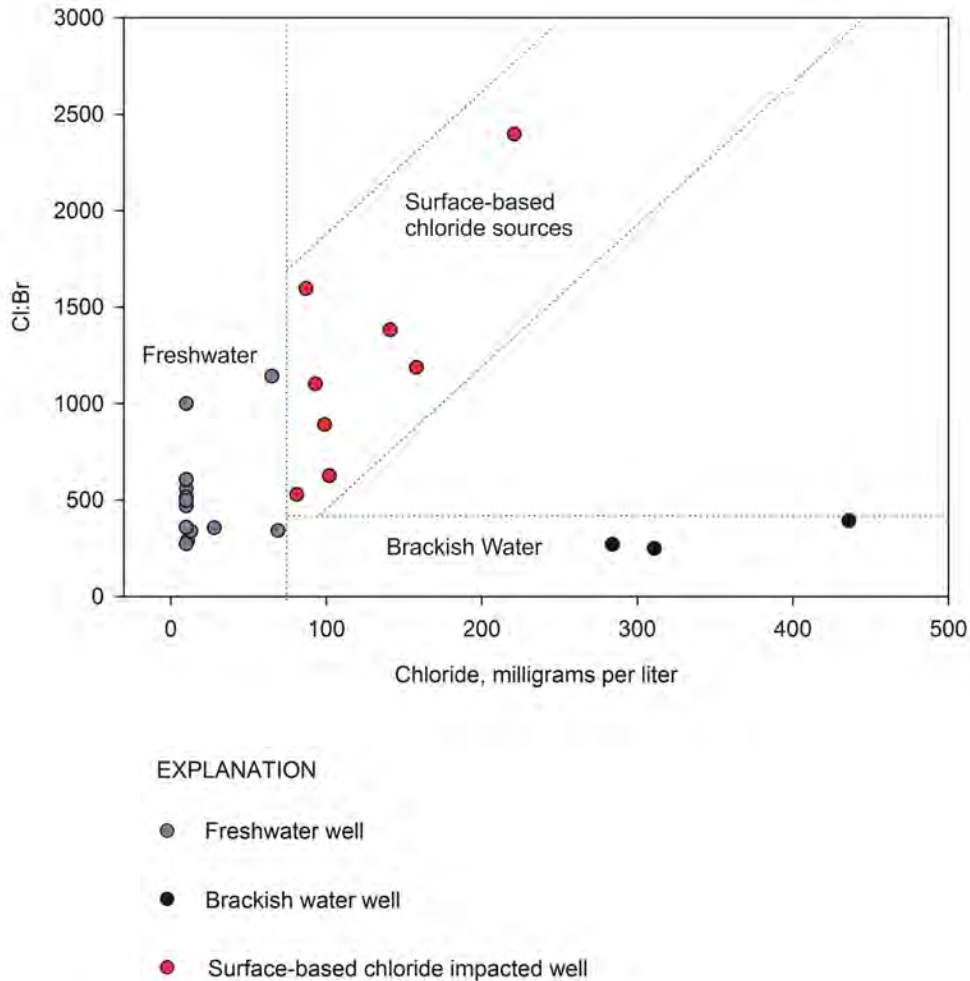


Figure 20. Relation of chloride to Cl:Br ratio. Approximate water chemistry groupings are denoted by dashed lines.

depths, as these constituents are redox reactive. Sodium concentrations also decrease rapidly below approximately 80 ft bsl, possibly suggesting that the Aquia aquifer may at least be partially confined and therefore not susceptible to surface contamination (i.e. application of road salt) at depth. It is also possible that sodium concentrations decrease along the groundwater flowpath. There were no significant trends with calcium and depth, which suggests that cation exchange is not the likely source of decreasing sodium concentrations. Most of the wells impacted by surface-based chloride sources are completed above 80 ft bsl, with the exception of well AA-95-3423 (completed at 110 ft bsl). The weathered zone may indicate a zone of increased permeability or porosity, or lack of a confining layer. Based on the lack of elevated chloride and

cadmium, acidic pH, and reduced conditions, in the western portion of the peninsula it is possible that the weathered zone may thin out towards the western shore. Additional testing and subsurface investigations would be required in order to fully delineate the horizontal extent of the Aquia weathered zone within the study area. Because of the presence of the weathered zone, water quality in the Aquia aquifer generally improves with depth.

Elevated chloride concentrations can at times serve as a proxy for the presence of other chemical constituents and aquifer properties. To examine possible correlations between chloride and well depth, a Spearman's Rank Order Correlation was performed (tab. 7). The Spearman's Rank Order Correlation is a nonparametric test that does not require data points to be normally distributed with a

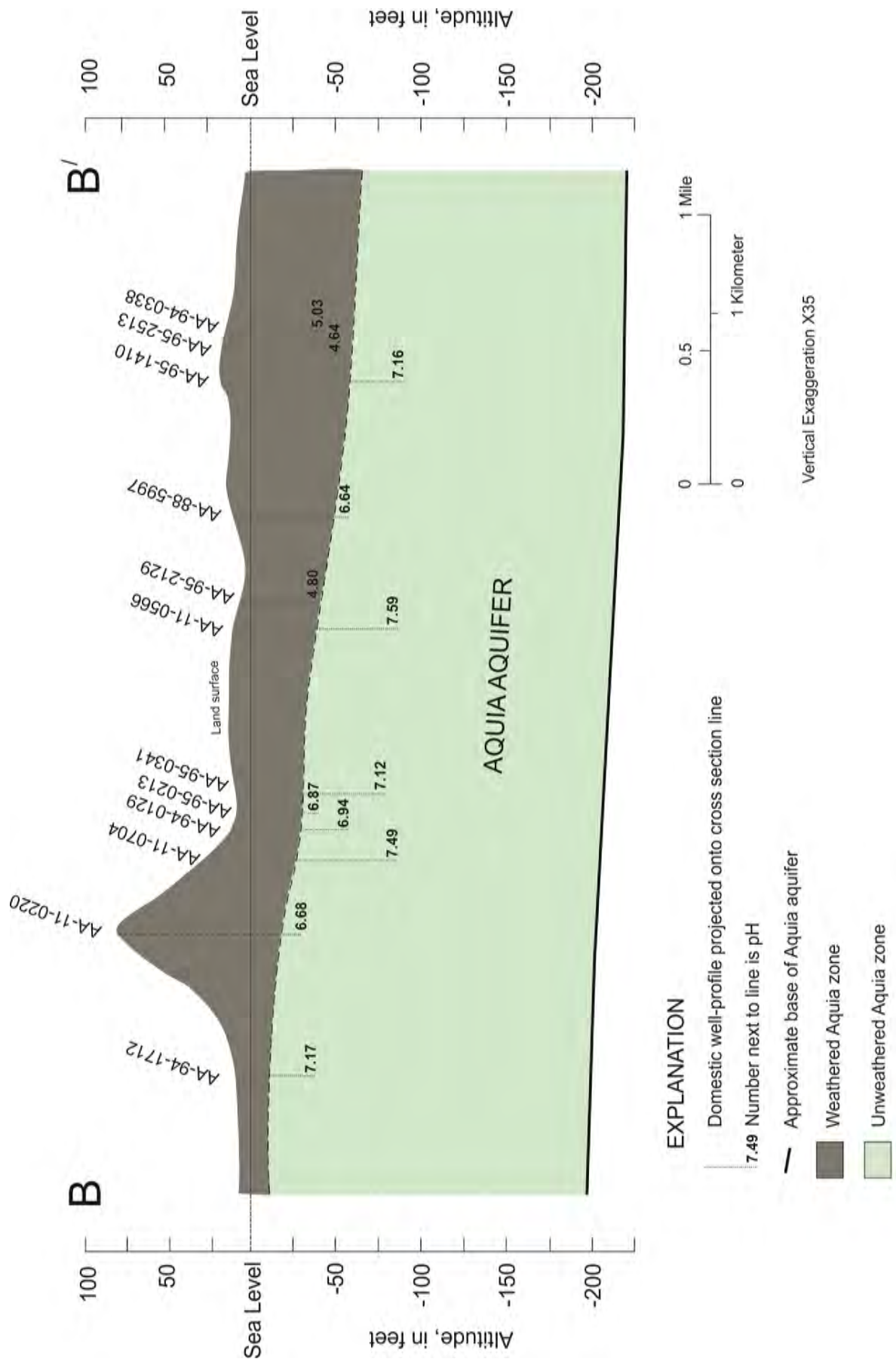


Figure 21. Cross section of weathered Aquia zone. Location of cross section is shown in Figure 18.

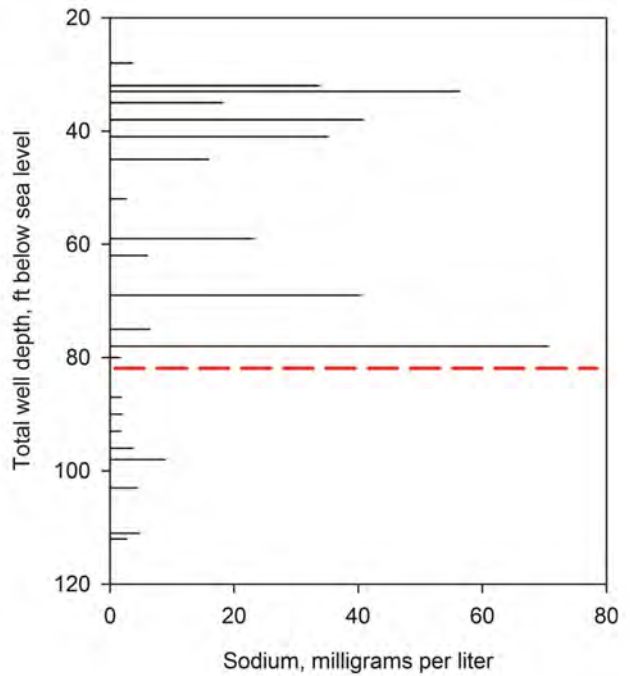
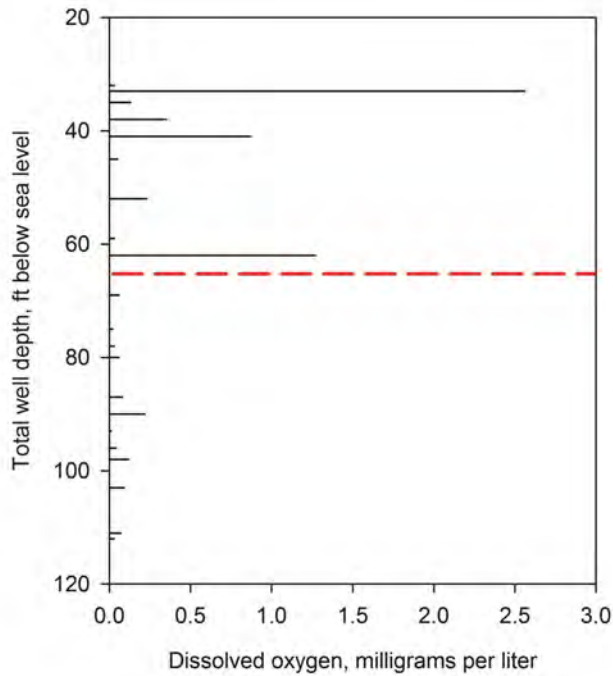
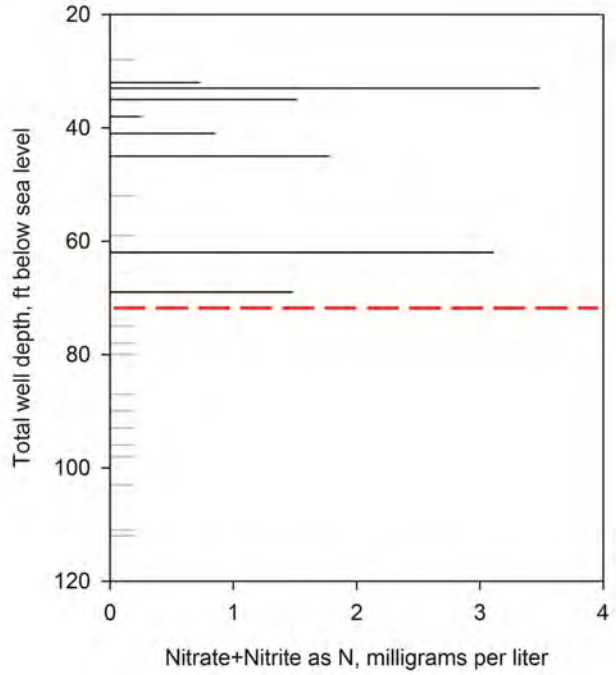
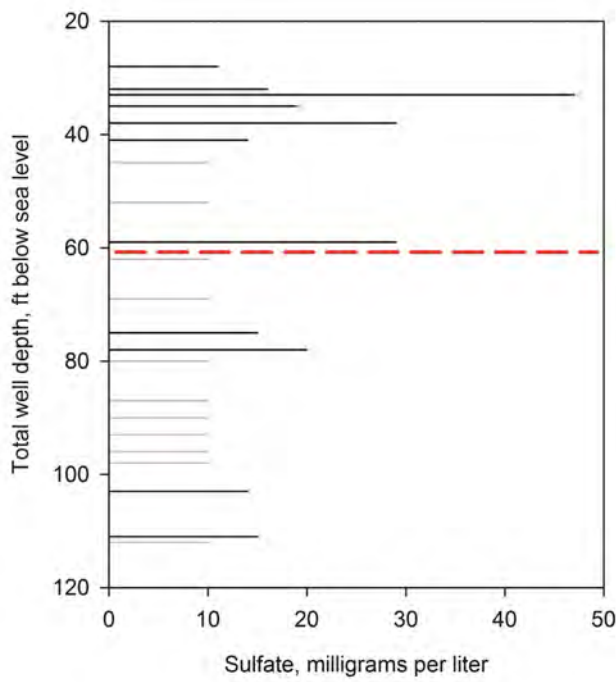


Figure 22. Selected chemical constituents with respect to total well depth. Red dashed lines indicate approximate base of weathered Aquia zone. Concentrations below their respective reporting levels are shown in gray.

Table 7. Spearman's Rank Order Correlation results for selected constituents.

Cell Contents:
Correlation Coefficient
p-value

The pair(s) of variables with positive correlation coefficients and p-values below 0.050 tend to increase together. For the pairs with negative correlation coefficients and p-values below 0.050, one variable tends to decrease while the other increases. For pairs with p-values greater than 0.050, there is no significant relationship between the two variables. A significant correlation was determined for variable pairs with p-values less than 0.050 and the critical correlation as noted by Zar (1984). Shaded/bolded cells indicate significant correlations.

Constituents	pH	Dissolved Oxygen	Bromide	Calcium	Chloride	Iron	Magnesium	Nitrate/ Nitrite	Sodium	Sulfate
Total Well Depth	0.491 0.0151	-0.325 0.119	-0.503 0.0123	0.0175 0.934	-0.481 0.0175	0.382 0.0649	-0.311 0.137	-0.695 0.000116	-0.629 0.00102	-0.389 0.0593
pH		-0.0983 0.644	-0.595 0.00225	0.202 0.340	-0.598 0.00208	-0.0828 0.697	-0.657 0.000459	-0.638 0.000791	-0.730 0.00000120	-0.393 0.0569
Dissolved Oxygen			0.161 0.448	-0.179 0.398	0.146 0.491	-0.420 0.0408	0.0577 0.787	0.574 0.00348	0.246 0.243	-0.00965 0.963
Bromide				0.383 0.0643	0.910 0.0000002	0.0607 0.774	0.659 0.000435	0.414 0.0441	0.677 0.000237	0.415 0.0436
Calcium					0.357 0.0853	0.0423 0.840	0.210 0.322	-0.230 0.277	0.110 0.603	0.156 0.463
Chloride						-0.0431 0.837	0.715 0.0000350	0.504 0.0122	0.746 0.0000002	0.415 0.0431
Iron							-0.0493 0.815	-0.556 0.00497	0.0141 0.947	0.0922 0.664
Magnesium								-0.472 0.0199	0.629 0.00102	0.438 0.0321
Nitrate/Nitrite									0.593 0.00234	0.155 0.466
Sodium										0.666 0.000349

constant variance or linearly related. The Spearman's Rank Order Correlation coefficient does not assign variables as independent or dependent but rather the strength of association is measured between variables. Correlations between constituents were identified as significant with a p-value less than 0.05 and a correlation coefficient greater than the critical value (0.344) of the Spearman's Ranked Correlation Coefficient, based on 24 pairs of parameters (Zar, 1984). Positive correlation coefficients indicate that the variables are increasing together, and negative correlation coefficients indicate that one variable increases as the other variable decreases.

Positive correlations were observed between chloride and specific conductance, bromide, magnesium, manganese, nitrate/nitrite, potassium, sodium, sulfate, and TDS. Because chloride can occur at elevated concentrations on the peninsula, chloride can make up a large portion of specific conductance as well as TDS. Negative correlations were observed between chloride and total well depth and pH. These correlations likely represent groundwater in the weathered zone (high chloride concentrations), where wells are shallower and pH is acidic.

COMPARISON TO THE MAGOTHY AQUIFER WATER QUALITY

The deeper Magothy aquifer is an alternative source for water supply on the Mayo Peninsula. The Magothy has been utilized for domestic supply in cases where brackish-water intrusion in the Aquia aquifer is a problem. While the Magothy aquifer (a confined, artesian aquifer) is not generally susceptible to brackish-water intrusion or contamination from surficial sources, it does have relatively high concentrations of iron. Iron concentrations may range from 14.0 to 26.0 mg/L (Andreasen, 2002). Treatment required for removal of iron, along with the greater well depths, makes the Magothy aquifer a more costly alternative to the Aquia aquifer. The iron concentration in the Magothy well sampled in this study was 27.13 mg/L. The Magothy aquifer commonly contains lignite and pyrite (Drummond and Bolton, 2010) which may result in elevated concentrations of hydrogen sulfide (Andreasen, 2002). Chloride was not detected in the Magothy well.

SUMMARY

The Mayo Peninsula may experience an increase in withdrawals from the Aquia aquifer as a result of the lifting of a building moratorium enacted in 2008 while improvements were being made to the public sewage-treatment system. A total of approximately 630 homes could be built resulting in an increase of between 0.093 and 0.158 Mgal/d, assuming per household water-use rates of 147 and 250 gal/day, respectively. This study evaluated the potential effects (drawdown and brackish-water intrusion) of projected increases. Additionally, the study evaluated the water quality of the Aquia aquifer to determine possible constraints on its potability, including elevated chloride from brackish-water intrusion and surface-based chloride sources.

Drinking-water supply on the peninsula is supplied almost entirely by the shallow, mostly unconfined Aquia aquifer. The Aquia aquifer consists primarily of the Aquia Formation but also includes the less permeable Brightseat and Severn Formations. The aquifer is separated from the deeper Magothy aquifer by the relatively low

permeability Matawan Clay confining unit. Water enters the Aquia aquifer on the peninsula as precipitation and discharges along the shoreline to the South, West, and Rhode Rivers, and Chesapeake Bay.

A one-layer, numerical groundwater-flow model (MODFLOW) was constructed to simulate steady-state flow in the Aquia aquifer on the peninsula. The model, calibrated to observed groundwater levels by adjusting recharge rates and horizontal hydraulic conductivity of the model layer and general-head boundary, was used to estimate the effects of future withdrawals. Modeling indicates that the potential development could result in generally less than about 0.25 ft of drawdown in the Aquia aquifer on the peninsula. However, greater drawdowns of up to 2.1 ft could occur near Glebe Bay, and to a lesser extent near Selby Bay. Comparison of the predicted drawdowns to those modeled in a previous study indicates that the brackish-water/freshwater interface could rise 55 to more than 65 ft in the areas of greatest drawdown, which could pose a

risk to existing wells near the shoreline. To reduce the effects on the Aquia aquifer potential future withdrawals could be shifted to the deeper Magothy aquifer.

Samples were collected from 24 wells on the peninsula and analyzed for major ions, trace metals, nutrients, gross alpha-particle activity, and bromide. An additional sample was collected from a well completed in the Magothy aquifer. Freshwater wells were determined to be calcium-magnesium bicarbonate dominated; brackish water wells were dominated by calcium, magnesium, sulfate, and chloride and; wells impacted by surface-based chloride sources were dominated by either sodium, chloride, and sulfate or calcium, magnesium and bicarbonate. Brackish water was

determined to have impacted three wells on the peninsula. These wells were characterized by chloride concentrations greater than 70 mg/L and a Cl:Br ratio close to 290. All of these wells were located within 600 ft of the shoreline. Surface-based chloride sources were determined to have impacted 33 percent of wells sampled on the peninsula. These wells were characterized by chloride concentrations greater than 70 mg/L and a Cl:Br ratio greater than 400. The uppermost portion of the Aquia aquifer is weathered (maximum depth approximately 75 ft bsl) and produces water that may be acidic (pH less than 6.5), with elevated cadmium and chloride concentrations. Water quality in the Aquia aquifer generally improves with depth.

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APPENDIXES

Appendix A. Water quality results from wells sampled on the Mayo Peninsula.

[μ S/cm, microsiemens per centimeter; mg/L, milligrams per liter; constituents that exceed their respective drinking water standard are bolded and italicized; “-” indicates that no measurement was collected]

	Well Permit	Sample Date	pH (field)	Specific Conductance (uS/cm @25 °C) (field)	Dissolved Oxygen (field-mg/L)	Alkalinity (field – mg CaCO ₃ /L)
Wells sampled previously ² with elevated chlorides near the shore (less than 300 ft)	AA-94-0129	6/5/2017	6.94	891	<1	321
	AA-95-2513	6/6/2017	4.64	623	<1	6
	AA-94-0338	6/21/2017	5.03	294	<1	9
	AA-95-0341	7/12/2017	7.12	1223	<1	293
	AA-95-3423	8/21/2017	7.08	765	<1	254
	AA-11-0249	10/10/2017	7.14	2498	<1	179
Wells sampled previously ² with elevated chloride away from the shore (more than 300 ft)	AA-93-1307	6/6/2017	7.11	540	<1	240
	AA-95-0213	6/7/2017	6.87	765	<1	205
	AA-95-2129	7/10/2017	4.80	1065	<1	5
	AA-94-1712	7/12/2017	7.17	734	<1	227
	AA-94-0535	7/24/2017	5.42	380	<1	23
	AA-94-3321	8/15/2017	4.35	590	<1	- ¹
	AA-95-0710	8/29/2017	6.67	617	<1	171
	AA-94-0336	9/27/2017	5.83	1547	2.56	59
Wells sampled previously ² that had no detected chlorides	AA-11-0220	6/7/2017	6.68	293	<1	127
	AA-11-0765	6/12/2017	7.31	442	<1	216
	AA-11-0566	6/20/2017	7.59	304	<1	140
	AA-11-0704	8/8/2017	7.49	276	<1	134
	AA-95-1682	8/21/2017	7.34	443	<1	214
	AA-94-9923	8/22/2017	7.38	411	<1	171
	AA-88-5997	8/22/2017	6.64	307	1.27	100
	AA-95-1410	8/23/2017	7.16	462	<1	213
	AA-92-0557	9/6/2017	7.02	546	<1	255
	AA-95-5638	10/25/2017	7.37	435	<1	237
Magothy	AA-95-5706	7/10/2017	6.46	244	<1	78

¹Field alkalinity not performed because water was too acidic.

²Sampled by Anne Arundel County Department of Health.

Appendix A., Continued

Well Permit	Ammonia, as N (mg/L)	Antimony (mg/L)	Arsenic (mg/L)	Barium (mg/L)	Beryllium (mg/L)	Bromide (mg/L)	Cadmium (mg/L)
AA-94-0129	<0.2	<0.0025	<0.002	<0.1	<0.001	0.202	<0.0025
AA-95-2513	<0.2	<0.0025	<0.002	0.23	<0.001	0.102	0.0075
AA-94-0338	<0.2	<0.0025	<0.002	<0.1	<0.001	0.153	<0.0025
AA-95-0341	<0.2	<0.0025	<0.002	<0.1	<0.001	0.0922	<0.0025
AA-95-3423	<0.2	<0.0025	0.004	<0.1	<0.001	0.111	<0.0025
AA-11-0249	<0.2	<0.0025	0.005	0.31	<0.001	1.05	<0.0025
AA-93-1307	<0.2	<0.0025	<0.002	<0.1	<0.001	0.0378	<0.0025
AA-95-0213	<0.2	<0.0025	<0.002	<0.1	<0.001	0.163	<0.0025
AA-95-2129	<0.2	<0.0025	<0.002	0.33	0.001	1.25	0.0737
AA-94-1712	<0.2	<0.0025	<0.002	<0.1	<0.001	0.0545	<0.0025
AA-94-0535	<0.2	<0.0025	<0.002	0.11	<0.001	0.0844	<0.0025
AA-94-3321	<0.2	<0.0025	<0.002	0.11	0.004	0.133	0.0202
AA-95-0710	<0.2	<0.0025	<0.002	<0.1	<0.001	0.0499	<0.0025
AA-94-0336	<0.2	<0.0025	<0.002	<0.1	<0.001	1.11	<0.0025
AA-11-0220	<0.2	<0.0025	<0.002	<0.1	<0.001	0.0179	<0.0025
AA-11-0765	<0.2	<0.0025	0.004	0.114	<0.001	0.0279	<0.0025
AA-11-0566	<0.2	<0.0025	<0.002	<0.1	<0.001	0.0194	<0.0025
AA-11-0704	<0.2	<0.0025	0.002	<0.1	<0.001	0.0165	<0.0025
AA-95-1682	<0.2	<0.0025	<0.002	<0.1	<0.001	0.0366	<0.0025
AA-94-9923	<0.2	<0.0025	<0.002	<0.1	<0.001	0.0786	<0.0025
AA-88-5997	<0.2	<0.0025	<0.002	<0.1	<0.001	0.0384	<0.0025
AA-95-1410	0.5	<0.0025	0.016	<0.1	<0.001	0.0213	<0.0025
AA-92-0557	<0.2	<0.0025	0.009	0.154	<0.001	0.0201	<0.0025
AA-95-5638	<0.2	<0.0025	<0.002	<0.1	<0.001	<0.01	<0.0025
AA-95-5706	<0.2	<0.0025	<0.002	<0.1	<0.001	0.0129	<0.0025

Appendix A., Continued

Well Permit	Calcium (mg/L)	Chloride - lab (mg/L)	Cl:Br Ratio	Chromium (mg/L)	Total Coli-forms	E. Coli
AA-94-0129	156.1	69	-	<0.01	Negative	Negative
AA-95-2513	24.57	141	1382	<0.01	Negative	Negative
AA-94-0338	5.43	81	529	<0.01	-	-
AA-95-0341	146	221	2397	<0.01	-	-
AA-95-3423	105.3	99	892	<0.01	-	-
AA-11-0249	192.9	284	270	<0.01	-	-
AA-93-1307	76.46	11	-	<0.01	Positive	Negative
AA-95-0213	109.7	102	626	<0.01	Negative	Negative
AA-95-2129	101.5	311	249	<0.01	-	-
AA-94-1712	109.7	87	1596	<0.01	Positive	Negative
AA-94-0535	15.59	93	1102	<0.01	-	-
AA-94-3321	27.3	158	1188	<0.01	Negative	Negative
AA-95-0710	87.49	65	-	<0.01	-	-
AA-94-0336	183.3	436	393	0.013	-	-
AA-11-0220	46.14	<10	-	<0.01	Positive	Negative
AA-11-0765	81.83	<10	-	<0.01	-	-
AA-11-0566	53.89	<10	-	<0.01	-	-
AA-11-0704	49	<10	-	<0.01	-	-
AA-95-1682	75.43	<10	-	<0.01	-	-
AA-94-9923	63.75	28	-	<0.01	-	-
AA-88-5997	44.9	13	-	<0.01	-	-
AA-95-1410	80.3	<10	-	<0.01	Negative	Negative
AA-92-0557	81.21	<10	-	<0.01	-	-
AA-95-5638	76.65	<10	-	<0.01	-	-
AA-95-5706	16.9	<10	-	<0.01	-	-

Appendix A., Continued

Well Permit	Fluoride (mg/L)	Gross-Alpha (pCi/L); 72 hours ¹	Gross-Alpha error (pCi/L) ²	Iron (mg/L)	Lead (mg/L)	Magnesium (mg/L)
AA-94-0129	<0.1	<2	-	3.09	<0.005	3
AA-95-2513	<0.1	5.1	1.7	0.1	<0.005	11.8
AA-94-0338	<0.1	3.7	1.3	12.55	<0.005	4.2
AA-95-0341	<0.1	<2	-	3.8	<0.005	3.2
AA-95-3423	<0.1	<2	-	4.84	<0.005	2.8
AA-11-0249	0.11	<2	-	2.64	<0.005	6.4
AA-93-1307	0.15	<2	-	<0.1	<0.005	1.4
AA-95-0213	0.11	<2	-	2.9	<0.005	2.4
AA-95-2129	<0.1	<2	-	<0.1	<0.005	26.6
AA-94-1712	<0.1	<2	-	<0.1	<0.005	4.6
AA-94-0535	<0.1	<2	-	<0.1	<0.005	8.8
AA-94-3321	<0.1	7.1	2	8.3	0.008	8.3
AA-95-0710	<0.1	<2	-	6.98	<0.005	3.5
AA-94-0336	<0.1	<2	-	<0.1	<0.005	9.8
AA-11-0220	<0.1	<2	-	5.03	<0.005	1.3
AA-11-0765	0.12	<2	-	1.41	<0.005	2.5
AA-11-0566	<0.1	<2	-	1.17	<0.005	<1
AA-11-0704	0.1	<2	-	0.98	<0.005	1.1
AA-95-1682	<0.1	<2	-	1.82	<0.005	1.6
AA-94-9923	<0.1	<2	-	1.54	<0.005	1.5
AA-88-5997	<0.1	<2	-	<0.1	<0.005	1.2
AA-95-1410	0.2	<2	-	3.12	<0.005	2.7
AA-92-0557	0.14	2.1	1.3	2.11	<0.005	7.2
AA-95-5638	<0.1	<2	-	1.15	<0.005	2.1
AA-95-5706	0.4	8	2.5	27.13	<0.005	5

¹ Measured within approximately 72 hours of sample collection

² For samples with Gross-Alpha greater than 2 pCi/L

Appendix A., Continued

Well Permit	Manganese (mg/L)	Nitrate+Nitrite (mg/L as N)	Potassium (mg/L)	Selenium (mg/L)	Sodium (mg/L)	Sulfate (mg/L)
AA-94-0129	<0.05	<0.2	6.73	<0.025	23.15	29
AA-95-2513	0.22	2.06	8.58	<0.025	54.55	47
AA-94-0338	<0.05	0.25	2.7	<0.025	40.76	29
AA-95-0341	<0.05	<0.2	6.4	<0.025	70.67	20
AA-95-3423	<0.05	<0.2	5.01	<0.025	8.95	<10
AA-11-0249	<0.05	<0.2	6.1	<0.025	4.77	15
AA-93-1307	<0.05	0.85	3.81	<0.025	35.13	14
AA-95-0213	0.08	<0.2	5.4	<0.025	27.7	18
AA-95-2129	0.77	1.78	13.56	<0.025	15.88	<10
AA-94-1712	<0.05	1.51	4.74	<0.025	18.12	19
AA-94-0535	0.09	0.73	3.87	<0.025	33.77	16
AA-94-3321	0.22	1.48	9.02	<0.025	40.42	<10
AA-95-0710	0.12	<0.2	8.3	<0.025	6.41	15
AA-94-0336	<0.05	3.48	6.92	<0.025	56.3	11
AA-11-0220	<0.05	<0.2	3.42	<0.025	3.64	11
AA-11-0765	<0.05	<0.2	5.97	<0.025	2.71	<10
AA-11-0566	<0.05	<0.2	4.02	<0.025	1.8	<10
AA-11-0704	<0.05	<0.2	3.9	<0.025	1.99	<10
AA-95-1682	<0.05	<0.2	6.23	<0.025	2.6	<10
AA-94-9923	<0.05	<0.2	5.11	<0.025	1.65	<10
AA-88-5997	<0.05	3.11	3.55	<0.025	5.99	<10
AA-95-1410	<0.05	<0.2	5.89	<0.025	3.71	<10
AA-92-0557	<0.05	<0.2	8.46	<0.025	4.4	14
AA-95-5638	<0.05	<0.2	5.11	<0.025	1.72	<10
AA-95-5706	0.29	<0.2	3.18	<0.025	1.36	39

Appendix A., Continued

Well Permit	TDS (mg/L)	Thallium (mg/L)	Uranium (mg/L)
AA-94-0129	573	<0.001	<0.001
AA-95-2513	366	<0.001	<0.001
AA-94-0338	200	<0.001	<0.001
AA-95-0341	933	<0.001	<0.001
AA-95-3423	622	<0.001	<0.001
AA-11-0249	1143	<0.001	<0.001
AA-93-1307	319	<0.001	<0.001
AA-95-0213	549	<0.001	<0.001
AA-95-2129	962	<0.001	<0.001
AA-94-1712	557	<0.001	<0.001
AA-94-0535	281	<0.001	<0.001
AA-94-3321	428	<0.001	<0.001
AA-95-0710	429	<0.001	<0.001
AA-94-0336	1104	<0.001	<0.001
AA-11-0220	189	<0.001	<0.001
AA-11-0765	273	<0.001	<0.001
AA-11-0566	191	<0.001	<0.001
AA-11-0704	171	<0.001	<0.001
AA-95-1682	327	<0.001	<0.001
AA-94-9923	305	<0.001	<0.001
AA-88-5997	344	<0.001	<0.001
AA-95-1410	290	<0.001	<0.001
AA-92-0557	359	<0.001	<0.001
AA-95-5638	258	<0.001	<0.001
AA-95-5706	138	<0.001	<0.001

Appendix B. List of constituents with their respective reporting levels and methods.

[MDDH, Maryland Department of Health; ALS, ALS Environmental]

Analyte	Reporting Level	Method	Lab
Calcium	1.00 mg/L	EPA 200.7	MDDH
Magnesium	1.00 mg/L	EPA 200.7	MDDH
Sodium	1.00 mg/L	EPA 200.7	MDDH
Potassium	1.00 mg/L	EPA 200.7	MDDH
Nitrate+Nitrite	0.2 mg/L	EPA 353.2 colorimetric	MDDH
Ammonium	0.2 mg/L	EPA 350.1 colorimetric	MDDH
Alkalinity	2 mg/L	SM 2320 B	MDDH
Sulfate	10.0 mg/L	EPA 375.2	MDDH
Chloride	10.0 mg/L	SM 4500CLE	MDDH
Fluoride	0.10 mg/L	SM 4500FC	MDDH
TDS	2.0 mg/L	SM 2540C	MDDH
Antimony	0.0025 mg/L	EPA 200.7, 200.8	MDDH
Arsenic	0.002 mg/L	EPA 200.7, 200.8	MDDH
Barium	0.10 mg/L	EPA 200.7, 200.8	MDDH
Beryllium	0.001 mg/L	EPA 200.7, 200.8	MDDH
Cadmium	0.0025 mg/L	EPA 200.7, 200.8	MDDH
Chromium	0.010 mg/L	EPA 200.7, 200.8	MDDH
Iron	0.10 mg/L	EPA 200.7	MDDH
Lead	0.005 mg/L	EPA 200.7, 200.8	MDDH
Manganese	0.050 mg/L	EPA 200.7, 200.8	MDDH
Selenium	0.025 mg/L	EPA 200.7, 200.8	MDDH
Thallium	0.001 mg/L	EPA 200.7, 200.8	MDDH
Gross-alpha-particle activity	2 pCi/L	EPA 900.0	MDDH
Uranium	0.001 mg/L	EPA 200.8	MDDH
Total and Fecal Coliform	Positive/Negative	Heterotrophic Plate Count	MDDH
Bromide	0.01 mg/L	EPA 300.1	ALS
pH	--	meter	Field
Specific Conductance	--	meter	Field
Dissolved Oxygen	--	meter	Field
Alkalinity	--	Titration	Field



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Lt. Governor

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Deputy Secretary

A message to Maryland's citizens;

The Maryland Department of Natural Resources (DNR) seeks to balance the preservation and enhancement of the living and physical resources of the state with prudent extraction and utilization policies that benefit the citizens of Maryland. This publication provides information that will increase your understanding of how DNR strives to reach that goal through the earth science assessments conducted by the Maryland Geological Survey.

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