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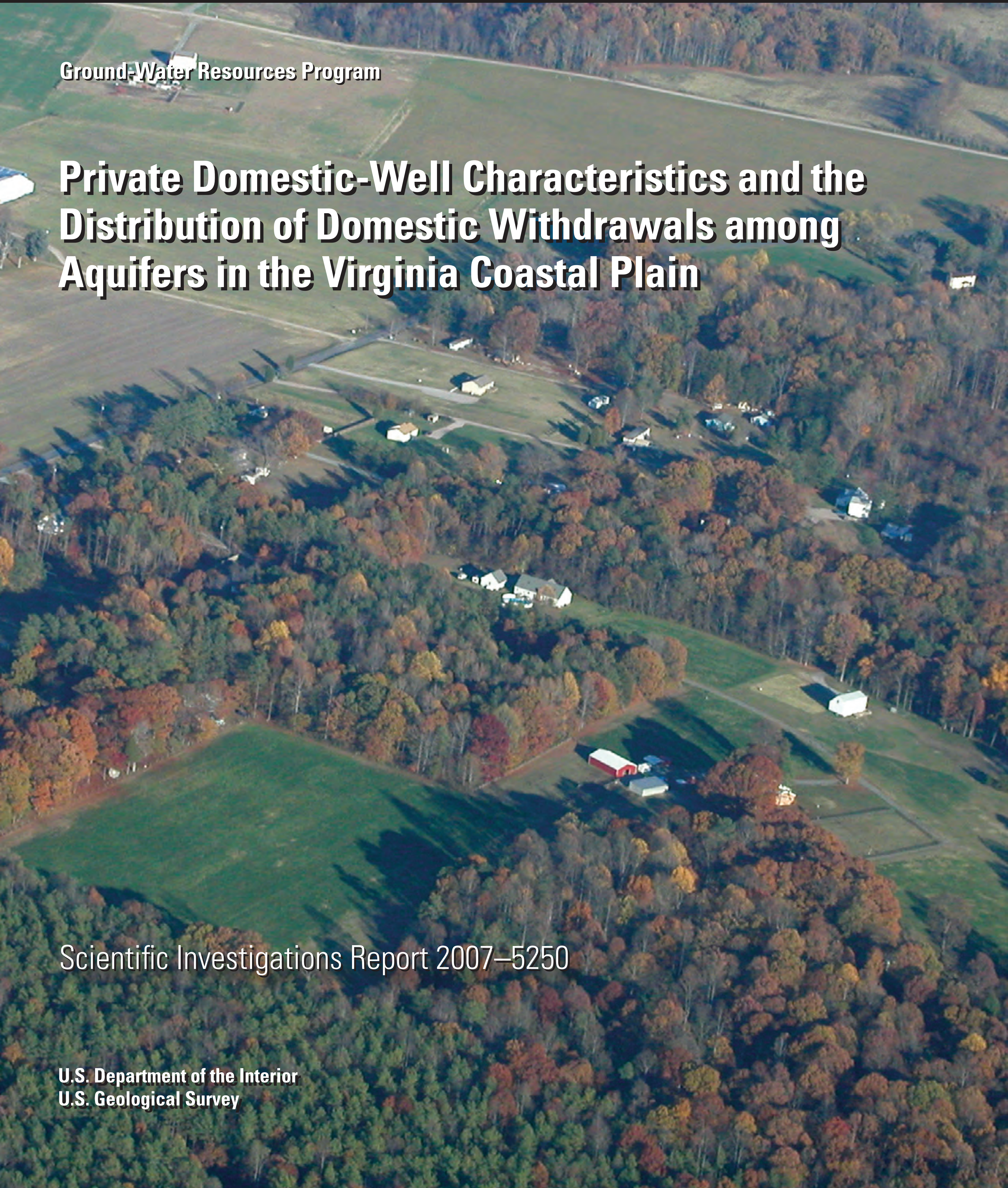
Private Domestic-Well Characteristics and the Distribution of Domestic Withdrawals among Aquifers in the Virginia Coastal Plain



Scientific Investigations Report 2007–5250

U.S. Department of the Interior
U.S. Geological Survey

Cover. **Aerial photograph of rural residences self supplied with ground water from private domestic wells in eastern Hanover County, Virginia, November 1, 2002** *(photograph taken by Jason P. Pope, U.S. Geological Survey).*

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By Jason P. Pope, E. Randolph McFarland, and R. Brent Banks

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow rate	
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 1929).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations Used in this Report:

DEM	digital elevation model
ESRI	Environmental Systems Research Institute, Inc.
GIS	geographic information system
HRPDC	Hampton Roads Planning District Commission
NED	National Elevation Dataset
RASA	Regional Aquifer-System Analysis
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
UWWCR	Uniform Water Well Completion Reports
VDEQ	Virginia Department of Environmental Quality

Terms Used in this Report

Domestic water use — as defined by the USGS National Water-Use Information Program, water used for all indoor household purposes, such as drinking, preparing food, bathing, clothes and dish washing, and toilet flushing, and for outdoor purposes, such as lawn and garden watering.

Independent city — an incorporated place that is a primary division of a State and not legally part of any county. The U.S. Census Bureau considers independent cities as county-equivalent entities for most purposes, and independent cities are included with counties as primary subdivisions of a State. Independent cities are designated only in Virginia and in three other States in the United States.

Irrigation water use — as defined by the USGS National Water-Use Information Program, water that is applied by an irrigation system to assist in the growing of crops and pastures or to maintain vegetation on recreational lands, such as parks and golf courses. In some areas of the Virginia Coastal Plain, private irrigation wells commonly are used to irrigate the lawns of individual residences.

Public-supply water use — as defined by the USGS National Water-Use Information Program, water withdrawn by public and private water suppliers that furnish water to at least 25 people or have a minimum of 15 connections. Water is publicly supplied for a variety of uses, including domestic, commercial, industrial, thermoelectric power, and public water use.

Private domestic well — a well supplying water to an individual residence for domestic use.

Private irrigation well — a well supplying water to an individual residence exclusively for outdoor purposes, such as lawn and garden watering.

Self-supplied withdrawal — water withdrawn directly from the source by a user rather than being obtained from a public supply. In Virginia, almost all known self-supplied withdrawals are from ground-water sources.

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Abstract

A comprehensive analysis of private domestic wells and self-supplied domestic ground-water withdrawals in the Coastal Plain Physiographic Province of Virginia indicates that the magnitudes of these withdrawals and their effects on local and regional ground-water flow are larger and more important than previous reports have stated. Self-supplied ground-water withdrawals for domestic use in the Virginia Coastal Plain are estimated to be approximately 40 million gallons per day, or about 28 percent of all ground-water withdrawals in the area. Contrary to widely held assumptions, only 22 percent of domestic wells in the Virginia Coastal Plain are completed in the shallow, unconfined surficial aquifer to which the water is returned directly by home septic systems. Fifty-three percent of the wells are completed in six deeper confined aquifers, and the remaining 25 percent are completed in the Potomac aquifer and confining zone, the deepest units in the confined system. Assuming an equal rate of withdrawal per well, 78 percent of domestic ground-water withdrawal, or about 30 million gallons per day, is removed from the regional confined ground-water system.

Domestic ground-water withdrawal from an estimated 200,000 private wells supplies more than 15 percent of the population of the area and provides almost the entire source of water in some rural counties. The geographic distribution of these withdrawals is dependent on the self-supplied population and is highly variable. Domestic-well characteristics vary spatially as well, primarily because of geographic differences in depths to particular aquifers, but also because of well-drilling practices that are influenced by geographic, regulatory, and socioeconomic factors.

Domestic ground-water withdrawals in the Virginia Coastal Plain were characterized as part of a larger study to analyze the regional ground-water flow system. Characterizing the withdrawals required differentiation of the withdrawals among the aquifers in the area in addition to determination of the geographic distribution of the withdrawals. Because of a lack of comprehensive data on private-well construction and distribution, a sample of private domestic-well records was used to estimate well characteristics and approximate the proportion of wells and withdrawals associated with each aquifer. Construction data on 2,846 private domestic wells were collected from 29 counties and independent cities (localities) having appreciable self-supplied populations and representing private domestic withdrawals of about 31 million gallons per day. Within each locality, geographically stratified random sampling of well records by tax plat characterized details of well construction for the population of domestic wells. Because neither specific location data nor aquifer elevations were available for individual wells, the primary aquifer in which each well is completed was estimated by cross-referencing the screen elevation estimated from the well record with a generalized configuration of hydrogeologic units underlying the locality in which the well is located. For each locality, summarizing the results of this process allowed the determination of the proportion of wells and withdrawals associated with each aquifer.

Additional evaluation of spatial data was used to apply the domestic withdrawal rates developed for each aquifer in each locality to a detailed ground-water study of the portion of the Virginia Coastal Plain east of the Chesapeake Bay, which is known as the Eastern Shore Peninsula. Because domestic withdrawal estimates are based on the self-supplied population, the geographic distribution of withdrawals within each of the Eastern Shore counties was estimated by using population data from the 2000 U.S. Census at the resolution of census block groups and further refining the distribution based on road density. The allocation of withdrawals among aquifers was then determined by cross-referencing the spatial distribution of withdrawals with the previously determined proportion of wells and withdrawals associated with each aquifer in each county. This procedure resulted in a detailed spatial distribution of domestic withdrawals for the Eastern Shore Peninsula and provides an example of how the domestic-well data and withdrawal estimates could be applied to other ground-water investigations.

Introduction

Ground water is a vital and heavily used resource in the Virginia Coastal Plain Physiographic Province (fig. 1) for water supply to a large and growing regional population. Approximately 3.29 million people live in the Coastal Plain of Virginia, which is about 46 percent of Virginia's total population of 7.08 million, based on analysis of 2000 census block group data (U.S. Census Bureau, 2001, 2003a). The rate of ground-water withdrawal in this area has increased almost continuously since the beginning of the 20th century, from less than 10 million gallons per day (Mgal/d) to almost 140 Mgal/d, and the most substantial increase has occurred in the last half century.

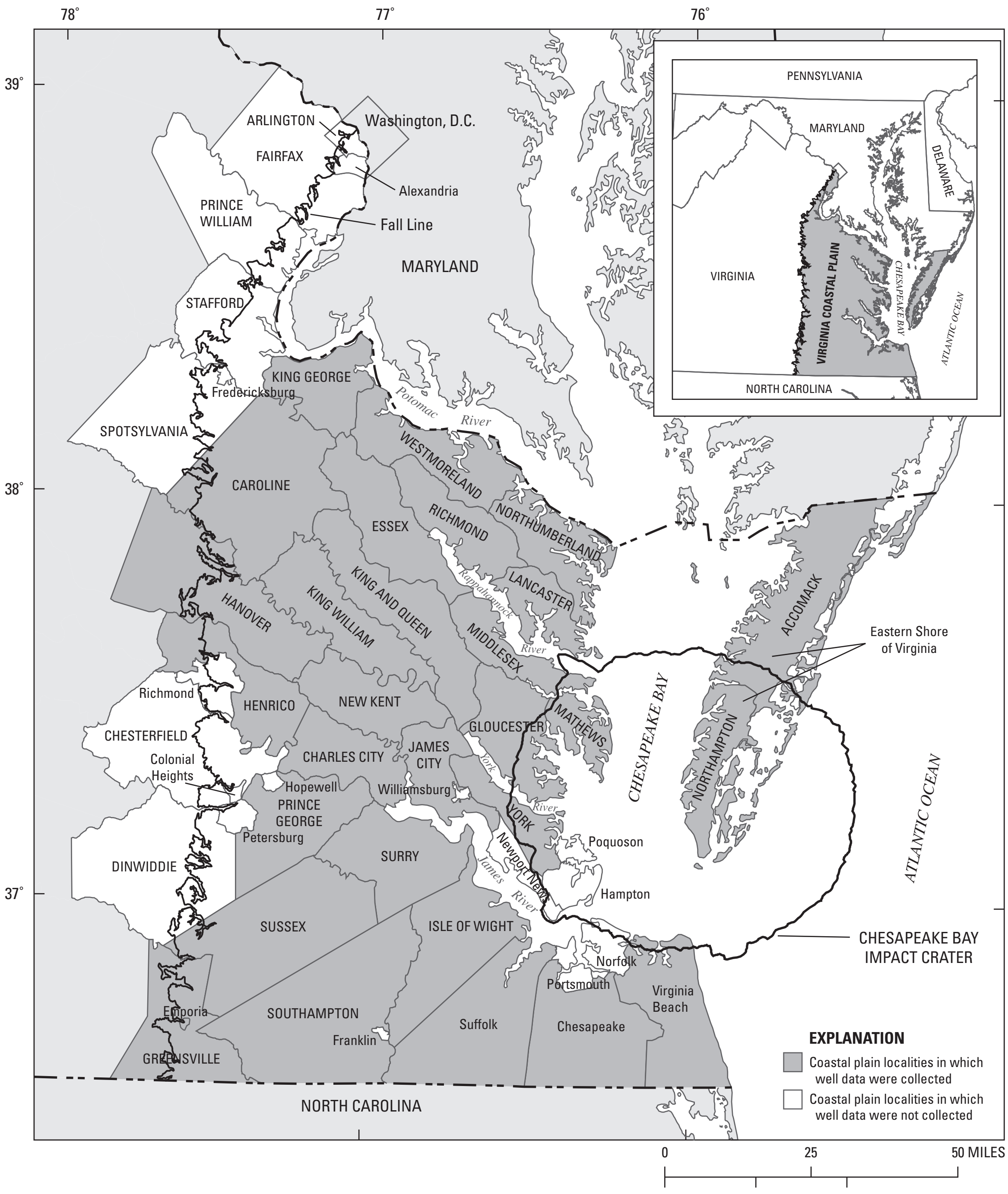

Figure 1. Locations of counties and independent cities, the Chesapeake Bay impact crater, and other important geographic and physiographic features of the Virginia Coastal Plain.

In 2000, ground water was withdrawn from the Northern Atlantic Coastal Plain aquifer system in Virginia at an estimated rate of 137.4 Mgal/d (fig. 2) based on an analysis of the most recent data (U.S. Geological Survey, 2002). This sum includes withdrawals from portions of counties and independent cities (see "Terms Used in this Report") only partially in the Coastal Plain Physiographic Province and accounts for nearly 44 percent of the estimated total ground-water withdrawal of 313.5 Mgal/d for all of Virginia. Of the 137.4 Mgal/d in withdrawals, 62.6 Mgal/d (46 percent) were used for industrial and commercial purposes, 38.5 Mgal/d (28 percent) were self supplied for domestic purposes, 32.3 Mgal/d (24 percent) were used for public supply, and 2.5 Mgal/d (2 percent) were used for agricultural irrigation. The remaining 1.5 Mgal/d were used for other purposes (fig. 2; U.S. Geological Survey, 2002).

Continued, long-term withdrawals for industrial, commercial, public-supply, domestic, and irrigation uses have caused ground-water levels to decline by as much as 200 feet (ft) near large pumping centers, resulting in growing concern among water users and resource managers about local and regional ground-water supplies. Large declines in water levels have altered ground-water flow gradients from a previous seaward direction to a landward direction (Harsh and Laczniak, 1990), which creates the potential for saltwater intrusion. Projected increases in withdrawals could result in further water-level declines and limit continued use of the ground-water resources of the Virginia Coastal Plain.

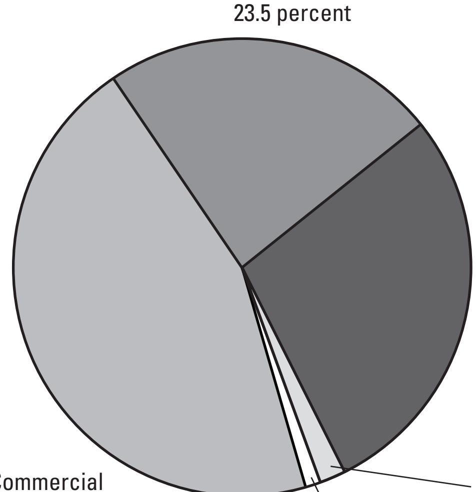

Figure 2. Estimated ground-water withdrawals by category of use in the Virginia Coastal Plain in 2000 (derived from U.S. Geological Survey, 2002).

Concern about this limited resource has resulted in regulation and management of ground-water withdrawals by the Virginia Department of Environmental Quality (VDEQ). In order to maintain and provide a scientific basis for sound ground-water management decisions, the VDEQ and other State and local agencies participate in cooperative programs with the U.S. Geological Survey (USGS) to develop and enhance the scientific understanding of Virginia Coastal Plain hydrogeology. In recent years, concern about limitations of ground-water resources, hydrogeologic effects of the recently discovered Chesapeake Bay impact crater (fig. 1) and the saline water associated with its sediments, and current and proposed withdrawals of saline ground water for public water supplies have all led to comprehensive and ongoing investigations of the aquifer system.

The VDEQ regulates large withdrawals in heavy-use areas of the Coastal Plain, which are designated Ground Water Management Areas (Virginia Department of Environmental Quality, 2006a). These areas include southeastern Virginia and the two Eastern Shore counties of Accomack and Northampton. In the Ground Water Management Areas, withdrawals greater than 300,000 gallons per month must be approved by the Virginia Ground-water Withdrawal Permit Program, which requires the evaluation of the potential effects of new withdrawals on the ground-water system. Elsewhere in the Coastal Plain and in Virginia, the VDEQ requires non-agricultural withdrawals of greater than 10,000 gal per day (gal/d) to be recorded and reported annually (Virginia Department of Environmental Quality, 2006b).

As part of the regulatory program of the VDEQ, total withdrawals of almost 100 Mgal/d for commercial, industrial, public-supply, and some agricultural use for the year 2000 were directly measured and reported from site-specific data. Detailed location, elevation, and construction data for over 1,100 wells in these categories are maintained by the VDEQ. Borehole logs for these wells generally were analyzed by professional geologists and hydrologists; therefore, good data on aquifer sources usually are available for these reported withdrawals. For wells with no aquifer data available, accurate well-location and screen-elevation data allow the aquifers to be inferred from available spatial data on hydrogeologic unit elevations. Thus, reasonably complete information is available for wells associated with major reported withdrawals, which enables a better understanding of the effects of these withdrawals on the ground-water flow system.

In contrast to the large, regulated and reported ground-water withdrawals that compose about 72 percent of the estimated withdrawals in the Virginia Coastal Plain, little is known about domestic supplies to individual homes from private wells, which compose the remaining 28 percent. Little information is readily available on the locations or rates of these withdrawals, and even less is known about which aquifers are the sources of the water. Self-supplied domestic withdrawals in Virginia have been estimated almost entirely from population data because these withdrawals are not measured or reported, as is the case in many states (Hutson and others, 2004). In 2000, about 22 percent of the Virginia Coastal Plain population, or approximately 723,500 people, relied on ground water for household use; over 71 percent of these users, or approximately 514,400 people, were self supplied. This population of self-supplied domestic users is spatially variable, as shown in figure 3.

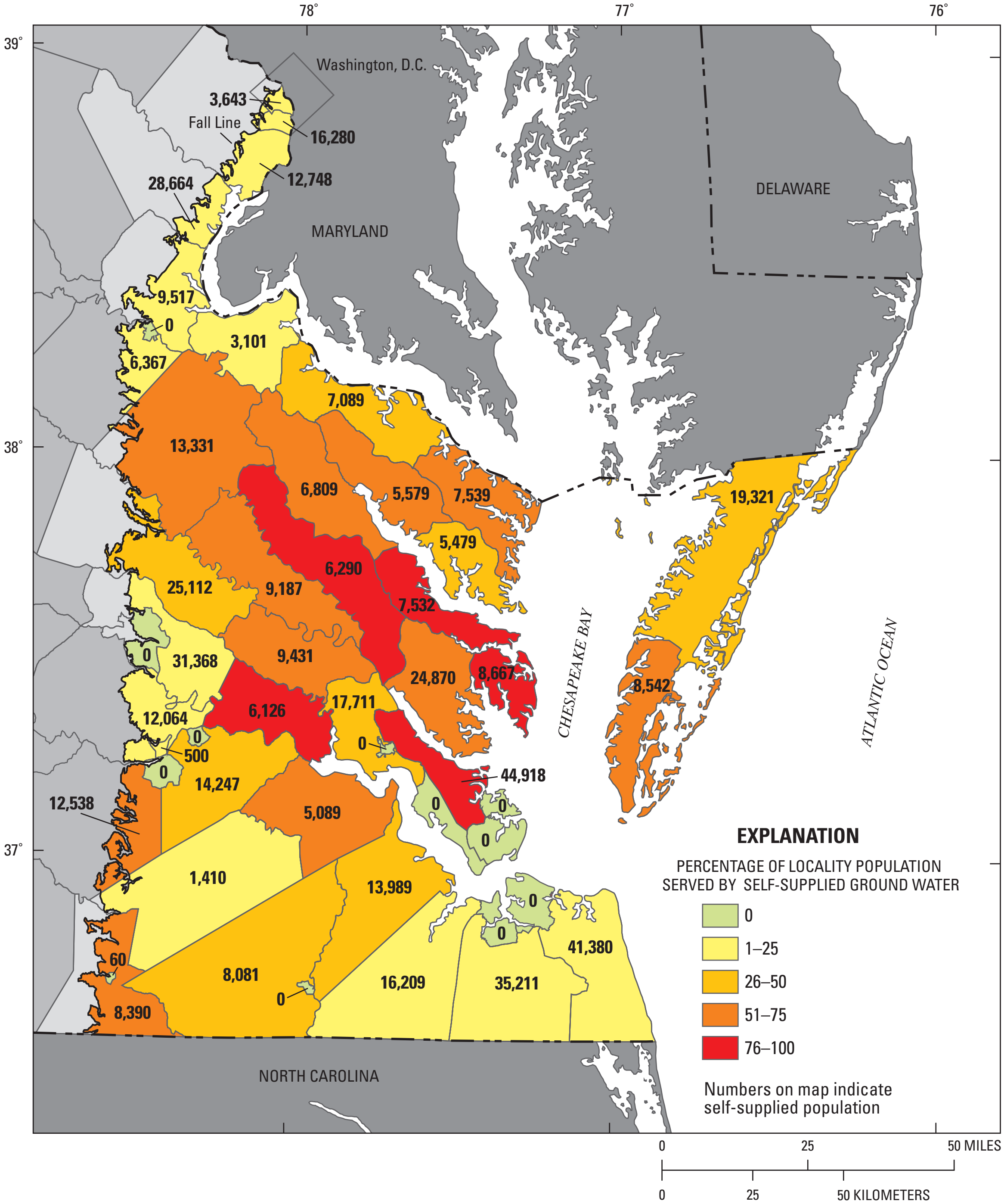

Figure 3. Populations and percentages of populations in Virginia Coastal Plain localities served by self-supplied ground water in 2000 (locations shown in fig. 1).

Population estimates indicate that domestic wells may number nearly 200,000 in the Virginia Coastal Plain and withdrawals from these wells make up a large component of ground-water use, but recorded data on these wells are not readily available. Virginia laws have required reporting of well locations and construction details as part of household water well construction regulations since 1992. However, records for domestic wells installed prior to 1992 are less common, records for wells installed prior to 1982 are extremely rare, and no records were found for wells installed earlier than 1977. Well permit applications and completion reports are managed by local health departments, and these documents are often available only in paper files. Detailed location and construction data submitted on domestic-well forms may be incomplete, and the identification of source aquifers for domestic wells is not required. The approach of using population data to estimate domestic withdrawals is adequate for estimating rates of water use by geographic area, but it is inadequate for detailed ground-water resource studies because it fails to identify the source aquifers.

For a study of the complex, multiaquifer system underlying the Virginia Coastal Plain, withdrawal rates alone are of limited use without accompanying information regarding the aquifers supplying the water. Considerable spatial variation among water-supply aquifers can occur, and the hydrogeologic effects of withdrawals from shallow wells screened in the water-table aquifer may be different from withdrawals from deep wells screened in the lowermost confined aquifer. Nonetheless, the approach used with regulated wells to assign measured withdrawals to specific aquifers is not possible for domestic wells. Because domestic withdrawals are not measured and domestic-well locations and construction details typically are not readily available, a complete accounting of all domestic wells and withdrawals would require a substantial investment of time and resources.

The process of apportioning estimated, self-supplied domestic ground-water withdrawals in Virginia to specific wells or aquifers generally has not been attempted because domestic wells and withdrawals were thought to be insignificant in the context of a regional ground-water flow system and because domestic-well data are difficult to obtain, incomplete, or of poor quality. Consequently, while some previous assessments of ground water in the Virginia Coastal Plain have acknowledged the large magnitude of self-supplied domestic withdrawals, the effects of these withdrawals on regional ground-water conditions has been given little emphasis.

In the most recent comprehensive report on the Virginia Coastal Plain ground-water flow system, Harsh and Laczniak (1990) noted that complete records on domestic use were not available but concluded that domestic use represents only a small percentage of total ground-water use from the confined flow system. The reasoning behind this conclusion was that most ground water withdrawn for self-supplied domestic use is pumped from the unconfined aquifer and returned to the aquifer through septic-tank discharge. The large proportion of ground-water withdrawals supplied by domestic wells, however, indicated that a more thorough investigation of the withdrawals and wells was needed. Furthermore, State and local ground-water professionals questioned the assumption that the unconfined aquifer is the water source for most domestic self-supply wells. Experts have cited numerous examples of domestic wells tapping confined aquifers and have noted that many new and replacement wells have screens installed in the confined aquifer system to provide a more dependable source of high-quality water than can be provided by shallow wells in the unconfined aquifer.

The relatively large withdrawals of self-supplied domestic ground water in this region, along with evidence that an appreciable proportion of private domestic wells are screened in the confined aquifers, motivated a comprehensive study of private domestic wells and self-supplied ground-water withdrawals in the Virginia Coastal Plain. The most immediate need for this information was to address a substantial, long-standing gap in the ground-water withdrawal data being applied to the Virginia Coastal Plain and Virginia Eastern Shore regional ground-water models currently under development.

Purpose and Scope

This report documents the results of an investigation completed between 2002 and 2005 to collect data pertaining to private, domestic water-supply wells in the Virginia Coastal Plain from a statistical sampling of well-construction records dating from 1977 through 2002. The methods developed for selecting and sampling the records, estimating and analyzing elevation data to assign wells to aquifers, and estimating withdrawals by aquifer are discussed along with the results. The methods were developed and the data were collected and analyzed to enhance understanding of the geographic variability in the characteristics of domestic wells and the aquifers used for domestic water supply.

Data were compiled and are summarized in this report from 2,846 records of domestic water-supply wells in the 29 counties and independent cities (called localities hereafter) in the Virginia Coastal Plain that have appreciable populations self supplied with ground water. Statistics on reported well and screen depths and estimated screen elevations are presented for each locality, and spatial variations in well-screen depths and elevations are described and explained. Other ancillary data from the sampling of private domestic-well records also are summarized. Data collected incidentally for 91 private irrigation wells from 8 counties are not included with the domestic-well information but are presented separately.

Methods for combining well data and spatial data on aquifer configurations to estimate the proportion of private domestic wells in each locality intersecting each Coastal Plain aquifer are discussed. These estimated proportions were evaluated along with water-use data to estimate aggregate rates of ground-water withdrawal from each aquifer from private domestic wells in each locality.

An example application from the Virginia Eastern Shore Peninsula is presented to demonstrate how the domestic withdrawal rates estimated by aquifer for each county or city were spatially distributed within a geographic area based on population and road density. The analysis presented here was done to support the development of a ground-water model of the Eastern Shore Peninsula; these methods and techniques could be used to address similar questions in similar settings elsewhere.

This report focuses on the localities within the Virginia Coastal Plain study area with appreciable populations self supplied with ground water from domestic wells. This excludes almost entirely urban localities, such as the independent Cities of Hampton and Norfolk, but includes other large independent cities with some rural areas, such as Virginia Beach and Chesapeake. The shaded localities in figure 1 are localities for which well data were collected.

Description of Study Area

The Coastal Plain Physiographic Province, henceforth called the Coastal Plain, occupies the entire eastern part of Virginia, a total area of approximately 13,000 square miles (mi^2) between approximately west longitude 77 degrees 30 minutes and the Atlantic Ocean (fig. 1). The Maryland and North Carolina borders bound the area to the north and south, respectively.

The Coastal Plain is defined geologically by the underlying mostly unconsolidated sediments of fluvial-deltaic and marine origin that thin to the west near the Fall Line (fig. 1), where the Coastal Plain sediments meet the crystalline rock of the Piedmont Physiographic Province. Fifty Virginia counties and independent cities lie entirely or partially within the Coastal Plain, which encompasses a land area of approximately 8,755 mi^2, or approximately 22 percent of the total Virginia land area.

The Virginia Coastal Plain population is concentrated in large urban areas, including the northern Virginia metropolitan area near Washington, D.C.; the Cities of Fredericksburg, Richmond, and Petersburg along the western boundary of the Coastal Plain; and the southeastern Virginia Cities of Chesapeake, Hampton, Norfolk, Portsmouth, and Virginia Beach near the mouth of the Chesapeake Bay (fig. 1; U.S. Census Bureau, 2003b). The remainder of the Virginia Coastal Plain is relatively sparsely populated, ranging from small towns to outlying rural areas composed of forested and agricultural lands.

The climate in this region is temperate, and annual mean precipitation is approximately 43 inches (National Climatic Data Center, 2005). The topography of the Virginia Coastal Plain is characterized by rolling terrain with deeply incised stream valleys in the northwestern section and gently rolling to level terrain with broad stream valleys in the eastern and southern sections. Land-surface elevations decline seaward, ranging from over 300 ft in the western Coastal Plain to sea level relative to National Geodetic Vertical Datum of 1929 (NGVD 1929) at the Atlantic coast.

Several major rivers drain eastward into Chesapeake Bay, and most become brackish as they enter estuarine areas east of the Fall Line. Consequently, rivers throughout most of the Virginia Coastal Plain are not used for water supply. The rivers and bay, however, subdivide the Virginia Coastal Plain into several regions. The area south of the Potomac River and north of the Rappahannock River is known as the Northern Neck Peninsula; the area between the Rappahannock and the York River is known as the Middle Peninsula; the area between the York and James Rivers is known as the York-James Peninsula; and the area south of the James River is referred to as southeastern Virginia. The area east of Chesapeake Bay is known as the Eastern Shore Peninsula. Additionally, the area of transition along the Fall Line between the Coastal Plain and the Piedmont Physiographic Provinces is known as the Fall Zone.

Previous Investigations

Numerous reports of previous investigations provide information useful to understanding the history of private domestic wells and historical self-supplied ground-water withdrawals in the Virginia Coastal Plain. While none of these reports has domestic wells and withdrawals as the primary focus, all mention domestic-well characteristics as part of the general discussion of wells and water resources. Comprehensive and thorough surveys of the literature on Virginia Coastal Plain geology and hydrogeology are provided in several major publications on those topics, particularly Meng and Harsh (1988), Harsh and Laczniak (1990), and more recently, McFarland and Bruce (2006).

Sanford (1913) provided some of the earliest comprehensive information on ground-water resources in Virginia. His report describes the geology and hydrogeology of the Coastal Plain in great detail as it was understood at that time. Sanford's report is particularly useful as background information on private domestic wells because it also includes a county-by-county overview of "water bearing beds" and characteristics of local wells, including some domestic wells. Sanford's discussion of wells, domestic and otherwise, is not a formal survey, however, so it is difficult to make definitive conclusions about domestic-well characteristics across the study area. Nonetheless, some trends are apparent even from his brief discussion. At the time of Sanford's report (1913), most domestic supply wells apparently were shallow, dug wells, particularly in areas near the Fall Line where other aquifers are not available at depth. Drilled wells apparently were less common for domestic purposes, though not rare. Numerous deep, drilled domestic wells were reported in many areas of the Coastal Plain, particularly where the aquifer system is thicker. In fact, drilled domestic wells up to 700 ft deep were noted by Sanford (1913), but it is unclear from his work what proportion of domestic wells were in each depth or construction category.

A few decades later, Cederstrom produced a series of reports covering the counties of southeastern Virginia (1945), the York-James Peninsula (1957), and the Middle Peninsula (1969) that provide information on characteristics of wells used for domestic supply at the time. In general, these reports describe the domestic-well distribution much as Sanford (1913) did. Although shallow, dug wells were clearly the most common source of self-supplied domestic water, deeper drilled wells were sometime used, and their distribution depended mostly on local hydrogeologic conditions.

More recent investigations by the Commonwealth of Virginia provide the most comprehensive data on domestic wells and withdrawals in the Virginia Coastal Plain available to date. Ground-water investigations in the Eastern Shore Peninsula (Sinnott and Tibbitts, 1968), the York-James Peninsula (Virginia State Water Control Board, 1973), southeastern Virginia (Virginia State Water Control Board, 1974), the Middle Peninsula (Siudyla and others, 1977), and the Northern Neck Peninsula (Newton and Siudyla, 1979) address domestic water supply and include detailed information on selected individual private domestic wells. In addition to discussing the most commonly used aquifers for domestic supply, these reports include lists of domestic-well construction data with locations retrieved from well-completion records, and some of these records include information on the aquifers in which the wells were completed.

The report on the Eastern Shore Peninsula (Sinnott and Tibbitts, 1968) indicates that many homes obtained water from dug or driven wells in the surficial aquifer, but deeper aquifers were used occasionally for domestic purposes. The Middle Peninsula report (Siudyla and others, 1977) also notes the importance of the unconfined aquifer for domestic supply but mentions the use of deeper aquifers by "many moderate to light water users," including domestic users in Essex, King William, and King and Queen Counties. Interestingly, the report by Siudyla and others (1977) notes the prevalent use of the surficial and Yorktown-Eastover aquifers on the eastern part of the peninsula, where brackish water is found in the deeper aquifers. This brackish water is now known to be associated with the Chesapeake Bay impact crater.

The report by Newton and Siudyla (1979) on the ground-water resources of the Northern Neck Peninsula provides the most recent published information on domestic wells in Virginia. The report notes that the surficial aquifer is a "significant source of domestic ground water," but also indicates the frequent use of other deeper aquifers for domestic supply. Most notably, several of the domestic wells listed in the report by Newton and Siudyla (1979) for Lancaster County apparently were completed in the Potomac aquifer. As a group, the reports that mention domestic wells document the continued importance of the surficial aquifer in most localities but also discuss the use of several confined aquifers, depending on local conditions.

The USGS has been involved in the study of Virginia Coastal Plain hydrogeology since the beginning of the 20th century, but the most current knowledge of this system is summarized in two reports completed as part of the USGS Regional Aquifer-System Analysis (RASA) program in the 1980s. A comprehensive description of the hydrogeologic system was developed by Meng and Harsh (1988), and a related computer model of ground-water flow was developed by Harsh and Laczniak (1990). Subsequently, a report by Richardson (1994) described the hydrogeology and ground-water flow system of the Eastern Shore Peninsula of Virginia in greater detail than the previous reports and included the development of a computer model to simulate ground-water flow and saltwater intrusion in the Eastern Shore. The descriptions of the Virginia Coastal Plain and Eastern Shore hydrogeology and the two computer models have been updated since their initial creation and adopted by the VDEQ as resource-management tools for evaluating the potential effects of current and proposed withdrawals (McFarland, 1998). Neither modeling study, however, included domestic withdrawals because domestic use was assumed to represent only a small portion of water not returned to the flow system, and it was thought that there could be no practical way of collecting domestic withdrawal data by aquifer.

Several developments in more recent years have advanced the understanding of the geology and hydrology of the Virginia Coastal Plain in general and the Eastern Shore in particular. The most important of these is the discovery of a large meteor-impact crater beneath the Chesapeake Bay (fig. 1), which substantially revised the previous understanding of the ground-water system (Powars and Bruce, 1999; Powars, 2000). In addition to a variety of improvements in the understanding of certain geologic relations, improved understanding of ground-water flow and geochemistry in the system was made possible by the accumulation of additional hydrologic data (McFarland, 1998). Substantial amounts of withdrawal and water-level data have been collected, which has improved the understanding of the relations between wells and aquifers. Also, recent advances in computer modeling and data-processing technologies and practices have improved simulation capabilities and revealed inadequacies in the previous models (McFarland, 1998).

Consequently, the USGS began a project in 2000, in cooperation with the VDEQ and the Hampton Roads Planning District Commission (HRPDC), to develop a new, comprehensive understanding of the hydrogeology of the Virginia Coastal Plain. The goals of the project are to incorporate the most current information about the geology, hydrology, and hydrologic conditions of the region and provide information and tools to meet the needs of future ground-water resource managers. A large and fundamental component of the project was the production of a revised and refined description of the Virginia Coastal Plain aquifer system that provides enhanced detail and incorporates new understandings of geologic relations (McFarland and Bruce, 2006). The work by McFarland and Bruce (2006) represents the most comprehensive and current understanding of the configuration (framework) of aquifers and confining units in the Virginia Coastal Plain. It is being used to support the development of a revised USGS computer model of the ground-water flow system that reflects current hydrogeologic concepts and conditions and can be used for predicting future ground-water conditions (Heywood, 2003). Concurrently, a computer model of the Eastern Shore of Virginia is being developed by the USGS to more accurately simulate ground-water flow and saltwater intrusion than has been possible with the Richardson (1994) model.

An important motivation for revising and updating the two ground-water models, in addition to incorporating new geologic information and better modeling technology, is the need for better ground-water withdrawal data in the study area. Most of the work on withdrawal data has focused on improving the completeness and accuracy of recorded information on large, regulated wells and the reported withdrawals, and on ensuring that the screens of these wells are correctly related to the newly configured aquifers and confining units, as described by McFarland and Bruce (2006). Another quite different but equally important improvement in the withdrawal data is the recent understanding that a large part of the ground-water withdrawal total for the Virginia Coastal Plain is composed of unregulated and unreported self-supplied withdrawals by domestic users from private wells.

Aquifers and Confining Units in the Virginia Coastal Plain

The Virginia Coastal Plain aquifer system is a subdivision of the more extensive Northern Atlantic Coastal Plain aquifer system. The geology of this region consists of a seaward-thickening wedge of eastward-dipping strata of unconsolidated to partly consolidated sediments of Cretaceous, Tertiary, and Quaternary age that overlie a basement of consolidated bedrock (McFarland and Bruce, 2006). The sediments of the Coastal Plain were deposited by seaward progradation of fluvial plains and deltas along the continental margin, followed by a series of marine transgressions and regressions (McFarland and Bruce, 2006). This depositional environment resulted in a thick, eastward-dipping sequence of nonmarine strata mostly of Cretaceous age covered by a much thinner sequence of marine strata of Tertiary age, which is covered by a very thin layer of terrace and flood-plain deposits mostly of Quaternary age (Meng and Harsh, 1988). The entire wedge of sediments ranges from a thin edge near the Fall Line to a thickness of more than 6,000 ft near the coast (Meng and Harsh, 1988).

The sediments of the Coastal Plain in Virginia were altered during the Tertiary period by the impact of a comet or meteorite near the current mouth of the Chesapeake Bay (Powars and Bruce, 1999). The crater left by this impact disrupted the entire sequence of sediments present at the time and was quickly filled by a complex variety of impact-related sediments that were buried by millions of years of subsequent deposition (McFarland and Bruce, 2006). The buried impact crater now extends more than 50 miles (mi) across part of the southeastern Virginia Coastal Plain (fig. 1).

The thick sequence of Coastal Plain sediments forms a complex, multilayered system of permeable aquifers and relatively less-permeable confining units (Meng and Harsh, 1988; fig. 4). Ground water in this system originates primarily from precipitation that infiltrates to the water-table aquifer and then either flows laterally to discharge in nearby streams or downward to recharge deeper confined aquifers (Harsh and Laczniak, 1990). Ground-water flow is mostly lateral through the confined aquifers from recharge areas in the west to discharge areas near the Atlantic coast and major rivers, except in areas around major municipal and industrial withdrawal centers (McFarland and Bruce, 2006).

The entire sequence of Virginia Coastal Plain aquifers and confining units, as described by McFarland and Bruce (2006), is presented in figure 5 in relation to the corresponding geologic units and time periods. This complex aquifer system has 19 interrelated and overlapping hydrogeologic units in the sequence of sediments overlying the bedrock basement, including units associated with the Chesapeake Bay impact crater. McFarland and Bruce (2006) is the primary source of the information on hydrogeology used and described herein, including elevations of the hydrogeologic units. Consequently, reference is made to McFarland and Bruce (2006) for greater detail on the characteristics and extent of all the hydrogeologic units described in condensed form in this report.

Of the hydrogeologic units described by McFarland and Bruce (2006), 10 are considered to be important water-supply sources for private domestic wells in the Virginia Coastal Plain. These units, from top (land surface) to bottom (basement), include the following: surficial aquifer, Yorktown confining zone, Yorktown-Eastover aquifer, Saint Marys aquifer, Piney Point aquifer, Aquia aquifer, Peedee aquifer, Virginia Beach aquifer, Potomac confining zone, and Potomac aquifer (fig. 5).

Notably, the Yorktown and Potomac confining zones are included here as aquifers because they may be indistinguishable from adjacent aquifers at a local scale and may yield water to wells completed in them. Additionally, screens for industrial or municipal wells, when compared by elevation to defined hydrogeologic unit elevations, have been known to intersect these units. While this situation may seem unusual using the traditional concept of aquifers and confining units, it is entirely consistent with the descriptions for these units outlined by McFarland and Bruce (2006).

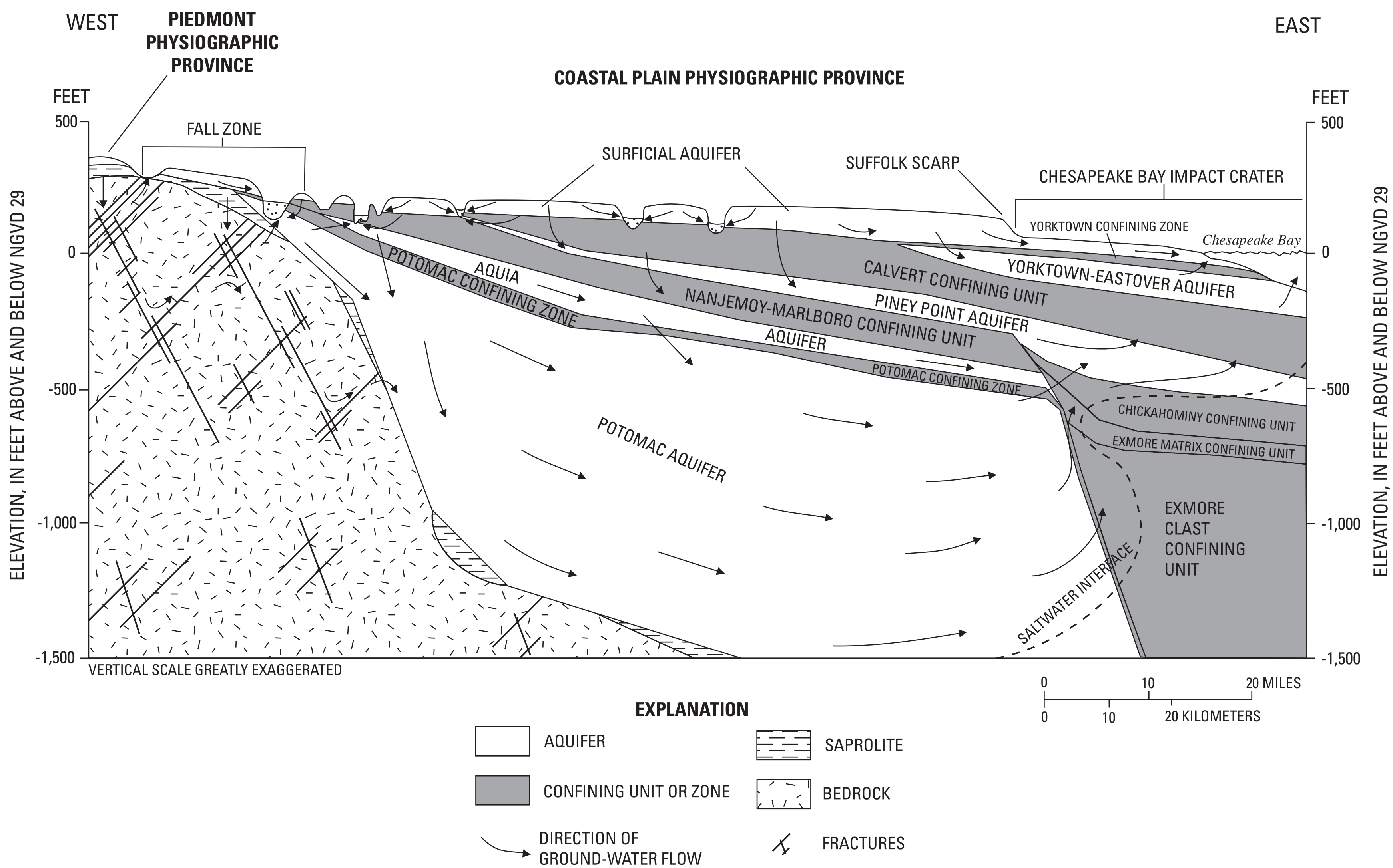

Figure 4. Generalized hydrogeologic section and directions of ground-water flow in the Virginia Coastal Plain (from McFarland and Bruce, 2006).

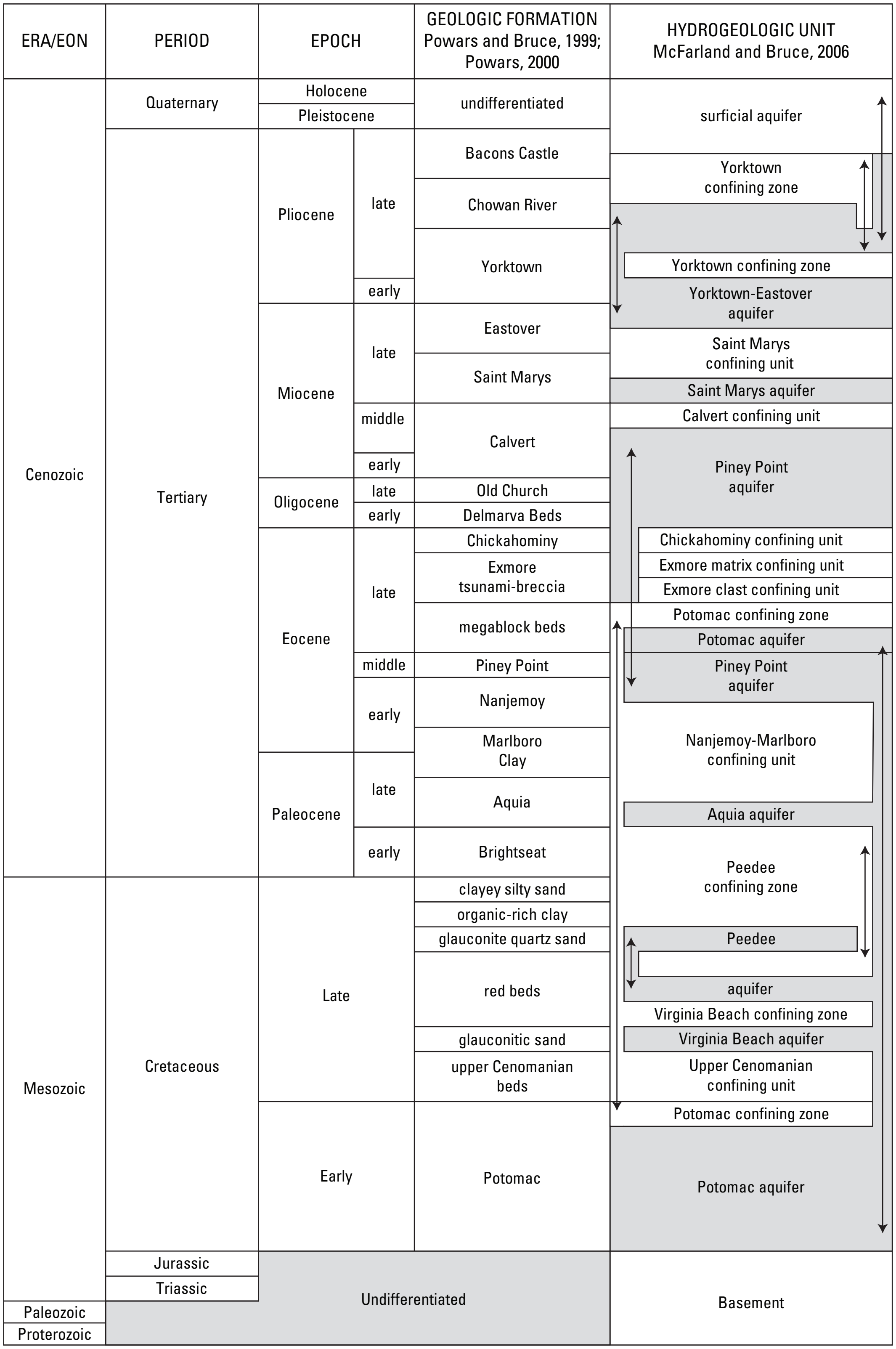

Figure 5. Stratigraphic correlations of hydrogeologic units of the Virginia Coastal Plain (modified from McFarland and Bruce, 2006). Vertical arrows indicate major hydrologic associations that cross stratigraphic boundaries; minor overlaps of hydrogeologic units among adjacent geologic formations are not depicted.

Surficial Aquifer

The surficial aquifer is a heterogeneous aquifer of sand and gravel covering the entire Virginia Coastal Plain (fig. 4). The top of the aquifer is at land surface, and its thickness ranges from several tens of feet in upland areas to a few tens of feet or less to the east. Most of the surficial aquifer is underlain by various confining units or zones. Near the Fall Line or along major rivers, however, the surficial aquifer directly overlies and may be connected to deeper aquifers.

The surficial aquifer is moderately used across the entire Virginia Coastal Plain, providing water primarily to users of relatively small volumes. This aquifer was the source of 0.4 Mgal/d of reported, regulated withdrawals in 2002, which was less than 1 percent of the reported total for the Virginia Coastal Plain (Quinlan, 2004). However, the surficial aquifer is the source of many unregulated and unreported domestic and agricultural withdrawals. Because it is shallow and easily accessible, the surficial aquifer historically has been an important water supply, but drought and decreasing water quality in recent years have caused users in some locations to abandon wells in the surficial aquifer in search of more dependable water supplies in deeper aquifers.

Yorktown Confining Zone

Designation as a confining zone addresses the variable configuration of this unit, which separates the underlying Yorktown-Eastover aquifer from the overlying surficial aquifer (figs. 4, 5). Both of these adjacent aquifers are extremely heterogeneous, and the confining zone between them exhibits characteristics of both units. Discontinuities in composition and texture across small distances mean that this zone functions as a confining unit only at the local level, despite its regional extent, and leakage may be enhanced in other areas where fine-grained interbeds do not exist. In practice, then, the surficial aquifer and the Yorktown-Eastover aquifer are closely related by the Yorktown confining zone between them, and these three units together form an array of hydraulic connections that link the unconfined and confined ground-water flow system. Thus, while no withdrawals have been reported for the Yorktown confining zone, its function as an aquifer in places is consistent with the definition of the unit by McFarland and Bruce (2006).

Yorktown-Eastover Aquifer

The Yorktown-Eastover aquifer is a heterogeneous and widely used aquifer that extends across most of the Virginia Coastal Plain except for several of the northwestern counties (fig. 4). The aquifer, composed of sand with some interbedded silt, is overlain across most of its extent by the Yorktown confining zone. However, in locally incised areas along rivers where it outcrops on steep slopes, it usually is covered by sediments of the surficial aquifer. The Yorktown-Eastover aquifer is hydraulically continuous on a regional scale but can exhibit local discontinuities as the result of interbedded fine-grained sediments.

The Yorktown-Eastover aquifer is a major source of both public and private water supplies, second only to the Potomac aquifer as a ground-water supply resource. It is an important source of water in the eastern part of the Virginia Coastal Plain, particularly on the Eastern Shore. In 2002, the Yorktown-Eastover aquifer supplied almost 6 Mgal/d in regulated, reported ground water across its extent, almost 6 percent of the total ground-water withdrawals for the Virginia Coastal Plain (Quinlan, 2004). Because it is generally a shallow and accessible aquifer with high-quality water, it is also commonly used for private domestic water supplies.

Saint Marys Aquifer

The Saint Marys aquifer is a homogeneous, little-used aquifer of limited regional extent composed of marine sands and shells. It consists of two separate areas—a northern part that covers most of the Eastern Shore and a southern part mostly in the City of Suffolk. The Saint Marys aquifer directly overlies the Calvert confining unit (fig. 5). It ranges in thickness from 150 ft to 200 ft in the northern part and is approximately 50 ft thick in the southern part.

The Saint Marys aquifer is a very limited water-supply resource only in its southern part, where it is considered a marginal water-production zone. No regulated withdrawals from the Saint Marys aquifer have been reported to the VDEQ, but the aquifer could provide limited water supplies. The northern part contains brackish water.

Piney Point Aquifer

The Piney Point aquifer is an extensive, homogenous, sandy aquifer that extends across most of the Virginia Coastal Plain, except in the southern part near the Fall Line, dipping eastward across its entire extent. Because it is composed of formations which both predate and post-date the Chesapeake Bay impact crater, the Piney Point aquifer extends across the crater (fig. 4). The aquifer is as much as 150 ft thick at its deepest section across the lower parts of Northern Neck Peninsula.

The Piney Point aquifer is a moderately used ground-water resource that supplies water to small municipalities in the middle sections of the Northern Neck Peninsula, Middle Peninsula, and York-James Peninsula. The Piney Point aquifer is not considered a productive aquifer south of the James River. In 2002, this aquifer produced a total of approximately 5.1 Mgal/d of regulated, reported ground water, less than 5 percent of the total reported ground-water withdrawals from the Virginia Coastal Plain aquifer system (Quinlan, 2004).

Aquia Aquifer

The Aquia aquifer is a homogeneous aquifer that is composed of medium to coarse sands and extends across all of the Virginia Coastal Plain except in the areas of the Chesapeake Bay impact crater, the Virginia Eastern Shore, and the southeastern zone near the Fall Line (fig. 4). Across most of its extent, the Aquia aquifer is no more than 50 ft thick.

The Aquia aquifer is a relatively minor water-supply resource, perhaps because of its composition or because it is relatively thin in some areas. The Aquia aquifer is used to supply public water to a few small towns and is tapped by a few private domestic wells, mostly in the northern part of the study area. In 2002, the Aquia aquifer was the source of approximately 0.2 Mgal/d in reported, regulated ground-water withdrawals, less than 1 percent of the reported ground-water use in the Virginia Coastal Plain (Quinlan, 2004).

Peedee Aquifer

The Peedee aquifer is a relatively heterogeneous aquifer composed of discontinuous fine-grained sediments interbedded with coarse-grained sediments. The extent of the Peedee aquifer is limited to the southern parts of the Cities of Chesapeake and Virginia Beach, and it is never more than several tens of feet thick. The Peedee aquifer overlies the Virginia Beach confining zone (fig. 5).

The Peedee aquifer is identified as a localized hydrogeologic unit that may provide a ground-water flow path across the southeastern part of the study area. It may represent the northern edge of the Peedee aquifer in North Carolina but appears to be a localized and unused water-supply resource in Virginia.

Virginia Beach Aquifer

The Virginia Beach aquifer is a relatively homogenous aquifer consisting of coarse-grained sands. It extends across most of Virginia Beach and westward across Chesapeake and Suffolk and into the southeastern corner of Southampton County where it attains thicknesses up to 70 ft. The Virginia Beach aquifer is a hydraulically continuous unit throughout its relatively limited extent and provides public water supplies to small towns and light commercial and industrial facilities, mostly in the City of Suffolk. Reported withdrawals from the Virginia Beach aquifer totaled less than 0.1 Mgal/d in 2002, less than 1 percent of the total ground-water withdrawals in the Virginia Coastal Plain (Quinlan, 2004).

Potomac Confining Zone

The Potomac confining zone overlies the Potomac aquifer across nearly its entire extent (fig. 5) and extends across the entire Virginia Coastal Plain except where it has been disrupted by the Chesapeake Bay impact crater (fig. 4). This unit is characterized by discontinuous clay interbeds and is designated as a confining zone to account for its variable configuration in the transition from the Potomac aquifer below to the overlying hydrogeologic units. The Potomac confining zone was defined and mapped for the first time by McFarland and Bruce (2006), so no withdrawals have been reported historically for this unit. Analyses of municipal and industrial withdrawal data have revealed, however, that some wells may be screened in the Potomac confining zone, and the possibility of production wells in this zone is consistent with the description of this unit by McFarland and Bruce (2006).

Potomac Aquifer

The Potomac aquifer is a highly heterogeneous aquifer that immediately overlies the bedrock basement and occupies the lowermost position in the hydrogeologic system (figs. 4, 5). The Potomac aquifer is the thickest aquifer in the Virginia Coastal Plain aquifer system and ranges in thickness from a thin edge near the Fall Line to several thousand feet at the coast. This sand and gravel aquifer is hydraulically continuous on a regional scale but contains local discontinuities as a result of many fine-grained clay interbeds. The aquifer extends across the entire Virginia Coastal Plain except for the interior of the Chesapeake Bay impact crater and is overlain across most of its extent by the Potomac confining zone, except for incised areas along major river channels and near the Fall Line. In these areas, the Potomac aquifer may crop out but is usually covered by sediments of the surficial aquifer, possibly providing direct hydraulic connections between the confined and unconfined systems.

The Potomac aquifer is the largest and most heavily used source of ground water in the Virginia Coastal Plain, supplying regulated withdrawals of more than 95 Mgal/d in 2002, about 89 percent of the reported annual total of 107 Mgal/d (Quinlan, 2004). The Potomac aquifer is an important water-supply source across most of its extent, except where it thins out near the Fall Line or where development is limited by brackish zones associated with the Chesapeake Bay impact crater and the Atlantic Ocean. Most withdrawals from the Potomac aquifer are regulated industrial and municipal withdrawals, including two large historical withdrawals for paper pulp mills located at Franklin and at West Point (in eastern King William County). In areas where brackish ground water underlies large populations, desalinization facilities have been developed to allow increased use of water resources from the Potomac aquifer. Increased development of the Potomac aquifer is expected as demand for water continues to grow in metropolitan areas of the southeastern Virginia Coastal Plain, but decreasing water levels in wells in recent decades have caused increased concerns about additional withdrawals from this aquifer in areas where it is heavily used.

Private Domestic-Well Characteristics

Domestic-well records were collected for this study in localities with appreciable populations self supplied with ground water. Within each selected locality, private domestic-well records were collected with a random-sampling technique, usually spatially stratified. Construction characteristics of private domestic wells determined from the sampled records in a locality were used to estimate the construction characteristics for the entire population of domestic wells in that locality. Of primary interest were the depths or elevations of the well screens or other information useful for designating the aquifers in which the wells were completed.

The parameter of most interest for this study is the depth of the well or, more specifically, the depth to the well screen. Well-screen elevations are more useful than depths for comparing wells spatially, but the calculation of screen elevations is dependent on well-head elevations, which usually were not available in collected well records. Consequently, well-screen elevations were estimated from well-screen depths by using aggregated median land-surface elevation values computed from a digital elevation model for each locality.

Several assumptions were required to estimate well-screen elevations from the limited available data, but the estimated screen elevations provide the basis of the comparison among well characteristics by locality. To clarify the relations and approximations invoked in this study, a conceptual example comparing measured, site-specific well data to estimated well data, as used in this study, is given in figure 6. The steps involved in data collection and analysis for this and subsequent sections of this report are outlined in a flow chart in figure 7. The flow chart demonstrates the relations between the study components and summarizes the methods, techniques, and products discussed in this report.

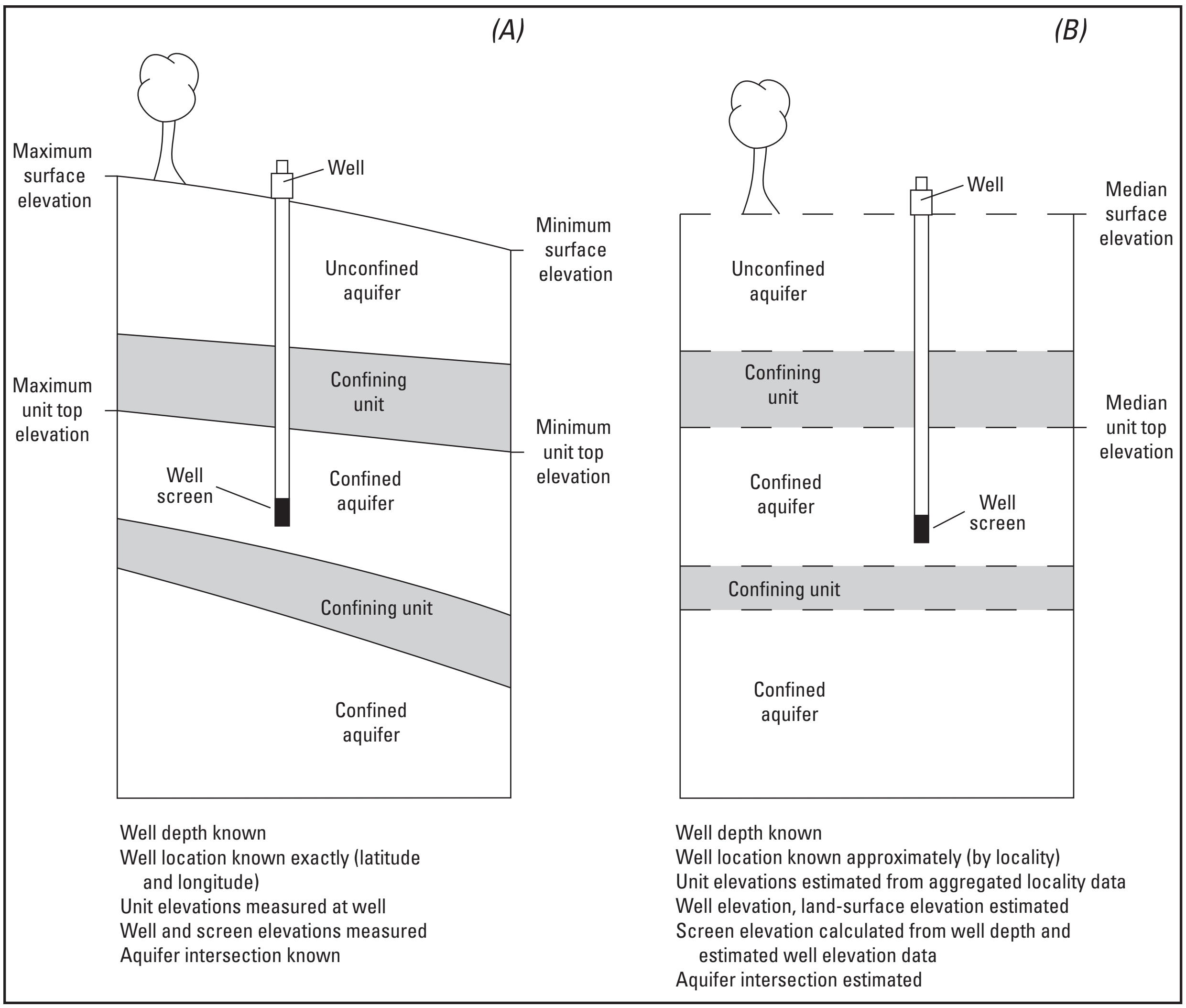

Figure 6. Conceptual diagram demonstrating the relations among well depth, well head and screen elevations, land-surface elevation, and hydrogeologic unit elevations for examples in which *(A)* domestic-well and aquifer elevations are measured, and *(B)* domestic-well and aquifer elevations are estimated.

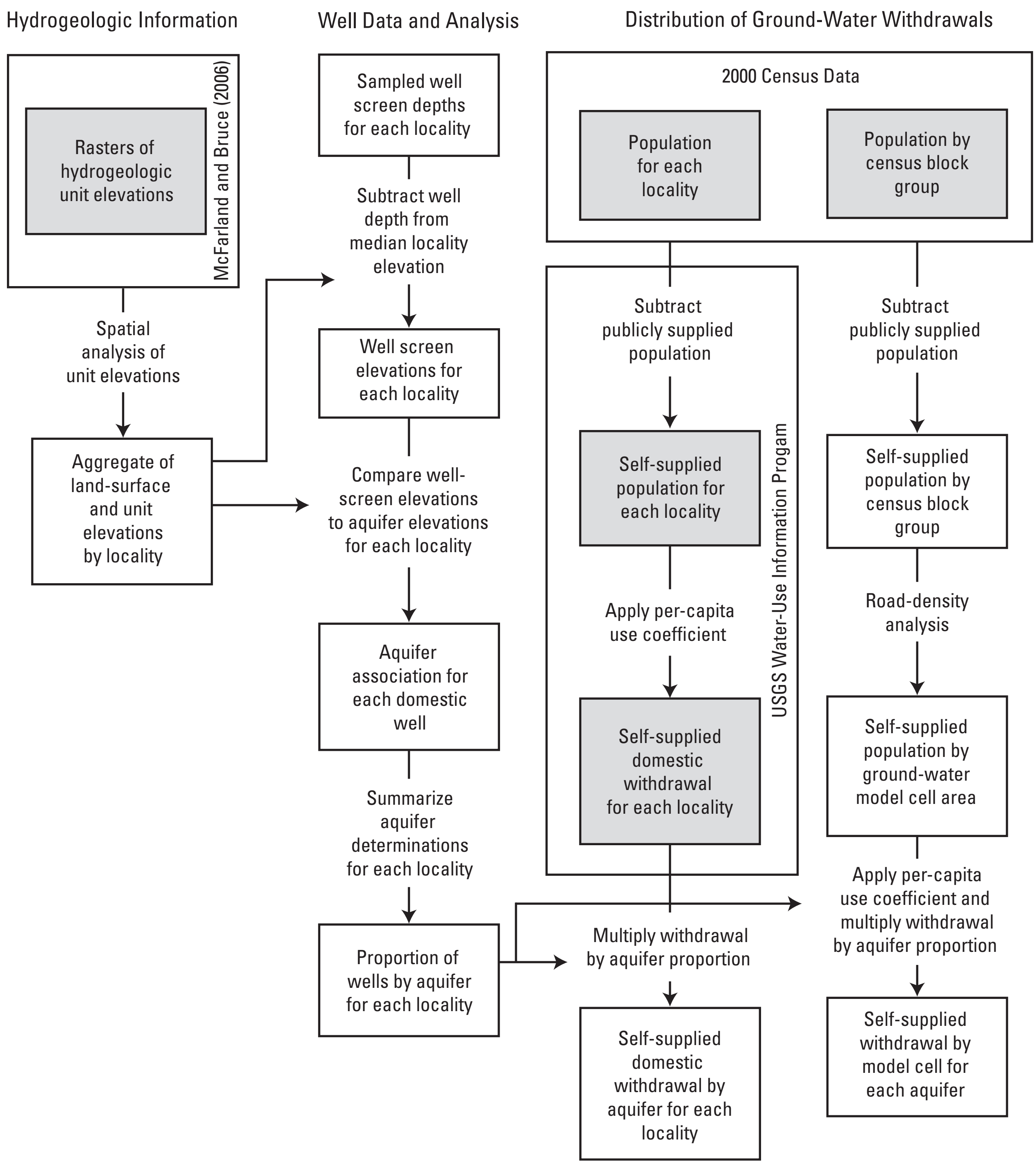

Figure 7. Flow chart of steps in the process of analyzing private domestic-well data, the apportionment of private domestic wells among aquifers, and the spatial distribution of self-supplied domestic withdrawals by aquifer in the Virginia Coastal Plain.

Selection of Localities for Sampling of Domestic-Well Records

Virginia Coastal Plain localities were selected for inclusion in the study of private domestic wells based on their self-supplied populations in 2000 (U.S. Geological Survey, 2002; Hutson and others, 2004). Selected localities were those with appreciable self-supplied domestic populations within the boundaries of the Coastal Plain. Predominantly urban localities in which most or all of the population is publicly supplied were excluded, as were localities in which most of the land area or population is located outside of the Coastal Plain.

Spatial analyses were used to calculate populations and areas of localities only partially within the Coastal Plain. Using geographic information system (GIS) software, locality boundary polygons were compared to spatial information on surficial geology defining the extent of Coastal Plain sediments. The source of the spatial geologic data was a geologic map of the Virginia Coastal Plain by Mixon and others (1989), from which a generalized Fall Line corresponding to the western limit of contiguous Coastal Plain sediments was digitized. Spatial data on population used for this study were taken from 2000 census block group data (U.S. Census Bureau, 2001), the highest level of spatial resolution available. The proportion of each Virginia locality situated within the Coastal Plain was calculated on the basis of both area and population. From the population proportion, the 2000 water-use estimates were used to calculate estimated ground-water use in the Coastal Plain localities, presumably withdrawn from wells in Coastal Plain sediments.

Of the 50 Virginia localities entirely or partially located within the Coastal Plain, 29 localities were selected for sampling of private domestic-well records (tables 1, 2; fig. 1). All Virginia Coastal Plain localities are given in figure 1 and tables 1 and 2, along with area, population, and ground-water use data; and the localities selected for sampling are shaded.

The process of selecting or rejecting localities only partly occupying the Coastal Plain required the interpretation of limited available geographic data. Neither the detailed geologic analysis nor the detailed population analysis by census block group had been examined at the time of the sampling design, so some localities that might otherwise have been included based on the stated selection criteria and the information in table 1 were excluded from this study. For example, Chesterfield, Dinwiddie, and Spotsylvania Counties all have only small portions of their land areas within the Coastal Plain (fig. 1), but their self-supplied populations may be large enough to merit their inclusion. However, the county populations within the Coastal Plain also appear to be located in publicly supplied areas; this is a level of spatial resolution that is not captured in table 1. Stafford County could have been included based on its relatively large Coastal Plain area, but it was excluded based on its small self-supplied population. Localities in the northern panhandle of the Coastal Plain were not included because supporting data on hydrogeologic-unit elevations were not available in that area, which includes Arlington, Fairfax, and Prince William counties and the City of Alexandria.

For the aforementioned reasons, the sampling of domestic wells may have excluded the wells of close to 100,000 people who rely on self-supplied ground water, mostly in the northern Coastal Plain of Virginia. The other Virginia Coastal Plain localities that were excluded from sampling are those with populations supplied predominantly or entirely with municipal water (tables 1, 2).

The 29 localities selected for sampling include approximately 412,000 people who are self supplied with ground water from private domestic wells. USGS methods used here for estimating self-supplied domestic withdrawals are based almost entirely on per-capita water-use estimates rather than information on available numbers of domestic wells or measured withdrawals from such wells. In fact, the population served by domestic supply is entirely calculated as the difference between the census population of a locality and the publicly supplied population total for that same locality from U.S. Environmental Protection Agency (USEPA) community water-supply records. The self-supplied population for each locality then was multiplied by the per-capita domestic water-use coefficient (75 gal/d for Virginia), to obtain the estimated self-supplied domestic withdrawal rate (Hutson and others, 2004). Furthermore, it is possible to estimate the number of private domestic wells for a given locality based on the average household size in the locality, the total self-supplied domestic population, and the public-supply population. This estimate was calculated for each locality and is included in table 1.

Sampling of Private Domestic-Well Records

In Virginia, most available records for private domestic wells are collected and maintained by the local health department for each locality. These are paper records stored in file cabinets in health department offices, and the data typically are not available in electronic form. Consequently, the sampling approach involved manually collecting well data from the files of local health departments. Regional VDEQ offices and local well-drilling companies also were considered as sources of data for this study, but data-collection efforts ultimately focused on the records from local health departments based on consultation with State and local experts who believe these records are the best source of current, locality-level information on domestic wells. Local health departments were contacted in localities selected for domestic-well sampling, and all granted access to available domestic-well data.

Since 1992, Virginia regulations require drillers of private domestic wells to complete Uniform Water Well Completion Reports (UWWCRs) and file them with the health department in the locality where a well is drilled (Virginia Department of Health, 2005). These completion reports contain information on the general location, construction details, and installation date of each well.

Table 1. Area, population, and water-supply characteristics of Virginia Coastal Plain localities, based on 2000 population and water-use data.

[Shading indicates locality in which well data were collected for this study. —, not applicable]

Locality (fig. 1)	Coastal Plain area, in square miles	Area proportion within Coastal Plain	Population proportion within Coastal Plain	Total population[a]	Coastal Plain population	Self-supplied proportion[b]	Self-supplied Coastal Plain population	Census household size[b]	Estimated number of domestic wells
Accomack County	466	1.000	1.000	38,998	38,998	0.495	19,321	2.45	7,895
Alexandria, City of	17	0.982	1.000	128,283	128,283	0.127	16,280	2.04	7,972
Arlington County	15	0.562	0.857	189,453	162,377	0.022	3,643	2.15	1,698
Caroline County	504	0.937	1.000	22,121	22,121	0.603	13,331	2.69	4,963
Charles City County	200	1.000	1.000	6,926	6,926	0.885	6,126	2.59	2,362
Chesapeake, City of	351	1.000	1.000	199,184	199,184	0.177	35,211	2.79	12,617
Chesterfield County	122	0.280	0.413	259,903	107,345	0.112	12,064	2.73	4,425
Colonial Heights, City of	6	0.908	1.000	16,897	16,897	0.030	500	2.37	211
Dinwiddie County	127	0.250	0.694	24,533	17,020	0.737	12,538	2.58	4,852
Emporia, City of	2	0.913	1.000	5,665	5,665	0.011	60	2.43	25
Essex County	269	1.000	1.000	9,989	9,989	0.682	6,809	2.46	2,768
Fairfax County	88	0.224	0.280	973,393	272,488	0.047	12,748	2.74	4,660
Franklin, City of	4	1.000	1.000	8,346	8,346	0.000	0	2.39	0
Fredricksburg, City of	6	0.963	1.000	19,279	19,279	0.000	0	2.09	0
Gloucester County	220	1.000	1.000	34,780	34,780	0.715	24,870	2.62	9,478
Greensville County	173	0.582	1.000	11,560	11,560	0.726	8,390	2.51	3,337
Hampton, City of	54	1.000	1.000	146,437	146,437	0.000	0	2.49	0
Hanover County	246	0.513	0.897	86,320	77,472	0.324	25,112	2.71	9,282
Henrico County	173	0.724	0.560	262,300	146,873	0.214	31,368	2.39	13,121
Hopewell, City of	9	1.000	1.000	22,354	22,354	0.000	0	2.43	0
Isle of Wight County	323	1.000	1.000	29,728	29,728	0.471	13,989	2.61	5,359
James City County	153	1.000	1.000	48,102	48,102	0.368	17,711	2.47	7,183
King and Queen County	333	1.000	1.000	6,630	6,630	0.949	6,290	2.48	2,536
King George County	187	1.000	1.000	16,803	16,803	0.185	3,101	2.70	1,148
King William County	285	1.000	1.000	13,146	13,146	0.699	9,187	2.69	3,412
Lancaster County	124	1.000	1.000	11,567	11,567	0.474	5,479	2.23	2,460
Mathews County	86	1.000	1.000	9,207	9,207	0.941	8,667	2.32	3,729
Middlesex County	139	1.000	1.000	9,932	9,932	0.758	7,532	2.27	3,311
New Kent County	224	1.000	1.000	13,462	13,462	0.701	9,431	2.65	3,555
Newport News, City of	56	1.000	1.000	180,150	180,150	0.000	0	2.50	0
Norfolk, City of	57	1.000	1.000	234,403	234,403	0.000	0	2.45	0
Northampton County	211	1.000	1.000	13,093	13,093	0.652	8,542	2.39	3,572
Northumberland County	188	1.000	1.000	12,259	12,259	0.615	7,539	2.24	3,367
Petersburg, City of	27	0.947	1.000	33,740	33,740	0.000	0	2.38	0
Poquoson, City of	19	1.000	1.000	11,566	11,566	0.000	0	2.75	0
Portsmouth, City of	33	1.000	1.000	100,565	100,565	0.000	0	2.51	0
Prince George County	281	1.000	1.000	34,749	34,749	0.410	14,247	2.76	5,154
Prince William County	54	0.156	0.413	280,813	116,014	0.247	28,664	2.94	9,736
Richmond County	195	1.000	1.000	8,809	8,809	0.633	5,579	2.40	2,322
Richmond, City of	47	0.709	0.915	197,790	181,059	0.000	0	2.21	0
Southampton County	607	1.000	1.000	17,482	17,482	0.462	8,081	2.53	3,188
Spotsylvania County	81	0.193	0.841	90,395	76,038	0.084	6,367	2.87	2,219
Stafford County	136	0.494	0.711	92,446	65,760	0.145	9,517	3.01	3,159
Suffolk, City of	408	1.000	1.000	63,677	63,677	0.255	16,209	2.69	6,019
Surry County	263	1.000	1.000	6,829	6,829	0.745	5,089	2.61	1,952
Sussex County	508	0.987	1.000	12,504	12,504	0.113	1,410	2.41	584
Virginia Beach, City of	303	1.000	1.000	425,257	425,257	0.097	41,380	2.70	15,306
Westmoreland County	247	1.000	1.000	16,718	16,718	0.424	7,089	2.43	2,921
Williamsburg, City of	5	1.000	1.000	11,998	11,998	0.000	0	2.07	0
York County	125	1.000	1.000	56,297	56,297	0.798	44,918	2.78	16,137
Total	**8,755**	**—**	**—**	**4,526,838**	**3,291,938**	**0.156**	**514,390**	**2.59**	**197,994**

[a] U.S. Census Bureau, 2003a.

[b] U.S. Geological Survey, 2002.

Table 2. Estimated ground-water withdrawals in Virginia Coastal Plain localities in 2000.

[Shading indicates locality in which well data were collected for this study. Data for localities partially within the Coastal Plain are calculated from the proportion of the locality population within the Coastal Plain. Mgal/d; million gallons per day; —, not applicable]

Locality (fig. 1)	Coastal Plain proportion	Self-supplied proportion[a]	Locality ground-water withdrawal (Mgal/d)[a]					Coastal Plain ground-water withdrawal (Mgal/d)				
			Public supply	Domestic	Industrial/ commercial	Irrigation	Total	Public supply	Domestic	Industrial/ commercial	Irrigation	Total
Accomack County	1.000	0.495	0.82	1.42	3.01	1.01	6.26	0.82	1.42	3.01	1.01	6.26
Alexandria, City of	1.000	0.127	0.00	1.22	0.01	0.00	1.23	0.00	1.22	0.01	0.00	1.23
Arlington County	0.857	0.022	0.00	0.32	0.00	0.04	0.36	0.00	0.27	0.00	0.03	0.31
Caroline County	1.000	0.603	0.33	1.00	0.00	0.01	1.34	0.33	1.00	0.00	0.01	1.34
Charles City County	1.000	0.885	0.04	0.46	0.00	0.07	0.57	0.04	0.46	0.00	0.07	0.57
Chesapeake, City of	1.000	0.177	4.53	2.64	0.05	0.00	7.22	4.53	2.64	0.05	0.00	7.22
Chesterfield County	0.413	0.112	0.00	2.22	0.34	0.01	2.57	0.00	0.92	0.14	0.00	1.06
Colonial Heights, City of	1.000	0.030	0.00	0.04	0.00	0.00	0.04	0.00	0.04	0.00	0.00	0.04
Dinwiddie County	0.694	0.737	0.00	1.36	0.00	0.06	1.42	0.00	0.94	0.00	0.04	0.99
Emporia, City of	1.000	0.011	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Essex County	1.000	0.682	0.41	0.51	0.00	0.00	0.92	0.41	0.51	0.00	0.00	0.92
Fairfax County	0.280	0.047	0.20	3.48	0.04	0.11	3.83	0.06	0.97	0.01	0.03	1.07
Franklin, City of	1.000	0.000	1.11	0.00	0.00	0.00	1.11	1.11	0.00	0.00	0.00	1.11
Fredricksburg, City of	1.000	0.000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Gloucester County	1.000	0.715	0.00	1.87	0.00	0.01	1.88	0.00	1.87	0.00	0.01	1.88
Greensville County	1.000	0.726	0.00	0.63	0.00	0.03	0.66	0.00	0.63	0.00	0.03	0.66
Hampton, City of	1.000	0.000	0.00	0.00	0.00	0.03	0.03	0.00	0.00	0.00	0.03	0.03
Hanover County	0.897	0.324	1.22	2.10	0.00	0.03	3.35	1.09	1.88	0.00	0.03	3.01
Henrico County	0.560	0.214	0.16	4.20	0.00	0.08	4.44	0.09	2.35	0.00	0.04	2.49
Hopewell, City of	1.000	0.000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Isle of Wight County	1.000	0.471	1.44	1.05	33.72	0.00	36.21	1.44	1.05	33.72	0.00	36.21
James City County	1.000	0.368	9.63	1.33	0.01	0.00	10.97	9.63	1.33	0.01	0.00	10.97
King and Queen County	1.000	0.949	0.01	0.47	0.00	0.00	0.48	0.01	0.47	0.00	0.00	0.48
King George County	1.000	0.185	0.79	0.23	0.06	0.00	1.08	0.79	0.23	0.06	0.00	1.08
King William County	1.000	0.699	0.53	0.69	19.47	0.01	20.70	0.53	0.69	19.47	0.01	20.70
Lancaster County	1.000	0.474	0.41	0.41	0.00	0.00	0.82	0.41	0.41	0.00	0.00	0.82
Mathews County	1.000	0.941	0.00	0.65	0.00	0.01	0.66	0.00	0.65	0.00	0.01	0.66
Middlesex County	1.000	0.758	0.15	0.56	0.00	0.00	0.71	0.15	0.56	0.00	0.00	0.71
New Kent County	1.000	0.701	0.17	0.71	0.00	0.01	0.89	0.17	0.71	0.00	0.01	0.89
Newport News, City of	1.000	0.000	2.35	0.00	0.00	0.00	2.35	2.35	0.00	0.00	0.00	2.35
Norfolk, City of	1.000	0.000	0.00	0.00	0.22	0.03	0.25	0.00	0.00	0.22	0.03	0.25
Northampton County	1.000	0.652	0.26	0.64	0.05	0.57	1.52	0.26	0.64	0.05	0.57	1.52
Northumberland County	1.000	0.615	0.16	0.57	0.02	0.00	0.75	0.16	0.57	0.02	0.00	0.75
Petersburg, City of	1.000	0.000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Poquoson, City of	1.000	0.000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Portsmouth, City of	1.000	0.000	0.00	0.00	0.42	0.04	1.60	0.00	0.00	0.42	0.04	1.60
Prince George County	1.000	0.410	0.17	1.02	0.00	0.00	1.19	0.17	1.02	0.00	0.00	1.19
Prince William County	0.413	0.247	0.64	5.20	0.10	0.04	5.98	0.26	2.15	0.04	0.02	2.47
Richmond County	1.000	0.633	0.02	0.42	0.00	0.01	0.45	0.02	0.42	0.00	0.01	0.45
Richmond, City of	0.915	0.000	0.00	0.00	0.02	0.06	0.08	0.00	0.00	0.02	0.05	0.07
Southampton County	1.000	0.462	0.50	0.61	5.03	0.00	6.14	0.50	0.61	5.03	0.00	6.14
Spotsylvania County	0.841	0.084	0.00	0.57	0.01	0.00	0.58	0.00	0.48	0.01	0.00	0.49
Stafford County	0.711	0.145	0.00	1.00	0.01	0.01	1.02	0.00	0.71	0.01	0.01	0.73
Suffolk, City of	1.000	0.255	5.39	1.22	0.06	0.00	6.67	5.39	1.22	0.06	0.00	6.67
Surry County	1.000	0.745	0.13	0.38	0.00	0.18	1.00	0.13	0.38	0.00	0.18	1.00
Sussex County	1.000	0.113	0.51	0.11	0.17	0.01	0.80	0.51	0.11	0.17	0.01	0.80
Virginia Beach, City of	1.000	0.097	0.00	3.10	0.01	0.12	3.23	0.00	3.10	0.01	0.12	3.23
Westmoreland County	1.000	0.424	0.91	0.53	0.02	0.04	1.50	0.91	0.53	0.02	0.04	1.50
Williamsburg, City of	1.000	0.000	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.01	0.01
York County	1.000	0.798	0.07	3.37	0.00	0.00	3.44	0.07	3.37	0.00	0.00	3.44
Total	**—**	**0.156**	**33.06**	**48.31**	**62.85**	**2.64**	**148.31**	**32.34**	**38.54**	**62.56**	**2.46**	**137.36**

[a] U.S. Geological Survey, 2002.

Prior to this 1992 regulation, the Virginia State Water Control Board (now part of the VDEQ) collected information on new domestic wells, which was recorded on Virginia Water Well Completion Reports (Form GW–2) submitted to the appropriate regional office of the State Water Control Board. Some of these forms are still on file in regional VDEQ offices, but many are now located in the files of local health departments. These GW–2 forms require much more detailed information than the UWWCR and were intended to be completed by professional staff of the Virginia State Water Control Board or VDEQ. However, VDEQ and local health department officials indicated that these completion reports typically were submitted for only a small portion of the domestic wells drilled (T.S. Bruce, Virginia Department of Environmental Quality, oral commun., 2002). Even after the UWWCR form was introduced in 1992, the GW–2 form often was used in place of the UWWCR, but this practice appears to have declined with time. Of the 2,846 records collected for the period 1977 through 2002, 1,518 were GW–2 forms, and 1,328 were UWWCR forms.

Regardless of the form used to report domestic-well data, this survey revealed that the form rarely was filled out completely or accurately. Lithologic logs on these forms for private domestic wells are extremely generalized or non-existent, and information was almost never included about aquifers that were intersected. Requested location data on the GW–2 form includes latitude and longitude, but these coordinates rarely were supplied by the well driller or homeowner. The postal address of the property is requested on both forms, but a complete postal address rarely was given. Instead, local driving directions often were given, which is useful for locating an individual property but of little use for locating wells with any automated address system. Potentially useful location data generally included on the well form is the county tax-map identification number, which indicates the location of the property in the county tax-plat book. However, most of the locality tax maps are available only in paper form, not as spatially referenced digital maps useful in a GIS. Digitizing and georeferencing all county tax maps was not within the scope of project resources. Furthermore, several localities updated their tax-map systems at least once between 1977 and 2002, the period of record covered by this study, and it was often difficult to discern which tax-map system was used for a given well permit.

Following initial examination of the well forms, a database was created to record the useful information common for most of the domestic wells. Database fields included locality name, location of well or property, tax-map identification number, health department identification number, type of well record (UWWCR or GW–2), well-completion date, drilling method (usually auguring or boring for shallow wells, and mud-rotary drilling for deeper wells), hole diameter, hole depth, depth to the top of the well screen, depth to the bottom of the well screen, well type (domestic supply well, or domestic irrigation well), and miscellaneous notes. Data were not available on measured withdrawals from any of the domestic wells.

The goal of the data-collection phase of this study was the acquisition of a representative sample of domestic-well characteristics for each locality. Consequently, the sampling scheme initially was designed to select well records randomly from the domestic-well files located in each health department office. In most counties, however, it was quickly discovered that domestic-well records typically are filed in groups by tax-map number; therefore, tax-map grouping was used to spatially stratify the random sampling approach and assure that wells were geographically distributed across the locality. Thus, approximately the same number of well records was collected for each tax-map group in a particular locality.

The total number of well records collected for each locality was influenced by the amount of time needed to collect and record the well data from health department files and by the number of records needed to acquire a representative sample of the population. The goal of this approach was to obtain for each county the percentage of domestic wells intersecting each of the Coastal Plain aquifers from a sampling of well-completion reports. Mathematically, well depth could be considered a continuous random variable, but well depth can be used to determine the aquifer in which the well is screened. Consequently, the problem can be simplified by sorting the well depths into discrete categories representing the aquifers used for domestic water supply and creating a categorical variable. The proportion of the population of wells in each of these aquifers then can be estimated from the proportion of the sampled well records.

The number of records sampled in each locality had to be large enough to generate statistically significant results. In other words, the sample size had to be large enough so that the sample proportion of wells in each aquifer was an accurate estimator of the population proportion. Going a step further, a confidence interval for the estimation was developed for a given error bound on the population proportion. For an error bound of 0.05 on the population proportion with a 90-percent level of confidence, a sample size of 271 well records was required. This turned out to be an unrealistic sample size based on time constraints for the project, which allowed only one day for sampling in each locality. It quickly became apparent during the study that a sample of 100 well records for each locality was a reasonable goal. The required sample size becomes smaller with a lower confidence level and higher error bound on the proportion of wells in each aquifer. Actually, by changing the error bound to 0.10, a more realistic sample size of 68 was obtained, which was well within the time constraints of the study. Stated another way, if 100 records were sampled for a given locality, the error bound typically would be between 0.05 and 0.10, with a 90-percent confidence level. These error criteria were judged to be acceptable for this study.

In practice, data collection from the files of each health department involved randomly selecting each well record file from a tax-map group, manually recording the data into the database, then returning the well record to its place in the file cabinet along with a temporary flag to prevent multiple sampling of the same record. In a few localities, the use of other organizational schemes required quick adjustments to the sampling method in an attempt to gather samples with an even geographic distribution across the locality. In Charles City County and City of Virginia Beach, records were arranged by year of well installation. In King and Queen County, records were arranged alphabetically by owner. Records were arranged by road or address in City of Chesapeake, Henrico County, Prince George County, and Surry County (for records since 2001 only).

General Characteristics of Private Domestic Wells

In all, 2,846 records of private domestic wells were collected from spatially stratified random samples of well records in 29 localities in the Virginia Coastal Plain. The deepest (865 ft) of the sampled wells is located in Lancaster County on the Northern Neck Peninsula. The shallowest well (14 ft) is located in King William County. The mean depth to the bottom of a well screen is 202.2 ft, and the median depth is 141.5 ft, which indicates the depth distribution is skewed toward greater depths. The most common value, or mode, is 40 ft. The sample standard deviation is 173.5 ft. A histogram of all well depths is presented in figure 8, along with summary statistics for the depths to the bottoms of the well screens.

Installation dates for sampled wells ranged from 1977 to 2002, the year of the sampling effort. In most localities, well records became more numerous in later years, particularly after 1992 when new well regulations took effect. It was not possible to discern definitive trends in well installation frequency from sampled records, because they are obscured by obvious trends in data collection and organization.

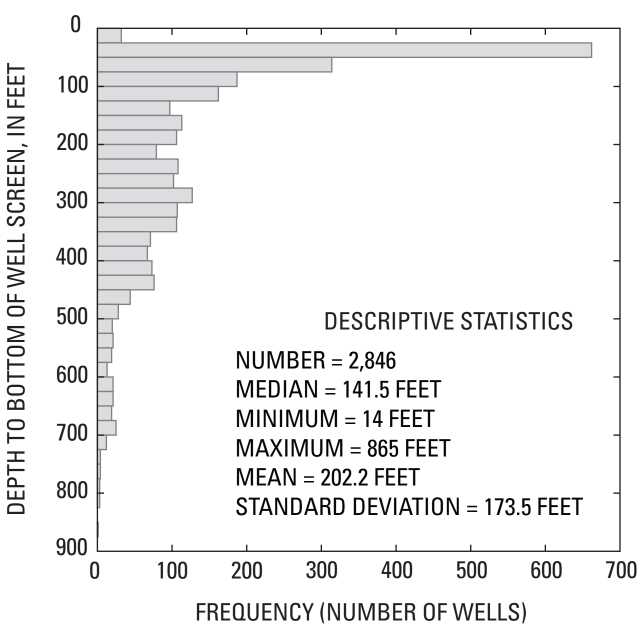

Figure 8. Histogram of depths to bottom of screen for private domestic wells in the Virginia Coastal Plain.

Of the wells for which records were sampled, 2,017 (70.9 percent) were drilled using the mud-rotary method. Well diameters ranged from 1.25 inches (in.) to 6.25 in., and 4 in. was the most common value. Drilled wells ranged from 22 ft to 865 ft in depth, with a median value of 245 ft and a mean value of 267.4 ft. Recorded screen intervals for rotary-drilled wells ranged from 2 to 156 ft, with 10 ft being the most common interval and 15 ft being the median. Of the total wells for which data were collected, 800 were bored wells (28.1 percent). Bored wells ranged in depth from 14 ft to 93 ft, with a median depth of 43 ft and a mean of 44.5 ft. Of the bored wells, 517 (64.6 percent) had a diameter of 30 in., and 271 (33.8 percent) had a diameter of 24 in.

The remaining wells that were not mud-rotary drilled or bored were constructed using a variety of methods. Seven sampled wells in the City of Suffolk were jetted. Five wells in a variety of locations were constructed with the cable-tool method, and the deepest of these was 235 ft. Two sampled wells were dug, one was augured by hand, and two in Northampton County were driven by hand. Records indicated that 11 wells in Greensville County were constructed in bedrock by the air-rotary method; the deepest of these was 305 ft. One well record in New Kent County had no construction method specified.

Well-screen depths substantially influence the hydrogeologic effects of domestic wells; thus, screen depth was the parameter investigated in the most detail for this study. Statistics for depth to bottom of well screen are presented by locality in table 3. Because the distribution of screen depths in most localities is often skewed, or otherwise far from normal, the median screen depth is thought to be the most representative statistic for each locality. These summary statistics alone provide an incomplete perspective of the varied distribution of well depths in each locality; however, they provide a condensed overview for comparing well characteristics among localities. The spatial variations in well depths are discussed in more detail below.

Characteristics of Incidentally Sampled Private Irrigation Wells

In the process of randomly sampling records for private domestic wells, records for 91 private irrigation wells (usually used for watering lawns and gardens) were obtained for the following localities: Accomack County, City of Chesapeake, James City County, Northampton County, City of Poquoson, City of Suffolk, City of Virginia Beach, and York County. Although these irrigation well records were found among the records for domestic wells, some localities maintain separate files for private irrigation wells. These wells are classified by VDEQ as Class IV wells, and applications for Class IV wells are subject to an expedited permitting process with fewer

Table 3. Statistics for depth, in feet, to bottom of well screen for a sample of private domestic wells in Virginia Coastal Plain localities.

[Values in feet are relative to National Geodetic Vertical Datum of 1929]

Locality (fig. 1)	Number sampled	Median	Mean	Maximum	Minimum	Standard deviation	Variance	Mode
Accomack County	96	190.0	193.3	290	100	50.1	2506.2	160
Caroline County	122	51.0	114.2	606	21	125.3	15712.3	42
Charles City County	81	45.0	115.0	450	25	111.9	12528.9	42
Chesapeake, City of	103	70.0	79.0	600	25	58.8	3463.1	80
Essex County	95	248.0	221.6	534	26	163.6	26761.9	42
Gloucester County	96	90.0	113.4	584	25	104.7	10954.2	90
Greensville County	54	38.3	76.4	305	16	79.9	6391.4	28
Hanover County	110	220.0	210.4	450	20	155.8	24261.5	45
Henrico County	90	47.0	115.1	355	27	108.8	11827.7	36
Isle of Wight County	123	380.0	303.1	500	26	164.9	27205.4	440
James City County	72	255.0	261.9	540	40	94.1	8855.4	230
King and Queen County	109	250.0	225.7	595	22	153.2	23458.8	300
King George County	101	352.0	357.6	820	30	200.5	40186.1	320
King William County	107	166.0	182.1	541	14	146.8	21548.7	45
Lancaster County	97	445.0	412.3	865	24	253.9	64453.3	622
Mathews County	106	110.0	106.1	168	30	21.7	470.5	120
Middlesex County	102	102.5	198.7	696	21	177.7	31594.6	120
New Kent County	98	225.0	229.2	560	28	121.5	14759.7	200
Northampton County	115	160.0	159.7	300	16	58.8	3454.2	160
Northumberland County	110	454.0	476.0	809	20	235.4	55421.6	400
Prince George County	102	55.8	92.4	370	27	74.6	5563.3	49
Richmond County	93	305.0	272.6	590	30	130.5	17031.3	290
Southampton County	123	202.0	194.5	387	22	106.9	11431.0	30
Suffolk, City of	101	440.0	328.5	693	24	220.2	48488.9	30
Surry County	107	54.0	159.0	432	21	147.9	21861.7	300
Sussex County	86	45.5	71.5	362	18	64.3	4137.5	34
Virginia Beach, City of	96	73.0	80.3	212	25	39.8	1582.9	40
Westmoreland County	113	232.0	229.8	648	27	163.8	26829.5	42
York County	38	120.0	159.8	445	45	103.1	10625.5	120
All records	2,846	141.5	202.2	865	14	173.5	30094.8	40

regulatory requirements. The occurrence of these wells seems to vary widely depending on the locality, but health department and VDEQ professionals indicated that irrigation wells are quite common in many suburban areas and are sometimes referred to as "sprinkler wells." Unlike private domestic wells, private irrigation wells often are found in areas served by public water supplies.

Private irrigation wells are of keen interest among many ground-water and water-use professionals in the Virginia Coastal Plain. The spatial distribution and construction characteristics of these wells are not well documented and very little is known about water use for private household irrigation purposes. The well reports are filed separately in some localities, and no specific effort was made during this investigation to evaluate the occurrence of irrigation wells or the magnitude of withdrawals for private household irrigation, which was beyond the scope of this report. Therefore, the characteristics of these wells are not included in the analyses of private domestic wells. Instead, the characteristics of the sampled domestic irrigation wells are presented separately.

The irrigation wells for which records were collected were mostly small-diameter drilled wells, ranging in depth from 26 ft to 590 ft and in diameter from 1.25 in. to 4.5 in. The median well depth was 116 ft, the mean depth was 121.2 ft, and the most common depth was 140 ft. Screens ranged from 2 ft to 100 ft in length. Many (41 percent) of the sampled wells were specifically classified as being located in subdivisions. Most private irrigation wells clearly intersected either the surficial aquifer or the Yorktown-Eastover aquifer, but seven private irrigation wells in James City County had depths that likely would place them in either the Aquia or Potomac aquifers.

Spatial Variability in Domestic-Well Characteristics

Well construction is spatially variable across the Virginia Coastal Plain because of local conditions and needs, but it is most strongly associated with well depth and available aquifers. Shallow, bored wells, for example, are more common in the southwestern part of the Virginia Coastal Plain near the Fall Line where water is available from the surficial aquifer and local bedrock is relatively shallow. Drilled wells are more common in other areas where water from deeper aquifers is available.

Spatial variations in well characteristics, particularly well depth, are more apparent when the data are examined by locality. Median depths of private domestic wells are shown by locality in figure 9, and a few general trends are immediately apparent. Some variation in well depths by locality appears to be the result of a variety of socioeconomic factors, but these correlations are not definitive. For example, there may be a correlation between median home value and median well depth, which is not particularly surprising because deeper wells are more costly to construct. Similarly, median family income also appears to be somewhat correlated with well depth by locality.

Despite possible socioeconomic factors, most of the variation in well depth appears to be related to local hydrogeologic conditions. In general, median well depths tend to increase to the east, as the aquifer system becomes thicker and more transmissive and a larger number of aquifers are available for water supply. This trend is disrupted in localities near the Chesapeake Bay or Atlantic coast, where deeper aquifers contain brackish water. The effect of the buried Chesapeake Bay impact crater, which contains brackish water, can be observed in the relatively shallow well depths of York, Gloucester, Mathews, and Middlesex Counties. In contrast, the much greater median well depths in Northumberland and Lancaster Counties result from the availability of the very productive, high-quality Potomac aquifer. In the southeastern Virginia localities of the cites of Virginia Beach and Chesapeake, shallow well depths are the result of brackish water at deeper intervals. For the Eastern Shore counties of Accomack and Northampton, very shallow wells in the unconfined surficial aquifer are uncommon because of reported agricultural contamination and because the first confined aquifer, the Yorktown-Eastover, is a good source of water at moderate depths. However, salty water occupies the aquifers underlying the Yorktown-Eastover aquifer across the Eastern Shore, effectively prohibiting deeper domestic wells.

Estimated Elevations of Domestic-Well Screens

It is most appropriate to compare wells spatially based on screen elevations rather than depths, because land-surface and well-head elevations vary appreciably by locality across the study area. In the Virginia Coastal Plain, land-surface elevations decline from highest values in localities near the Fall Line to lowest values in southeastern localities, and aquifer elevations dip similarly from west to east. Unfortunately, useful well-location information typically is not available for private domestic wells. Furthermore, well-head elevations needed for calculating screen elevations from screen depths typically were not reported on private well records, and the principal technique for estimating the elevation from a map or digital elevation model (DEM) depends on appropriate well-location information. Short of a tremendous effort to locate each individual well manually on a map or digitize tax-plot maps to provide approximate locations, the best location attribute immediately available for a well record is the locality, which somewhat constrains the well-head elevation depending on the variability of land-surface elevation within the locality. Consequently, the best practical elevation data for the well is the median land-surface elevation for the locality. While this approach produces only a rough approximation of well-screen elevations, it allows more direct comparison between wells across localities than well depth alone. All subsequent analyses are based on the use of estimated well-screen elevations, which were also used to evaluate the aquifers intersected by each well. Estimated values for the elevations of the middle of the well screens are summarized statistically by locality in table 4, which also includes the median land-surface elevation for each locality.

Histograms of the elevations of the middle of well screens are arranged in alphabetical order by locality in figures 10*A*–*E*. The multimodal distributions seen in many of these histograms reveal groups of well-screen elevations that appear to correspond to various aquifers intersected by the wells. This is why the distribution of screen elevations becomes larger and more complex toward the east as the aquifer system becomes thicker and a larger number of aquifers are present. For example, the distribution of well-screen elevations in Northumberland County (fig. 10*D*) has three or more peaks, while the distribution in Greensville County (fig. 10*B*) appears to have only one peak. It is apparent from subsequent analyses that these peaks in the domestic-well histograms correspond at least approximately to the aquifers used for domestic water supply in each locality.

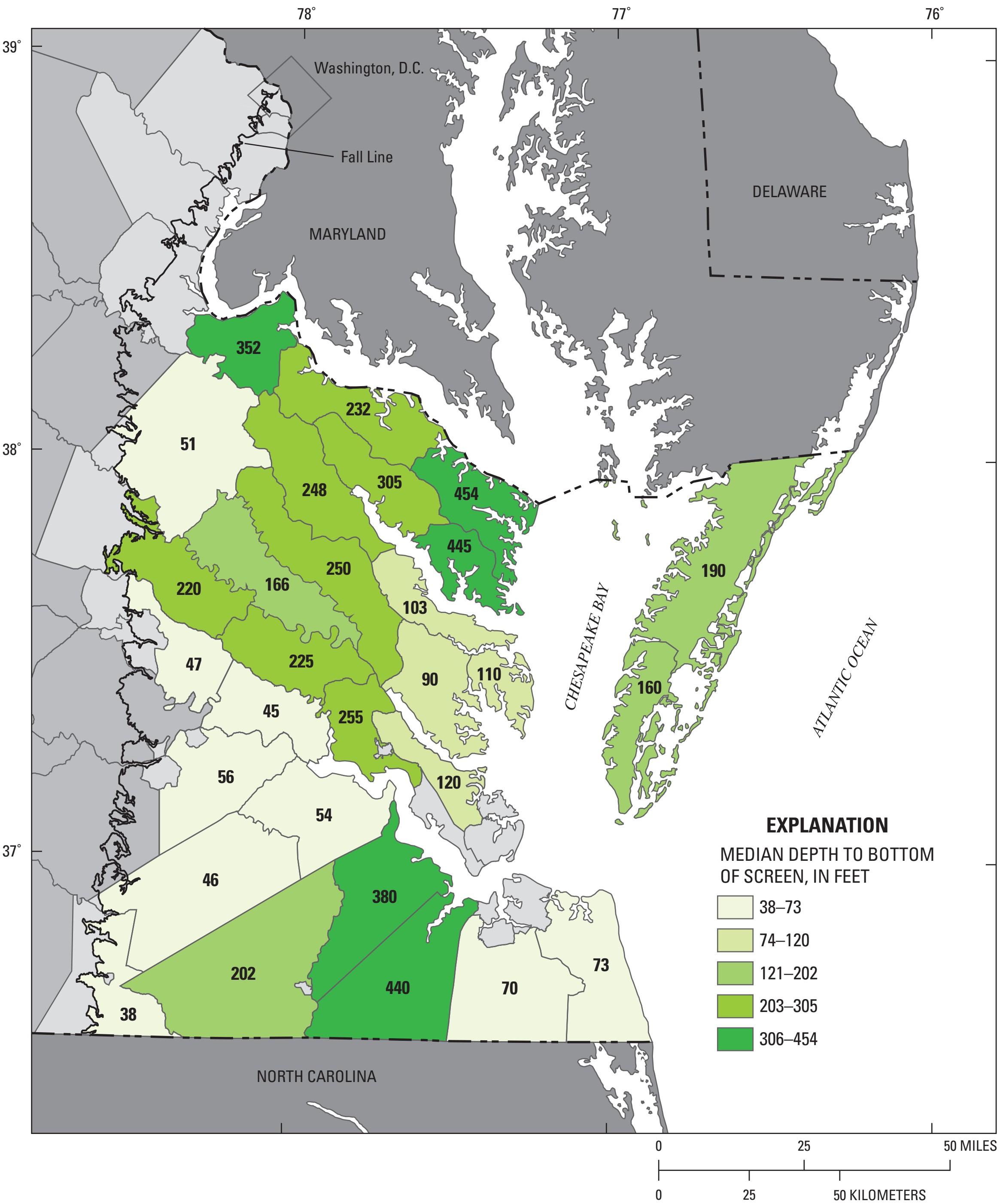

Figure 9. Median depths to bottom of screen by locality for private domestic wells in the Virginia Coastal Plain (locality names are shown in fig. 1).

Table 4. Statistics for estimated elevation, in feet, of middle of well screen for a sample of private domestic wells in Virginia Coastal Plain localities.

[Values in feet are relative to National Geodetic Vertical Datum of 1929]

Locality (fig. 1)	Median elevation (ft)	Number sampled	Median	Mean	Maximum	Minimum	Standard deviation	Variance	Mode
Accomack County	8	96	-174.5	-178.5	-87	-277	49.2	2420.5	-205
Caroline County	178	122	127.0	66.8	157	-413	120.2	14454.6	136
Charles City County	61	81	16.0	-50.1	36	-374	106.6	11365.5	19
Chesapeake, City of	14	103	-51.0	-60.0	-9	-581	58.4	3413.9	-51
Essex County	114	95	-119.0	-100.5	88	-413	159.3	25385.2	72
Gloucester County	48	96	-31.0	-54.7	26	-529	104.7	10953.5	-27
Greensville County	83	54	44.8	22.1	67	-140	52.3	2730.3	55
Hanover County	156	110	-54.0	-44.8	136	-279	147.7	21814.0	111
Henrico County	139	90	92.0	29.4	112	-196	101.5	10306.5	103
Isle of Wight County	61	123	-314.0	-237.4	38	-434	163.7	26800.4	-374
James City County	61	72	-185.3	-192.8	21	-469	93.1	8662.0	-164
King and Queen County	117	109	-119.0	-99.7	95	-471	148.9	22169.5	-138
King George County	82	101	-260.5	-269.6	52	-728	198.4	39366.2	52
King William County	97	107	-61.0	-78.1	83	-437	140.8	19829.9	52
Lancaster County	60	97	-375.0	-345.3	36	-795	250.9	62953.8	36
Mathews County	9	106	-87.5	-85.7	-19	-144	20.5	421.7	-101
Middlesex County	64	102	-27.5	-127.1	43	-622	177.3	31437.0	9
New Kent County	81	98	-139.0	-140.6	53	-469	118.1	13937.8	-97
Northampton County	12	115	-77.0	-75.4	64	-215	58.3	3401.6	-77
Northumberland County	63	110	-381.5	-404.6	43	-739	233.5	54529.4	-272
Prince George County	108	102	52.3	18.6	81	-252	70.8	5011.8	59
Richmond County	103	93	-192.0	-162.5	73	-480	127.3	16204.2	-180
Southampton County	69	123	-125.5	-121.4	49	-313	105.4	11111.7	39
Suffolk, City of	45	101	-381.5	-278.8	23	-643	219.1	48013.4	15
Surry County	89	107	35.0	-67.0	68	-338	145.2	21095.6	-206
Sussex County	100	86	54.5	30.4	82	-260	61.7	3803.6	66
Virginia Beach, City of	6	96	-61.3	-69.4	-17	-196	39.2	1537.2	-59
Westmoreland County	69	113	-156.0	-156.1	42	-574	161.0	25932.9	27
York County	34	38	-71.0	-112.9	-1	-401	105.0	11032.4	-71

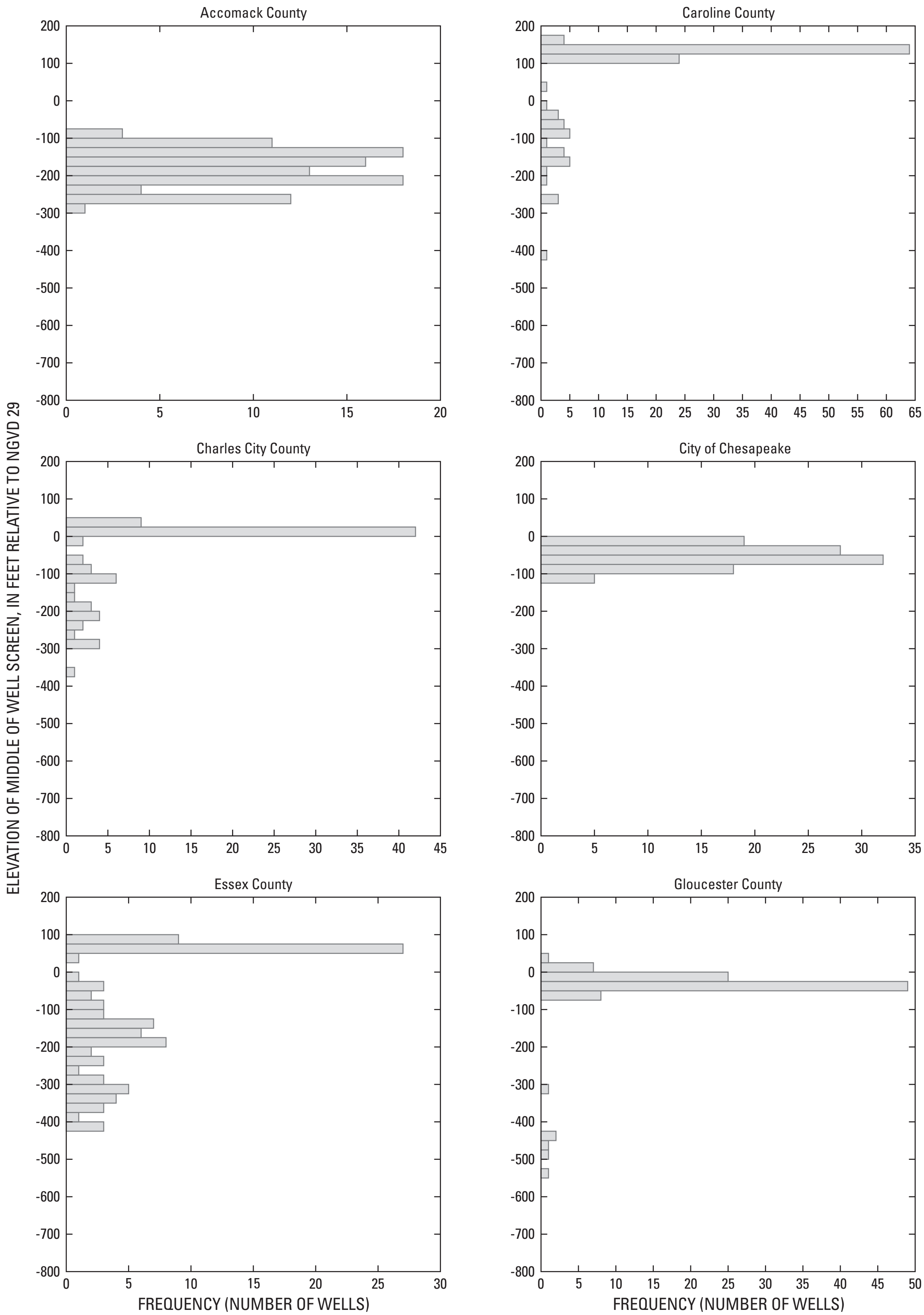

Figure 10*A*. Histograms of estimated domestic well-screen elevations for Virginia Coastal Plain localities.

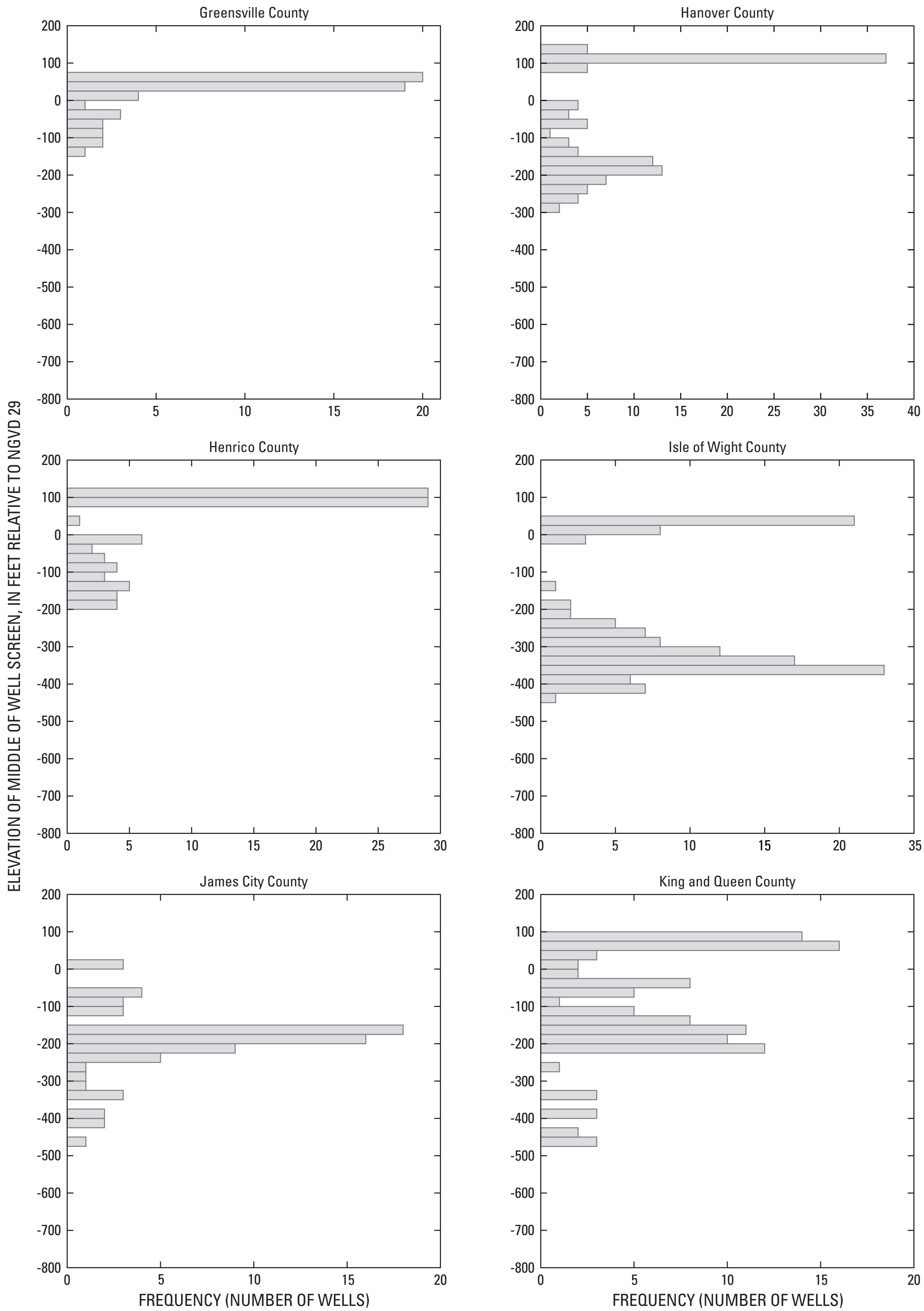

Figure 10*B*. Histograms of estimated domestic well-screen elevations for Virginia Coastal Plain localities.

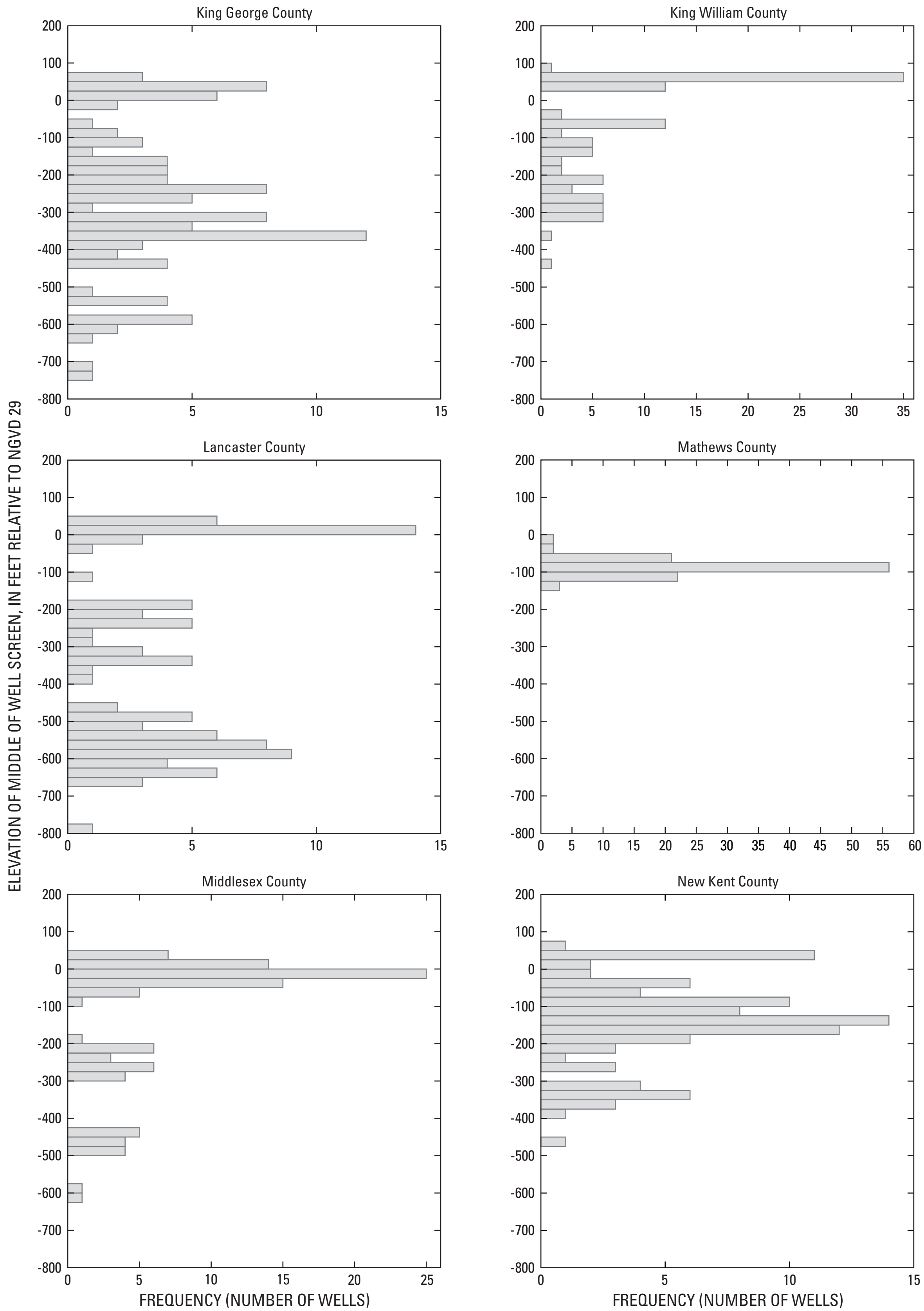

Figure 10*C*. Histograms of estimated domestic well-screen elevations for Virginia Coastal Plain localities.

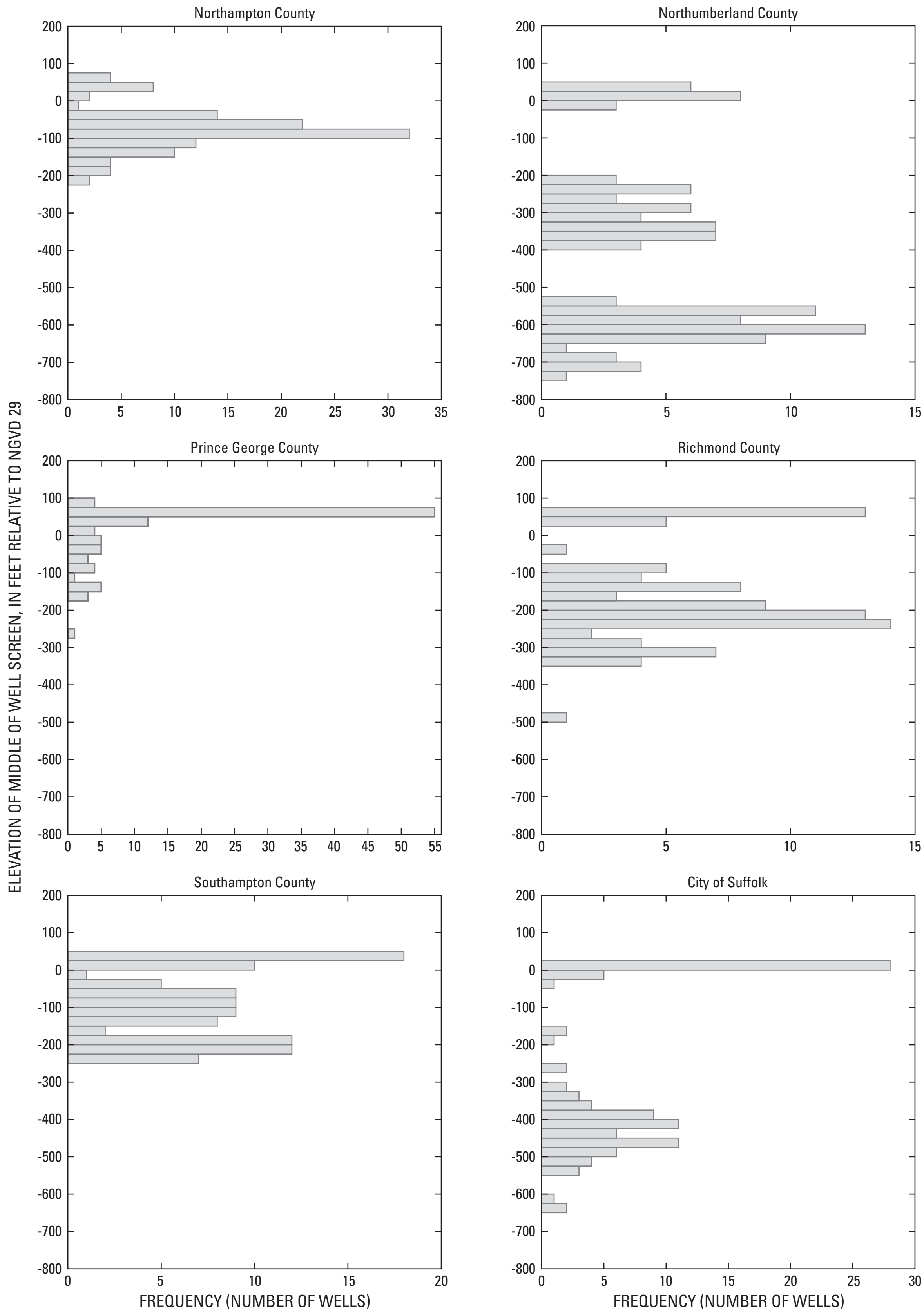

Figure 10*D*. Histograms of estimated domestic well-screen elevations for Virginia Coastal Plain localities.

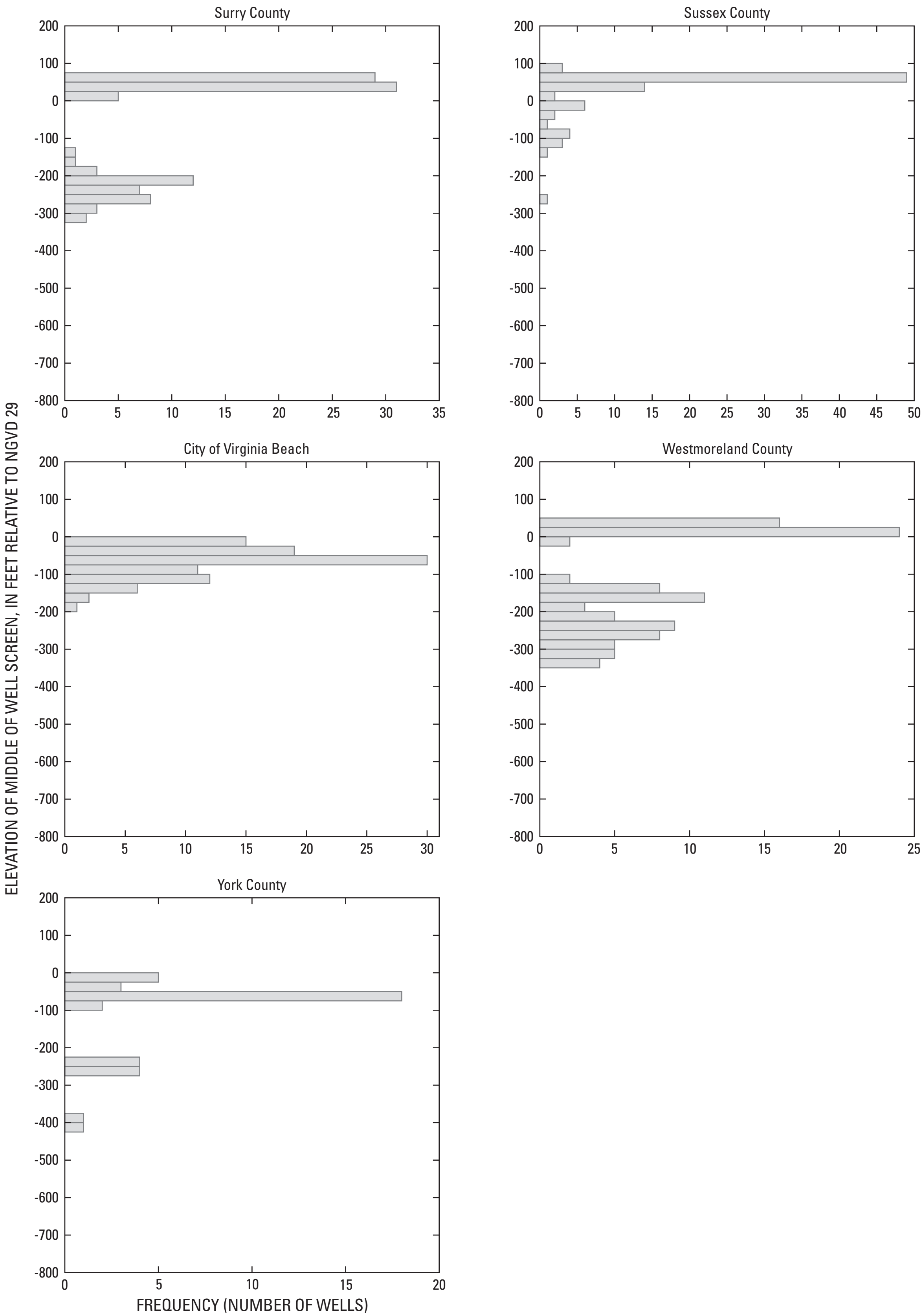

Figure 10*E*. Histograms of estimated domestic well-screen elevations for Virginia Coastal Plain localities.

Assumptions and Limitations Related to Estimating Domestic-Well Characteristics

The approach of estimating well characteristics from a stratified random sample and estimating self-supplied water use from population data was chosen because it was the only practical way to answer the necessary questions given the limitations in both data and resources. The use of population data and coefficients to estimate self-supplied domestic withdrawals commonly is applied in the USGS National Water Use Program and has been used without exception in all States and territories in the compilation of the 2000 water-use data (Kenney, 2004). Even with unlimited resources, it would be impossible to complete a census of all private domestic wells because records simply do not exist for many of the wells that have been drilled. In general terms, the stratified random sampling approach used for estimating well data and the coefficient-based approach of indirectly estimating water use from population data are associated with advantages and limitations that are well documented in the water-use literature (National Research Council Water Science and Technology Board, 2002).

Aside from the incomplete nature of the sampled records, one of the primary questions in any sampling effort is whether the sample is representative of the population. Neglecting formal statistical treatment of variability in the data, there are a number of uncontrollable factors that could affect the validity of the sampled well data. While great effort was expended to obtain a good, spatially stratified random sample of the well records available, some evidence indicates that the well records on file in a locality may not be truly representative of the wells extant in the locality.

For example, the estimated total number of records on file in many localities is much smaller than the total number of wells estimated from the population in the locality, which indicates that records do not exist for many wells. Furthermore, the lack of data prior to the late 1970s casts doubt on the completeness of the analyses. Clearly, many wells were installed in the Coastal Plain prior to the late 1970s, but no data are available on the characteristics of these earlier wells, which may still be in use. With these limitations in mind, the sample taken for this study may overestimate the depth of the well distribution for many localities. Several health department officials indicated a trend toward installing deeper, drilled wells for new homes and as replacements for shallow wells that fail during drought conditions. Unfortunately, the lack of earlier data makes this trend impossible to quantify. Nonetheless, this limitation should be considered with the sample results.

It would be more accurate to describe this study as a sample of the population of wells drilled since 1977 rather than as a sample of the population of all Virginia Coastal Plain wells. However, the well records sampled do not show a noticeable change in well-depth characteristics with time over the sampling period 1977 to 2002 other than perhaps a small increase in depths during the first few years that data were available.

Distribution of Domestic Wells and Withdrawals among Aquifers

The distribution of domestic wells and withdrawals among the aquifers of the Virginia Coastal Plain was based on the evaluation of the construction characteristics of sampled wells (described in the previous section of this report) and aggregated information on land-surface and hydrogeologic-unit elevations from the localities of interest. Neither aquifer-unit elevations nor aquifer designations were available for individual wells, so digital hydrogeologic-unit elevations developed for the McFarland and Bruce (2006) study were used to create a generalization of aquifer and confining-unit elevations for each locality. Estimated well-screen elevations were then compared to median aquifer elevations in each locality to estimate the primary aquifer in which each well was completed. A simple diagram of the spatial relations involved in this analysis is provided in figure 6, which illustrates well depth, well-head and well-screen elevations, land-surface elevation, and aquifer and confining-unit elevations for an example well location. The analysis involved in determining the aquifer for a well from measured screen and aquifer data (fig. 6*A*) is compared with the analysis in which the well-screen and aquifer elevations are estimated, as in this report (fig. 6*B*). The process is conceptually simple, but a number of assumptions are required to produce the necessary estimates.

From the determination of the aquifer for each well, the proportion of private domestic wells completed in each aquifer was calculated for each locality, and the proportions from all localities were summed for the entire Virginia Coastal Plain. For each locality, the estimated proportions of wells in each aquifer were used along with estimated rates of private domestic ground-water withdrawals derived from USGS water-use data (U.S. Geological Survey, 2002; Hutson and others, 2004) to compute rates of withdrawal from each aquifer. The steps involved in data collection, estimation, and analysis are outlined in a flow chart in figure 7. This chart illustrates the process of analyzing private domestic-well data, apportioning private domestic wells and withdrawals among aquifers, and distributing self-supplied domestic withdrawals spatially.

Analyses of Hydrogeologic-Unit Elevations by Locality

Data on land-surface and hydrogeologic-unit top elevations for each locality were derived from DEMs for the Virginia Coastal Plain produced from the work of McFarland and Bruce (2006). Using a GIS, McFarland and Bruce (2006) developed maps of the structural contours (top elevations) and extents of each of 19 aquifers and confining units and bedrock basement. The structural contours were used to develop raster representations of unit-top elevations in feet relative to NGVD 1929 at a horizontal resolution of 264 ft (1/20 mile).

The DEM used for the land-surface elevation and the top elevation of the surficial aquifer was derived from the National Elevation Dataset (NED; U.S. Geological Survey, 2004). The standard 30-meter (98.4 ft) NED raster data were resampled to the same 264-ft horizontal resolution as the rasters of the top elevations of aquifers and confining units, and the units of elevation were rounded and converted to integers to match the other unit-elevation rasters.

Statistical analyses of each of the 20 raster data sets were completed with a GIS. The GIS also was used to aggregate unit-top elevations by locality. Using Environmental Systems Research Institute, Inc. (ESRI), ArcGIS software, the “Zonal Statistics as Table” tool was implemented to summarize each of the raster grids by using polygons of the locality boundaries as the spatial zones for the computation. For localities situated in both the Piedmont and Coastal Plain, the Fall Line was used with the boundary polygons to create new polygons for only the Coastal Plain portion of the localities. Calculated aggregate statistics included the median, minimum, maximum, and mean values.

Data on the elevations of aquifers and confining units were not available for several northwestern Coastal Plain localities that were not included in the McFarland and Bruce (2006) study of the regional hydrogeology. These localities include the City of Alexandria, and Arlington, Fairfax, and Prince William Counties. Hydrogeologic-unit elevations were also not available for the City of Emporia in the southwestern part of the Virginia Coastal Plain because it is just outside of the McFarland and Bruce (2006) study area. As a result, these localities were not included in this study.

Of particular concern in the analyses were aquifers and confining units that do not extend across entire localities. Many of the hydrogeologic units pinch out as the wedge of Coastal Plain sediments thins to the west, and other units associated with the impact crater are limited in extent by the very nature of the impact event and subsequent geologic processes. The use of summary top-elevation values for an entire locality for aquifers and confining units that occupy only a small part of the locality was found to produce unsatisfactory results for the aggregate median unit elevations, specifically by creating negative unit thicknesses. To address this problem, units were considered to be present in a locality for the aggregate hydrogeology if they extended across more than 50 percent of the area; otherwise, they were considered to be absent.

The statistical analyses of DEMs for land-surface elevations and hydrogeologic-unit top elevations resulted in aggregate elevation values for each of these units for each locality. Aggregated values of elevations for each of these units are presented in tables 5–9. The most useful and appropriate aggregate elevation values for the hydrogeologic units are the median top elevations, presented in table 5, but other statistical values are presented to provide a measure of the variability of each of the unit surfaces within the boundaries of each locality. The minimum hydrogeologic-unit top elevations for each locality are presented in table 6, the maximum unit top elevations are presented in table 7, and the mean unit top elevations are presented in table 8. The proportions of each locality occupied by each hydrogeologic unit are presented in table 9 to more completely depict the known extent of each unit, including those considered to be absent in certain localities for the aggregated hydrogeology. Much more detailed information on the spatial variability of Virginia Coastal Plain hydrogeology is documented by McFarland and Bruce (2006). Clearly, the aggregated approach used here is a simplification but one that was necessary for this analysis.

Assignment of Domestic Wells and Withdrawals to Aquifers

With estimated well-screen elevations and a generalization of hydrogeologic-unit top elevations available for each locality of interest, it was possible to relate wells to hydrogeologic units on an aggregate basis simply by cross-referencing the estimated well-screen elevations with the estimated, aggregate hydrogeologic-unit elevations for each locality. This approach does not consider the component of variation in well-screen elevations due to the variable land-surface elevation within each locality, and it does not incorporate the sometimes substantial range of variation in the elevation of hydrogeologic units within a single locality. Nonetheless, the approach was valid for this region primarily because the land surface and the various hydrogeologic units are relatively flat and dip gently in approximately the same direction, which is to the east. Partly because of this configuration, the difference between the elevations of aquifers in which private domestic wells are completed generally is larger than either the variability in the land-surface elevation within a locality or the variability in the top elevation for each of the aquifer units. This set of conditions in many cases allows for considerable uncertainty with respect to a well-screen elevation without changing the estimate of the aquifer the well is thought to intersect.

In practice, each of the wells in a locality was assigned to an aquifer by comparing the estimated screen top and bottom elevations to the calculated median values for the hydrogeologic units present in the locality. This sometimes resulted in the initial assignment of a well to more than one hydrogeologic unit; in these cases, the assigned unit was the one intersected by the larger portion of the well screen. In some cases, the comparison of well-screen elevations resulted in the assignment of a well to a confining unit only; in these cases, the vertically closest aquifer unit was assigned as the most likely unit intersected by the well screen. In most cases, however, only one aquifer designation was apparent, and it was a reasonable aquifer selection.

Table 5. Median elevations, in feet, of top of hydrogeologic units in Virginia Coastal Plain localities.

[SURF, surficial aquifer; YTCZ, Yorktown confining zone; YEAQ, Yorktown-Eastover aquifer; SMCU, Saint Marys confining unit; SMAQ, Saint Marys aquifer; CACU, Calvert confining unit; PPAQ, Piney Point aquifer; CHCU, Chickahominy confining unit; XMCU, Exmore matrix confining unit; XCCU, Exmore clast confining unit; NMCU, Nanjemoy-Marlboro confining unit; AQAQ, Aquia aquifer; PDCU, Peedee confining unit; PDAQ, Peedee aquifer; VBCZ, Virginia Beach confining zone; VBAQ, Virginia Beach aquifer; UCCU, Upper Cenomanian confining unit; POCZ, Potomac confining zone; POAQ, Potomac aquifer; BSMT, basement; –, unit is not present over less than 50 percent of the locality area. Shading indicates locality in which well data were collected]

Locality (fig. 1)[a]	SURF	YTCZ	YEAQ	SMCU	SMAQ	CACU	PPAQ	CHCU	XMCU	XCCU	NMCU	AQAQ	PDCU	PDAQ	VBCZ	VBAQ	UCCU	POCZ	POAQ	BSMT
Accomack County	8	-70	-97	-357	-526	-713	-890	-999	–	–	–	–	–	–	–	–	–	-1,199	-1,322	-4,984
Caroline County	178	–	–	–	–	94	–	–	–	–	74	24	–	–	–	–	–	-24	-96	-376
Charles City County	61	–	–	10	–	16	-26	–	–	–	-61	-112	–	–	–	–	–	-141	-158	-658
Chesapeake, City of	14	-15	-27	-124	–	-427	-440	–	–	–	-457	-473	-554	-630	-601	-616	-619	-766	-776	-2,466
Chesterfield County	133	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	33
Colonial Heights, City of	62	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	10
Dinwiddie County	149	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	38
Essex County	114	–	–	86	–	12	-41	–	–	–	-89	-182	–	–	–	–	–	-299	-318	-1,523
Franklin, City of	29	11	-3	-35	–	–	-50	–	–	–	-59	-77	–	–	–	–	-108	-191	-215	-822
Fredricksburg, City of	93	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	41	-49	-142
Gloucester County	48	32	5	-104	–	-223	-288	-371	-578	–	–	–	–	–	–	–	–	-587	-607	-1,776
Greensville County	83	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	-16
Hampton, City of	8	-22	-37	-165	–	-408	-456	-600	-792	-871	–	–	–	–	–	–	–	-1,407	-1,423	-2,061
Hanover County	156	–	–	100	–	69	–	–	–	–	43	-26	–	–	–	–	–	-45	-70	-187
Henrico County	139	–	–	100	–	76	–	–	–	–	47	–	–	–	–	–	–	1	-11	-179
Hopewell, City of	44	–	–	–	–	–	–	–	–	–	25	–	–	–	–	–	–	6	0	-227
Isle of Wight County	61	36	-9	-54	–	–	-138	–	–	–	-156	-193	–	–	–	–	–	-245	-264	-1,127
James City County	61	53	13	-24	–	-98	-105	–	–	–	-165	-226	–	–	–	–	–	-259	-282	-1,224
King and Queen County	117	–	–	12	–	-39	-80	–	–	–	-159	-225	–	–	–	–	–	-283	-355	-1,361
King George County	82	–	–	–	–	78	–	–	–	–	14	-59	–	–	–	–	–	-132	-189	-1,244
King William County	97	–	–	60	–	24	-22	–	–	–	-47	-111	–	–	–	–	–	-181	-216	-1,005
Lancaster County	60	0	-26	-49	–	-155	-259	–	–	–	-355	-491	–	–	–	–	–	-517	-529	-2,263
Mathews County	9	-21	-35	-150	–	-291	-440	-542	-762	-832	–	–	–	–	–	–	–	-1236	-1278	-2,303
Middlesex County	64	31	2	-28	–	-116	-188	–	–	–	-258	-377	–	–	–	–	–	-438	-450	-1,819
New Kent County	81	–	–	1	–	-12	-29	–	–	–	-93	-149	–	–	–	–	–	-181	-210	-936
Newport News, City of	25	-17	-56	-137	–	-247	-294	-346	-544	–	–	–	–	–	–	–	–	-430	-474	-1,707
Norfolk, City of	10	-48	-84	-193	–	-499	-545	-679	-820	–	–	–	–	–	–	–	–	-765	-786	-2,368
Northampton County	12	-60	-90	-258	–	-589	-958	-1,088	-1267	-1316	–	–	–	–	–	–	–	–	–	-3,938
Northumberland County	63	25	-3	-23	–	-137	-264	–	–	–	-368	-508	–	–	–	–	–	-549	-569	-2,561
Petersburg, City of	140	–	111	–	–	–	–	–	–	–	–	–	–	–	–	–	–	59	24	6
Poquoson, City of	4	-21	-46	-138	–	-391	-460	-620	-835	-965	–	–	–	–	–	–	–	-1,526	-1,542	-2,133
Portsmouth, City of	10	-23	-42	-155	–	-380	-397	–	–	–	-419	-441	–	–	–	–	-466	-583	-599	-2,098
Prince George County	108	108	83	–	–	–	–	–	–	–	26	–	–	–	–	–	–	13	-19	-242
Richmond County	103	–	–	17	–	-34	-142	–	–	–	-221	-314	–	–	–	–	–	-420	-464	-1,962
Richmond, City of	177	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	68
Southampton County	69	68	25	0	–	–	–	–	–	–	-30	-40	–	–	–	–	–	-43	-72	-521
Spotsylvania County	211	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	37	-29	-108
Stafford County	141	–	–	–	–	–	–	–	–	–	–	85	–	–	–	–	–	24	-11	-283
Suffolk, City of	45	20	-12	-69	-163	-202	-196	–	–	–	-222	-250	–	–	–	–	-307	-410	-430	-1,541
Surry County	89	75	50	2	–	–	-84	–	–	–	-85	-132	–	–	–	–	–	-182	-218	-874
Sussex County	100	85	58	–	–	–	–	–	–	–	–	–	–	–	–	–	–	16	-10	-261
Virginia Beach, City of	6	-34	-58	-197	–	-648	-715	–	–	–	-754	-768	-843	-885	-912	-924	-962	-1,094	-1,130	-3,460
Westmoreland County	69	–	–	50	–	-7	-98	–	–	–	-150	-286	–	–	–	–	–	-369	-418	-2,039
Williamsburg, City of	70	68	39	-19	–	-143	-157	–	–	–	-199	-271	–	–	–	–	–	-302	-309	-1,361
York County	34	14	-8	-124	–	-244	-299	-413	-601	–	–	–	–	–	–	–	–	-527	-562	-1,735

[a]Localities are those included in a previous study of the hydrogeologic framework by McFarland and Bruce (2006).

Table 6. Minimum elevations, in feet, of top of hydrogeologic units in Virginia Coastal Plain localities.

[SURF, surficial aquifer; YTCZ, Yorktown confining zone; YEAQ, Yorktown-Eastover aquifer; SMCU, Saint Marys confining unit; SMAQ, Saint Marys aquifer; CACU, Calvert confining unit; PPAQ, Piney Point aquifer; CHCU, Chickahominy confining unit; XMCU, Exmore matrix confining unit; XCCU, Exmore clast confining unit; NMCU, Nanjemoy-Marlboro confining unit; AQAQ, Aquia aquifer; PDCU, Peedee confining unit; PDAQ, Peedee aquifer; VBCZ, Virginia Beach confining zone; VBAQ, Virginia Beach aquifer; UCCU, Upper Cenomanian confining unit; POCZ, Potomac confining zone; POAQ, Potomac aquifer; BSMT, basement; –, unit is not present over less than 50 percent of the locality area. Shading indicates locality in which well data were collected]

Locality (fig. 1)[a]	SURF	YTCZ	YEAQ	SMCU	SMAQ	CACU	PPAQ	CHCU	XMCU	XCCU	NMCU	AQAQ	PDCU	PDAQ	VBCZ	VBAQ	UCCU	POCZ	POAQ	BSMT
Accomack County	0	-197	-199	-516	-741	-833	-1,002	-1,099	–	–	–	–	–	–	–	–	–	-1,542	-1,560	-7,566
Caroline County	0	–	–	–	–	18	–	–	–	–	-39	-128	–	–	–	–	–	-232	-243	-1,289
Charles City County	0	–	–	-74	–	-73	-76	–	–	–	-124	-177	–	–	–	–	–	-214	-228	-1,043
Chesapeake, City of	0	-58	-74	-186	–	-626	-663	–	–	–	-688	-709	-755	-799	-895	-908	-934	-1,082	-1,119	-3,597
Chesterfield County	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	-370
Colonial Heights, City of	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	-75
Dinwiddie County	49	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	-45
Essex County	0	–	–	-25	–	-81	-158	–	–	–	-246	-345	–	–	–	–	–	-421	-440	-1,833
Franklin, City of	1	-2	-24	-45	–	–	-57	–	–	–	-68	-83	–	–	–	–	-149	-217	-249	-849
Fredricksburg, City of	2	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	-23	-74	-211
Gloucester County	0	-38	-63	-147	–	-295	-412	-538	-828	–	–	–	–	–	–	–	–	-1,435	-1,462	-2,127
Greensville County	22	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	-270
Hampton, City of	0	-65	-99	-204	–	-475	-585	-826	-1,029	-1,106	–	–	–	–	–	–	–	-1,705	-1,717	-2,324
Hanover County	1	–	–	50	–	-14	–	–	–	–	-43	-107	–	–	–	–	–	-165	-182	-922
Henrico County	0	–	–	-24	–	24	–	–	–	–	-49	–	–	–	–	–	–	-108	-130	-611
Hopewell, City of	0	–	–	–	–	–	–	–	–	–	-7	–	–	–	–	–	–	-23	-32	-273
Isle of Wight County	0	-48	-100	-178	–	–	-307	–	–	–	-341	-394	–	–	–	–	–	-498	-525	-1,720
James City County	0	-25	-48	-113	–	-210	-250	–	–	–	-291	-345	–	–	–	–	–	-415	-428	-1,615
King and Queen County	0	–	–	-57	–	-147	-182	–	–	–	-245	-357	–	–	–	–	–	-418	-454	-1,656
King George County	0	–	–	–	–	-27	–	–	–	–	-57	-168	–	–	–	–	–	-300	-319	-1,664
King William County	0	–	–	-60	–	-81	-96	–	–	–	-171	-265	–	–	–	–	–	-292	-366	-1,338
Lancaster County	0	-37	-95	-145	–	-226	-429	–	–	–	-450	-556	–	–	–	–	–	-597	-623	-2,604
Mathews County	0	-75	-101	-173	–	-351	-586	-789	-979	-1,162	–	–	–	–	–	–	–	-1,798	-1,815	-2,552
Middlesex County	0	-49	-83	-147	–	-252	-439	–	–	–	-381	-486	–	–	–	–	–	-723	-749	-2,485
New Kent County	0	–	–	-56	–	-107	-122	–	–	–	-191	-269	–	–	–	–	–	-305	-360	-1,347
Newport News, City of	0	-74	-99	-183	–	-407	-426	-512	-681	–	–	–	–	–	–	–	–	-949	-1,012	-1,989
Norfolk, City of	0	-73	-104	-224	–	-622	-693	-785	-985	–	–	–	–	–	–	–	–	-1,306	-1,356	-2,637
Northampton County	0	-193	-199	-457	–	-757	-1,020	-1,099	-1,299	-1,349	–	–	–	–	–	–	–	–	–	-5,999
Northumberland County	0	-35	-68	-105	–	-197	-379	–	–	–	-451	-593	–	–	–	–	–	-620	-702	-3,005
Petersburg, City of	1	–	4	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	-4	-115
Poquoson, City of	0	-46	-90	-173	–	-447	-556	-785	-985	-1,101	–	–	–	–	–	–	–	-1,700	-1,713	-2,296
Portsmouth, City of	0	-32	-86	-188	–	-454	-479	–	–	–	-502	-520	–	–	–	–	-545	-702	-721	-2,342
Prince George County	0	56	-17	–	–	–	–	–	–	–	-108	–	–	–	–	–	–	-152	-185	-759
Richmond County	0	–	–	-28	–	-129	-234	–	–	–	-343	-460	–	–	–	–	–	-494	-545	-2,335
Richmond, City of	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	-96
Southampton County	0	-21	-35	-46	–	–	–	–	–	–	-98	-146	–	–	–	–	–	-257	-287	-945
Spotsylvania County	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	-26	-69	-438
Stafford County	0	–	–	–	–	–	–	–	–	–	–	-24	–	–	–	–	–	-34	-55	-732
Suffolk, City of	0	-33	-94	-199	-264	-345	-365	–	–	–	-384	-395	–	–	–	–	-472	-640	-685	-2,180
Surry County	0	-4	-34	-62	–	–	-188	–	–	–	-224	-298	–	–	–	–	–	-319	-348	-1,417
Sussex County	1	51	-10	–	–	–	–	–	–	–	–	–	–	–	–	–	–	-171	-208	-913
Virginia Beach, City of	0	-124	-163	-261	–	-713	-837	–	–	–	-989	-1,006	-1,081	-1,126	-1,278	-1,296	-1,348	-1,358	-1,440	-4,669
Westmoreland County	0	–	–	-40	–	-65	-195	–	–	–	-278	-414	–	–	–	–	–	-490	-564	-2,600
Williamsburg, City of	1	22	-20	-34	–	-157	-181	–	–	–	-219	-294	–	–	–	–	–	-327	-340	-1,424
York County	0	-63	-128	-209	–	-622	-684	-749	-949	–	–	–	–	–	–	–	–	-1,437	-1,454	-2,551

[a]Localities are those included in a previous study of the hydrogeologic framework by McFarland and Bruce (2006).

Table 7. Maximum elevations, in feet, of top of hydrogeologic units in Virginia Coastal Plain localities.

[SURF, surficial aquifer; YTCZ, Yorktown confining zone; YEAQ, Yorktown-Eastover aquifer; SMCU, Saint Marys confining unit; SMAQ, Saint Marys aquifer; CACU, Calvert confining unit; PPAQ, Piney Point aquifer; CHCU, Chickahominy confining unit; XMCU, Exmore matrix confining unit; XCCU, Exmore clast confining unit; NMCU, Nanjemoy-Marlboro confining unit; AQAQ, Aquia aquifer; PDCU, Peedee confining unit; PDAQ, Peedee aquifer; VBCZ, Virginia Beach confining zone; VBAQ, Virginia Beach aquifer; UCCU, Upper Cenomanian confining unit; POCZ, Potomac confining zone; POAQ, Potomac aquifer; BSMT, basement; –, unit is not present over less than 50 percent of the locality area. Shading indicates locality in which well data were collected]

Locality (fig. 1[a])	SURF	YTCZ	YEAQ	SMCU	SMAQ	CACU	PPAQ	CHCU	XMCU	XCCU	NMCU	AQAQ	PDCU	PDAQ	VBCZ	VBAQ	UCCU	POCZ	POAQ	BSMT
Accomack County	64	-24	-49	-151	-243	-370	-540	-728	–	–	–	–	–	–	–	–	–	-779	-909	-3,526
Caroline County	315	–	–	–	–	156	–	–	–	–	129	90	–	–	–	–	–	42	16	197
Charles City County	176	–	–	90	–	74	35	–	–	–	30	-22	–	–	–	–	–	-11	-19	-271
Chesapeake, City of	41	3	-5	-99	–	-279	-284	–	–	–	-297	-335	-354	-361	-365	-366	-368	-480	-496	-1,835
Chesterfield County	303	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	160
Colonial Heights, City of	149	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	29
Dinwiddie County	231	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	139
Essex County	250	–	–	130	–	92	79	–	–	–	30	-57	–	–	–	–	–	-151	-198	-1,099
Franklin, City of	88	53	3	-22	–	–	-44	–	–	–	-52	-62	–	–	–	–	-94	-161	-199	-783
Fredricksburg, City of	253	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	50	-34	-87
Gloucester County	159	50	39	-24	–	-103	-138	-283	-448	–	–	–	–	–	–	–	–	-319	-356	-1,374
Greensville County	178	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	-	-	50
Hampton, City of	36	2	0	-123	–	-327	-369	-420	-578	-640	–	–	–	–	–	–	–	-633	-683	-1,859
Hanover County	300	–	–	135	–	92	–	–	–	–	86	51	–	–	–	–	–	26	7	151
Henrico County	321	–	–	157	–	110	–	–	–	–	90	–	–	–	–	–	–	99	89	188
Hopewell, City of	104	–	–	–	–	–	–	–	–	–	53	–	–	–	–	–	–	18	0	-158
Isle of Wight County	114	65	44	-8	–	–	-52	–	–	–	-63	-76	–	–	–	–	–	-154	-174	-824
James City County	157	83	75	32	–	-53	-59	–	–	–	-108	-163	–	–	–	–	–	-194	-207	-941
King and Queen County	273	–	–	130	–	65	37	–	–	–	31	-65	–	–	–	–	–	-165	-202	-865
King George County	232	–	–	–	–	150	–	–	–	–	92	75	–	–	–	–	–	-5	-27	-523
King William County	271	–	–	125	–	73	34	–	–	–	64	-7	–	–	–	–	–	-26	-69	-249
Lancaster County	164	30	0	-21	–	-90	-178	–	–	–	-282	-387	–	–	–	–	–	-443	-463	-1,960
Mathews County	67	39	19	-124	–	-245	-364	-410	-564	-578	–	–	–	–	–	–	–	-671	-693	-2,038
Middlesex County	152	50	25	1	–	-69	-125	–	–	–	-201	-290	–	–	–	–	–	-369	-407	-1,562
New Kent County	182	–	–	104	–	61	47	–	–	–	38	-33	–	–	–	–	–	-73	-98	-484
Newport News, City of	86	38	25	-88	–	-186	-211	-268	-345	–	–	–	–	–	–	–	–	-326	-338	-1,494
Norfolk, City of	34	-10	-25	-135	–	-413	-424	-546	-618	–	–	–	–	–	–	–	–	-626	-647	-2,125
Northampton County	42	0	-69	-208	–	-326	-860	-953	-1092	-1150	–	–	–	–	–	–	–	–	–	-2,999
Northumberland County	183	46	12	36	–	-52	-168	–	–	–	-239	-357	–	–	–	–	–	-465	-523	-2,221
Petersburg, City of	193	–	117	–	–	–	–	–	–	–	–	–	–	–	–	–	–	93	52	78
Poquoson, City of	24	-11	-15	-124	–	-328	-396	-524	-709	-823	–	–	–	–	–	–	–	-1,165	-1,250	-1,992
Portsmouth, City of	32	0	-9	-124	–	-337	-347	–	–	–	-348	-380	–	–	–	–	-393	-492	-497	-1,905
Prince George County	172	136	117	–	–	–	–	–	–	–	133	–	–	–	–	–	–	101	100	9
Richmond County	212	–	–	101	–	43	-23	–	–	–	-72	-180	–	–	–	–	–	-313	-338	-1,662
Richmond, City of	304	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	180
Southampton County	137	110	64	26	–	–	–	–	–	–	26	12	–	–	–	–	–	50	16	21
Spotsylvania County	322	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	50	-5	75
Stafford County	398	–	–	–	–	–	–	–	–	–	–	118	–	–	–	–	–	71	58	74
Suffolk, City of	100	62	29	-5	-72	-85	-48	–	–	–	-54	-65	–	–	–	–	-149	-224	-260	-862
Surry County	175	103	73	47	–	–	-47	–	–	–	22	12	–	–	–	–	–	4	-54	-393
Sussex County	231	116	107	–	–	–	–	–	–	–	–	–	–	–	–	–	–	75	53	44
Virginia Beach, City of	80	-20	-35	-138	–	-509	-510	–	–	–	-549	-591	-673	-731	-599	-606	-627	-749	-758	-2,507
Westmoreland County	212	–	–	112	–	79	45	–	–	–	4	-134	–	–	–	–	–	-243	-291	-1,431
Williamsburg, City of	106	75	64	-16	–	-120	-137	–	–	–	-175	-249	–	–	–	–	–	-282	-286	-1,294
York County	123	77	59	-15	–	-113	-125	-280	-363	–	–	–	–	–	–	–	–	-277	-299	-1,301

[a]Localities are those included in a previous study of the hydrogeologic framework by McFarland and Bruce (2006).

Table 8. Mean elevations, in feet, of top of hydrogeologic units in Virginia Coastal Plain localities.

[SURF, surficial aquifer; YTCZ, Yorktown confining zone; YEAQ, Yorktown-Eastover aquifer; SMCU, Saint Marys confining unit; SMAQ, Saint Marys aquifer; CACU, Calvert confining unit; PPAQ, Piney Point aquifer; CHCU, Chickahominy confining unit; XMCU, Exmore matrix confining unit; XCCU, Exmore clast confining unit; NMCU, Nanjemoy-Marlboro confining unit; AQAQ, Aquia aquifer; PDCU, Peedee confining unit; PDAQ, Peedee aquifer; VBCZ, Virginia Beach confining zone; VBAQ, Virginia Beach aquifer; UCCU, Upper Cenomanian confining unit; POCZ, Potomac confining zone; POAQ, Potomac aquifer; BSMT, basement; –, unit is not present over less than 50 percent of the locality area. Shading indicates locality in which well data were collected]

Locality (fig. 1)[a]	SURF	YTCZ	YEAQ	SMCU	SMAQ	CACU	PPAQ	CHCU	XMCU	XCCU	NMCU	AQAQ	PDCU	PDAQ	VBCZ	VBAQ	UCCU	POCZ	POAQ	BSMT
Accomack County	15	-71	-99	-349	-528	-706	-893	-993	–	–	–	–	–	–	–	–	–	-1,210	-1,324	-5,165
Caroline County	164	–	–	–	–	98	–	–	–	–	70	16	–	–	–	–	–	-41	-92	-440
Charles City County	64	–	–	13	–	8	-23	–	–	–	-56	-108	–	–	–	–	–	-139	-158	-670
Chesapeake, City of	13	-19	-34	-133	–	-433	-443	–	–	–	-462	-487	-550	-616	-602	-619	-631	-783	-798	-2,533
Chesterfield County	125	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	-13
Colonial Heights, City of	61	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	3
Dinwiddie County	145	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	44
Essex County	99	–	–	72	–	14	-40	–	–	–	-91	-186	–	–	–	–	–	-292	-315	-1,513
Franklin, City of	39	18	-4	-35	–	–	-50	–	–	–	-59	-76	–	–	–	–	-114	-189	-217	-821
Fredricksburg, City of	114	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	38	-50	-144
Gloucester County	48	22	0	-97	–	-214	-280	-380	-610	–	–	–	–	–	–	–	–	-625	-656	-1,774
Greensville County	89	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	-39
Hampton, City of	9	-24	-44	-162	–	-407	-464	-617	-801	-874	–	–	–	–	–	–	–	-1,282	-1,317	-2,074
Hanover County	144	–	–	98	–	66	–	–	–	–	35	-33	–	–	–	–	–	-51	-70	-201
Henrico County	127	–	–	100	–	76	–	–	–	–	41	–	–	–	–	–	–	-5	-17	-185
Hopewell, City of	43	–	–	–	–	–	–	–	–	–	31	–	–	–	–	–	–	6	-7	-224
Isle of Wight County	55	31	-13	-67	–	–	-146	–	–	–	-163	-205	–	–	–	–	–	-253	-272	-1,157
James City County	58	50	17	-33	–	-103	-115	–	–	–	-169	-230	–	–	–	–	–	-265	-286	-1,235
King and Queen County	109	–	–	18	–	-33	-72	–	–	–	-133	-216	–	–	–	–	–	-284	-326	-1,345
King George County	87	–	–	–	–	71	–	–	–	–	20	-51	–	–	–	–	–	-135	-186	-1,202
King William County	96	–	–	53	–	17	-26	–	–	–	-55	-124	–	–	–	–	–	-173	-221	-907
Lancaster County	57	2	-30	-53	–	-153	-266	–	–	–	-358	-488	–	–	–	–	–	-516	-531	-2,260
Mathews County	10	-22	-43	-152	–	-292	-448	-555	-755	-837	–	–	–	–	–	–	–	-1,235	-1,267	-2,294
Middlesex County	61	23	-4	-52	–	-139	-227	–	–	–	-267	-378	–	–	–	–	–	-467	-484	-1,873
New Kent County	76	–	–	15	–	-11	-30	–	–	–	-88	-149	–	–	–	–	–	-186	-210	-939
Newport News, City of	24	-23	-54	-140	–	-261	-305	-357	-533	–	–	–	–	–	–	–	–	-483	-514	-1,718
Norfolk, City of	9	-43	-79	-189	–	-502	-546	-685	-821	–	–	–	–	–	–	–	–	-867	-894	-2,368
Northampton County	15	-62	-99	-282	–	-577	-957	-1,070	-1,258	-1,303	–	–	–	–	–	–	–	–	–	-4,322
Northumberland County	58	18	-12	-26	–	-131	-268	–	–	–	-361	-495	–	–	–	–	–	-538	-577	-2,572
Petersburg, City of	125	–	108	–	–	–	–	–	–	–	–	–	–	–	–	–	–	60	25	1
Poquoson, City of	5	-23	-46	-139	–	-391	-460	-623	-827	-957	–	–	–	–	–	–	–	-1,505	-1,528	-2,126
Portsmouth, City of	9	-20	-45	-152	–	-383	-400	–	–	–	-424	-439	–	–	–	–	-463	-583	-601	-2,113
Prince George County	96	107	82	–	–	–	–	–	–	–	24	–	–	–	–	–	–	-10	-33	-274
Richmond County	90	–	–	23	–	-34	-135	–	–	–	-209	-311	–	–	–	–	–	-407	-449	-1,976
Richmond, City of	159	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	64
Southampton County	65	60	25	-2	–	–	–	–	–	–	-32	-45	–	–	–	–	–	-65	-92	-529
Spotsylvania County	186	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	35	-30	-128
Stafford County	143	–	–	–	–	–	–	–	–	–	–	77	–	–	–	–	–	24	-3	-273
Suffolk, City of	44	17	-17	-80	-163	-208	-194	–	–	–	-215	-243	–	–	–	–	-303	-409	-435	-1,499
Surry County	83	71	41	3	–	–	-92	–	–	–	-88	-135	–	–	–	–	–	-181	-211	-879
Sussex County	98	87	58	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	-24	-294
Virginia Beach, City of	7	-41	-69	-198	–	-646	-709	–	–	–	-756	-776	-853	-900	-917	-931	-972	-1,078	-1,110	-3,467
Westmoreland County	75	–	–	46	–	-7	-88	–	–	–	-138	-269	–	–	–	–	–	-376	-422	-2,007
Williamsburg, City of	66	66	35	-19	–	-142	-157	–	–	–	-199	-272	–	–	–	–	–	-304	-311	-1,361
York County	37	13	-8	-104	–	-233	-284	-415	-596	–	–	–	–	–	–	–	–	-578	-613	-1,699

[a]Localities are those included in a previous study of the hydrogeologic framework by McFarland and Bruce (2006).

Table 9. Proportions of Virginia Coastal Plain localities occupied by each hydrogeologic unit.

[SURF, surficial aquifer; YTCZ, Yorktown confining zone; YEAQ, Yorktown-Eastover aquifer; SMCU, Saint Marys confining unit; SMAQ, Saint Marys aquifer; CACU, Calvert confining unit; PPAQ, Piney Point aquifer; CHCU, Chickahominy confining unit; XMCU, Exmore matrix confining unit; XCCU, Exmore clast confining unit; NMCU,Nanjemoy-Marlboro confining unit; AQAQ, Aquia aquifer; PDCU, Peedee confining unit; PDAQ, Peedee aquifer; VBCZ, Virginia Beach confining zone; VBAQ, Virginia Beach aquifer; UCCU, Upper Cenomanian confining unit; POCZ, Potomac confining zone; POAQ, Potomac aquifer; BSMT, basement; –, unit is not present over less than 50 percent of the locality area. Shading indicates locality in which well data were collected]

Locality (fig. 1)[a]	SURF	YTCZ	YEAQ	SMCU	SMAQ	CACU	PPAQ	CHCU	XMCU	XCCU	NMCU	AQAQ	PDCU	PDAQ	VBCZ	VBAQ	UCCU	POCZ	POAQ	BSMT
Accomack County	1.00	0.95	1.00	1.00	1.00	1.00	0.92	0.90	0.16	0.14	0.10	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
Caroline County	1.00	0.00	0.00	0.48	0.00	0.73	0.12	0.00	0.00	0.00	0.87	0.88	0.00	0.00	0.00	0.00	0.00	0.87	0.87	1.00
Charles City County	1.00	0.13	0.18	0.89	0.00	0.58	0.78	0.00	0.00	0.00	0.99	0.94	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
Chesapeake, City of	1.00	0.98	1.00	1.00	0.00	1.00	1.00	0.00	0.00	0.00	1.00	1.00	0.51	0.51	0.93	0.93	1.00	1.00	1.00	1.00
Chesterfield County	1.00	0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.26	1.00
Colonial Heights, City of	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.15	0.24	1.00
Dinwiddie County	1.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.42	0.46	1.00
Essex County	1.00	0.00	0.00	0.76	0.00	0.94	0.98	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
Franklin, City of	1.00	0.80	0.99	1.00	0.00	0.00	1.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.02	0.02	1.00	1.00	1.00	1.00
Fredricksburg, City of	1.00	0.00	0.00	0.00	0.00	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.92	0.92	1.00
Gloucester County	1.00	0.77	1.00	1.00	0.00	1.00	1.00	0.59	0.53	0.47	0.41	0.41	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
Greensville County	1.00	0.24	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.22	1.00
Hampton, City of	1.00	0.82	1.00	1.00	0.00	1.00	1.00	1.00	1.00	0.97	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
Hanover County	1.00	0.00	0.00	0.50	0.00	0.57	0.15	0.00	0.00	0.00	0.61	0.60	0.00	0.00	0.00	0.00	0.00	0.67	0.67	1.00
Henrico County	1.00	0.00	0.00	0.51	0.00	0.56	0.15	0.00	0.00	0.00	0.60	0.46	0.00	0.00	0.00	0.00	0.00	0.74	0.77	1.00
Hopewell, City of	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.73	0.00	0.00	0.00	0.00	0.00	0.00	0.80	1.00	1.00
Isle of Wight County	1.00	0.86	1.00	1.00	0.17	0.33	1.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.01	0.01	0.31	1.00	1.00	1.00
James City County	1.00	0.67	0.98	1.00	0.00	1.00	1.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
King and Queen County	1.00	0.31	0.34	0.97	0.00	1.00	1.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
King George County	1.00	0.00	0.00	0.00	0.00	0.73	0.27	0.00	0.00	0.00	0.96	1.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
King William County	1.00	0.06	0.10	0.87	0.00	0.95	0.79	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
Lancaster County	1.00	0.99	1.00	1.00	0.00	1.00	1.00	0.07	0.01	0.00	0.93	0.93	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
Mathews County	1.00	0.81	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
Middlesex County	1.00	0.75	0.91	1.00	0.00	1.00	1.00	0.25	0.18	0.18	0.75	0.75	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
New Kent County	1.00	0.21	0.29	0.89	0.00	0.97	1.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
Newport News, City of	1.00	0.89	1.00	1.00	0.00	1.00	1.00	0.82	0.51	0.15	0.18	0.18	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
Norfolk, City of	1.00	1.00	1.00	1.00	0.00	1.00	1.00	0.65	0.60	0.14	0.35	0.35	0.00	0.00	0.01	0.01	0.35	1.00	1.00	1.00
Northampton County	1.00	0.94	1.00	1.00	0.50	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.46	0.46	1.00
Northumberland County	1.00	0.52	0.66	1.00	0.00	1.00	1.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
Petersburg, City of	1.00	0.47	0.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.63	0.63	1.00
Poquoson, City of	1.00	0.78	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
Portsmouth, City of	1.00	0.90	1.00	1.00	0.00	1.00	1.00	0.01	0.00	0.00	0.99	0.99	0.00	0.00	0.06	0.06	0.98	1.00	1.00	1.00
Prince George County	1.00	0.59	0.70	0.41	0.00	0.00	0.00	0.00	0.00	0.00	0.90	0.44	0.00	0.00	0.00	0.00	0.00	0.99	1.00	1.00
Richmond County	1.00	0.05	0.05	0.85	0.00	1.00	1.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
Richmond, City of	1.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.09	1.00
Southampton County	1.00	0.69	0.89	0.73	0.00	0.00	0.21	0.00	0.00	0.00	0.73	0.73	0.00	0.00	0.18	0.18	0.19	0.99	0.99	1.00
Spotsylvania County	1.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.35	0.35	0.00	0.00	0.00	0.00	0.00	0.76	0.76	1.00
Stafford County	1.00	0.00	0.00	0.00	0.00	0.21	0.00	0.00	0.00	0.00	0.43	0.56	0.00	0.00	0.00	0.00	0.00	0.73	0.76	1.00
Suffolk, City of	1.00	0.91	1.00	1.00	0.53	0.84	1.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.50	0.50	1.00	1.00	1.00	1.00
Surry County	1.00	0.85	0.96	1.00	0.00	0.02	0.70	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
Sussex County	1.00	0.84	0.91	0.38	0.00	0.00	0.04	0.00	0.00	0.00	0.47	0.40	0.00	0.00	0.00	0.00	0.00	0.97	0.97	1.00
Virginia Beach, City of	1.00	1.00	1.00	1.00	0.00	1.00	1.00	0.12	0.11	0.04	0.88	0.88	0.55	0.55	0.86	0.86	0.88	1.00	1.00	1.00
Westmoreland County	1.00	0.00	0.00	0.76	0.00	0.92	0.99	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
Williamsburg, City of	1.00	0.78	0.99	1.00	0.00	1.00	1.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
York County	1.00	0.73	1.00	1.00	0.00	1.00	1.00	0.64	0.62	0.33	0.36	0.36	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00

[a]Localities are those included in a previous study of the hydrogeologic framework by McFarland and Bruce (2006).

Once the aquifer designations were assigned for each of the wells, these designations were summarized by locality. The number of wells assigned to each aquifer within each locality is listed in table 10, along with the number and proportion of wells assigned to each aquifer for the entire Virginia Coastal Plain. The proportion of wells assigned to each aquifer within each locality is listed in table 11, along with the proportions for the entire Virginia Coastal Plain.

Nine different Coastal Plain aquifers and confining units were intersected by wells in this analysis: the Potomac aquifer (POAQ), the Potomac Confining Zone (POCZ), the Virginia Beach aquifer (VBAQ), the Aquia aquifer (AQAQ), the Piney Point aquifer (PPAQ), the Saint Marys aquifer (SMAQ), the Yorktown-Eastover aquifer (YEAQ), the Yorktown confining zone (YTCZ), and the surficial aquifer (SURF). In addition, some wells in localities near the Fall Line intersect the bed-rock basement immediately beneath Coastal Plain sediments. These wells were included because they intersect fractured bedrock directly beneath the Potomac aquifer sediments and may effectively withdraw water from the Coastal Plain aquifer system.

By using a published per-capita withdrawal coefficient of 75 gal/d for private domestic users in Virginia (Hutson and others, 2004), the mean daily self-supplied domestic with-drawal rate was calculated for each of the aquifers for each locality. The results of these calculations are listed in table 12, and the withdrawal totals for each locality correspond to the withdrawal totals for the “domestic” column in table 2.

In aggregate, the results for all the localities for which data were collected (tables 10, 11) reveal that 21.7 percent of the domestic wells and withdrawals in the Virginia Coastal Plain are associated with the unconfined surficial aquifer, 32.9 percent are associated either with the Yorktown-Eastover aquifer or the Yorktown confining zone, 8.3 percent are associ-ated with the Piney Point aquifer, 11.3 percent are associated with the Aquia aquifer, and 25.1 percent are associated either with the Potomac aquifer or the Potomac confining zone. Three wells intersect the Saint Marys aquifer, and five wells intersect the Virginia Beach aquifer, which results in a very small portion of withdrawals associated with these two aquifers (tables 10, 11, 12). In addition, 14 wells in localities near the Fall Line intersect the bedrock, which indicates that bedrock wells are a small source of water in areas where the Coastal Plain aquifer system is very thin (tables 10, 11, 12).

These results question the previously held assumption by some water-resources experts that private domestic withdrawals are unimportant to regional ground-water flow because they are taken from the unconfined aquifer and quickly replaced by return flow through home septic systems. This new information about domestic wells indicates that withdrawals from several confined aquifers of the Virginia Coastal Plain actually make up 78 percent of the estimated self-supplied domestic total. This represents about 24 Mgal/d for the localities sampled, or about 30 Mgal/d for all Virginia Coastal Plain localities. This is water that is effectively removed permanently from the confined system, though it may recharge the surficial aquifer through septic-tank discharge or flow into streams and rivers. The magnitude of these estimated withdrawals from the confined aquifers indicates that self-supplied domestic withdrawals of ground-water may have a much more important role in the regional ground-water flow system than previously believed.

Ongoing ground-water modeling investigations in this region may provide additional information about the relative influence of these withdrawals. In fact, ground-water model simulations indicate that domestic withdrawals have a less pronounced effect on the hydrogeologic system than large, centralized municipal and industrial withdrawals of similar magnitude, because the domestic withdrawals are more evenly distributed in time and space. The more numerous and spatially distributed domestic wells individually pump less water, so the relatively diffuse withdrawals from these wells do not appear to cause well-defined cones of depression in the Coastal Plain aquifers, and they have not lowered regional ground-water levels or altered ground-water flow rates as substantially as the larger industrial and municipal with-drawals (C.E. Heywood, U.S. Geological Survey, written commun., 2007).

Considerable local variation is apparent in the associa-tion of wells and withdrawals to aquifers. Consequently, the results from assigning wells to aquifers by locality can best be considered in terms of groups of spatially related localities. Because of the spatial correlation of hydrogeologic conditions, it is not surprising to find that adjacent localities yield similar results in this type of analysis. Some of this correlation can be visually noted in the similar appearance of the well-screen elevation histograms (figs. 10*A*–*E*) and more analytically from similar proportions in table 11.

For example, results were similar for Lancaster and Northumberland Counties in adjacent locations on the end of the Northern Neck Peninsula. In Northumberland County, 41.8 percent of the withdrawals were determined to be from the Potomac aquifer, while the percentage of wells in this aquifer in Lancaster County was 38.1. The proportions for the Aquia aquifer and the Piney Point aquifer also were similar, with some differences between the proportions in the shal-lower system, which actually could be the result of increased error where the units are closer together. The results in the Northern Neck counties of Richmond and Westmoreland also are similar, probably because of similar hydrogeologic conditions in these two adjacent localities. The similarities and differences between these two counties and Lancaster and Northumberland to the east also are notable.

Moving south to the Middle Peninsula of Virginia, the similarities between well proportions by aquifer are notable for Essex and Middlesex Counties. The largest difference in the well-screen distribution is the generally shallower charac-teristic of the distribution in Essex County, which is up-dip of Middlesex County; thus, the available aquifers are located at higher elevations. The distribution among aquifers in Essex

Table 10. Number of sampled domestic wells assigned to each aquifer in the Virginia Coastal Plain localities for which data were collected.

[SURF, surficial aquifer; YTCZ, Yorktown confining zone; YEAQ, Yorktown-Eastover aquifer; SMAQ, Saint Marys aquifer; PPAQ, Piney Point aquifer; AQAQ, Aquia aquifer; VBAQ, Virginia Beach aquifer; POCZ, Potomac confining zone; POAQ, Potomac aquifer; BSMT, basement]

Locality (fig. 1)	Sample number	SURF	YTCZ	YEAQ	SMAQ	PPAQ	AQAQ	VBAQ	POCZ	POAQ	BSMT
Accomack County	96	0	0	96	0	0	0	0	0	0	0
Caroline County	122	92	0	0	0	0	4	0	7	18	1
Charles City County	81	53	0	0	0	2	10	0	1	15	0
Chesapeake, City of	103	7	10	85	0	0	1	0	0	0	0
Essex County	95	37	0	0	0	10	32	0	3	13	0
Gloucester County	96	0	7	83	0	6	0	0	0	0	0
Greensville County	51	41	0	0	0	0	0	0	0	0	13
Hanover County	110	47	0	0	0	0	8	0	4	51	0
Henrico County	90	59	0	0	0	0	1	0	0	30	0
Isle of Wight County	123	7	23	2	0	1	9	0	2	79	0
James City County	72	0	1	7	0	20	34	0	0	10	0
King and Queen County	109	33	4	0	0	33	28	0	1	10	0
King George County	101	13	0	0	0	0	13	0	5	70	0
King William County	107	48	0	0	0	3	25	0	2	29	0
Lancaster County	97	20	3	2	0	23	12	0	0	37	0
Mathews County	106	2	1	103	0	0	0	0	0	0	0
Middlesex County	102	8	21	38	0	13	11	0	0	11	0
New Kent County	98	15	0	0	0	19	41	0	1	22	0
Northampton County	115	14	0	101	0	0	0	0	0	0	0
Northumberland County	110	6	10	1	0	37	8	0	2	46	0
Prince George County	102	0	1	71	0	0	0	0	8	22	0
Richmond County	93	18	0	0	0	45	29	0	0	1	0
Southampton County	123	24	1	4	0	0	3	0	11	80	0
Suffolk, City of	101	9	22	3	3	0	2	5	24	33	0
Surry County	107	0	28	37	0	0	5	0	8	29	0
Sussex County	86	0	38	30	0	0	0	0	1	17	0
Virginia Beach, City of	96	23	14	59	0	0	0	0	0	0	0
Westmoreland County	113	42	0	0	0	15	45	0	2	9	0
York County	38	0	0	28	0	10	0	0	0	0	0
Total number of wells	**2,846**	**618**	**184**	**750**	**3**	**237**	**321**	**5**	**82**	**632**	**14**

Table 11. Estimated proportions of sampled domestic wells assigned to each aquifer in the Virginia Coastal Plain localities for which data were collected.

[SURF, surficial aquifer; YTCZ, Yorktown confining zone; YEAQ, Yorktown-Eastover aquifer; SMAQ, Saint Marys aquifer; PPAQ, Piney Point aquifer; AQAQ, Aquia aquifer; VBAQ, Virginia Beach aquifer; POCZ, Potomac confining zone; POAQ, Potomac aquifer; BSMT, basement. Sum of proportions for some localities may not equal 1.000 because of rounding]

Locality (fig. 1)	Sample number	SURF	YTCZ	YEAQ	SMAQ	PPAQ	AQAQ	VBAQ	POCZ	POAQ	BSMT
Accomack County	96	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Caroline County	122	0.754	0.000	0.000	0.000	0.000	0.033	0.000	0.057	0.148	0.008
Charles City County	81	0.654	0.000	0.000	0.000	0.025	0.123	0.000	0.012	0.185	0.000
Chesapeake, City of	103	0.068	0.097	0.825	0.000	0.000	0.010	0.000	0.000	0.000	0.000
Essex County	95	0.389	0.000	0.000	0.000	0.105	0.337	0.000	0.032	0.137	0.000
Gloucester County	96	0.000	0.073	0.865	0.000	0.063	0.000	0.000	0.000	0.000	0.000
Greensville County	51	0.759	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.241
Hanover County	110	0.427	0.000	0.000	0.000	0.000	0.073	0.000	0.036	0.464	0.000
Henrico County	90	0.656	0.000	0.000	0.000	0.000	0.011	0.000	0.000	0.333	0.000
Isle of Wight County	123	0.057	0.187	0.016	0.000	0.008	0.073	0.000	0.016	0.642	0.000
James City County	72	0.000	0.014	0.097	0.000	0.278	0.472	0.000	0.000	0.139	0.000
King and Queen County	109	0.303	0.037	0.000	0.000	0.303	0.257	0.000	0.009	0.092	0.000
King George County	101	0.129	0.000	0.000	0.000	0.000	0.129	0.000	0.050	0.693	0.000
King William County	107	0.449	0.000	0.000	0.000	0.028	0.234	0.000	0.019	0.271	0.000
Lancaster County	97	0.206	0.031	0.021	0.000	0.237	0.124	0.000	0.000	0.381	0.000
Mathews County	106	0.019	0.009	0.972	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Middlesex County	102	0.078	0.206	0.373	0.000	0.127	0.108	0.000	0.000	0.108	0.000
New Kent County	98	0.153	0.000	0.000	0.000	0.194	0.418	0.000	0.010	0.224	0.000
Northampton County	115	0.122	0.000	0.878	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Northumberland County	110	0.055	0.091	0.009	0.000	0.336	0.073	0.000	0.018	0.418	0.000
Prince George County	102	0.000	0.010	0.696	0.000	0.000	0.000	0.000	0.078	0.216	0.000
Richmond County	93	0.194	0.000	0.000	0.000	0.484	0.312	0.000	0.000	0.011	0.000
Southampton County	123	0.195	0.008	0.033	0.000	0.000	0.024	0.000	0.089	0.650	0.000
Suffolk, City of	101	0.089	0.218	0.030	0.030	0.000	0.020	0.050	0.238	0.327	0.000
Surry County	107	0.000	0.262	0.346	0.000	0.000	0.047	0.000	0.075	0.271	0.000
Sussex County	86	0.000	0.442	0.349	0.000	0.000	0.000	0.000	0.012	0.198	0.000
Virginia Beach, City of	96	0.240	0.146	0.615	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Westmoreland County	113	0.372	0.000	0.000	0.000	0.133	0.398	0.000	0.018	0.080	0.000
York County	38	0.000	0.000	0.737	0.000	0.263	0.000	0.000	0.000	0.000	0.000
All localities		**0.217**	**0.065**	**0.264**	**0.001**	**0.083**	**0.113**	**0.002**	**0.029**	**0.222**	**0.005**

Table 12. Estimated self-supplied domestic withdrawals in 2000 by aquifer in Virginia Coastal Plain localities for which data were collected.

[SURF, surficial aquifer; YTCZ, Yorktown confining zone; YEAQ, Yorktown-Eastover aquifer; SMAQ, Saint Marys aquifer; PPAQ, Piney Point aquifer; AQAQ, Aquia aquifer; VBAQ, Virginia Beach aquifer; POCZ, Potomac confining zone; POAQ, Potomac aquifer; BSMT, basement; Mgal/d, million gallons per day. Units of estimated withdrawal values are million gallons per day]

Locality (fig. 1)	SURF	YTCZ	YEAQ	SMAQ	PPAQ	AQAQ	VBAQ	POCZ	POAQ	BSMT	Total (Mgal/d)
Accomack County	0.00	0.00	1.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.42
Caroline County	0.75	0.00	0.00	0.00	0.00	0.03	0.00	0.06	0.15	0.01	1.00
Charles City County	0.30	0.00	0.00	0.00	0.01	0.06	0.00	0.01	0.09	0.00	0.46
Chesapeake, City of	0.18	0.26	2.18	0.00	0.00	0.03	0.00	0.00	0.00	0.00	2.64
Essex County	0.20	0.00	0.00	0.00	0.05	0.17	0.00	0.02	0.07	0.00	0.51
Gloucester County	0.00	0.14	1.62	0.00	0.12	0.00	0.00	0.00	0.00	0.00	1.87
Greensville County	0.48	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.15	0.63
Hanover County	0.81	0.00	0.00	0.00	0.00	0.14	0.00	0.07	0.87	0.00	1.88
Henrico County	1.54	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.78	0.00	2.35
Isle of Wight County	0.06	0.20	0.02	0.00	0.01	0.08	0.00	0.02	0.67	0.00	1.05
James City County	0.00	0.02	0.13	0.00	0.37	0.63	0.00	0.00	0.18	0.00	1.33
King and Queen County	0.14	0.02	0.00	0.00	0.14	0.12	0.00	0.00	0.04	0.00	0.47
King George County	0.03	0.00	0.00	0.00	0.00	0.03	0.00	0.01	0.16	0.00	0.23
King William County	0.31	0.00	0.00	0.00	0.02	0.16	0.00	0.01	0.19	0.00	0.69
Lancaster County	0.08	0.01	0.01	0.00	0.10	0.05	0.00	0.00	0.16	0.00	0.41
Mathews County	0.01	0.01	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.65
Middlesex County	0.04	0.12	0.21	0.00	0.07	0.06	0.00	0.00	0.06	0.00	0.56
New Kent County	0.11	0.00	0.00	0.00	0.14	0.30	0.00	0.01	0.16	0.00	0.71
Northampton County	0.08	0.00	0.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.64
Northumberland County	0.03	0.05	0.01	0.00	0.19	0.04	0.00	0.01	0.24	0.00	0.57
Prince George County	0.00	0.01	0.71	0.00	0.00	0.00	0.00	0.08	0.22	0.00	1.02
Richmond County	0.08	0.00	0.00	0.00	0.20	0.13	0.00	0.00	0.00	0.00	0.42
Southampton County	0.12	0.00	0.02	0.00	0.00	0.01	0.00	0.05	0.40	0.00	0.61
Suffolk, City of	0.11	0.27	0.04	0.04	0.00	0.02	0.06	0.29	0.40	0.00	1.22
Surry County	0.00	0.10	0.13	0.00	0.00	0.02	0.00	0.03	0.10	0.00	0.38
Sussex County	0.00	0.05	0.04	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.11
Virginia Beach, City of	0.74	0.45	1.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.10
Westmoreland County	0.20	0.00	0.00	0.00	0.07	0.21	0.00	0.01	0.04	0.00	0.53
York County	0.00	0.00	2.48	0.00	0.89	0.00	0.00	0.00	0.00	0.00	3.37
Total	**6.41**	**1.69**	**12.10**	**0.04**	**2.38**	**2.32**	**0.06**	**0.67**	**5.01**	**0.16**	**30.84**

County is also very similar to that in King and Queen County, which lies directly to the south and almost along the strike of the hydrogeologic units.

In the similar well distributions in Gloucester and Mathews Counties, the lack of deep withdrawals is a result of the presence of the buried Chesapeake Bay impact crater, which is now known to be the source of brackish ground-water found at depth (McFarland and Bruce, 2005). The small numbers of deeper wells in Gloucester probably are located in the western part of the county and outside of the saline zone.

Farther south on the York-James Peninsula, the differences between the well distributions by aquifer in York and James City Counties may be the result of their somewhat different hydrogeologic settings despite their close proximity, because York County partly overlies the buried impact crater. New Kent, King and Queen, and King William Counties all have somewhat similar well distributions that are likely the result of their close proximity to each other. The causes of apparent small differences in the well distributions are unclear.

Charles City County would be expected to be similar to New Kent because of their close proximity and almost identical hydrogeologic setting, but the Charles City well distribution is characterized by much shallower well depths. A review of the well records reveals that all of the shallow wells in Charles City County are bored wells, although almost every record sampled in New Kent County is for a drilled well; this may indicate that the differences are related to the preferences of the local well driller(s), but perhaps other local conditions have influenced the distribution.

Moving south again, the similarities between the well distributions in Surry and Isle of Wight Counties are very likely the result of their similar hydrogeologic setting. The difference between these two counties is that Isle of Wight is located farther south and east, where the Potomac aquifer becomes thicker and more productive. Therefore, Isle of Wight has a much higher proportion of wells in the Potomac aquifer. Isle of Wight County is very similar in its distribution of withdrawals by aquifer to the City of Suffolk immediately to its south, especially if the Potomac aquifer and Potomac confining zone are considered together. The only difference is caused by the local presence of the deeper Virginia Beach aquifer in Suffolk. The wells and withdrawals in Caroline, Henrico, and Hanover Counties all appear to be split between the unconfined surficial aquifer and the Potomac aquifer, and the Fall Line is close enough that intervening units are thin or nonexistent.

Greensville, Prince George, Sussex, and Southampton Counties in the southwestern section of the Virginia Coastal Plain can be grouped together based on their similar well and aquifer distributions. These counties have wells completed primarily in the shallow surficial aquifer, the Yorktown units, or the Potomac aquifer. The well distribution in Southampton differs somewhat from the others, possibly because its more eastern location makes the thicker Potomac aquifer more attractive to well drillers.

On the Eastern Shore, it was not surprising to find similar distributions of wells and aquifers in Accomack and Northampton Counties. The only real difference is that Northampton County has a few wells in the unconfined system in addition to the Yorktown-Eastover aquifer that is the only confined aquifer containing freshwater on the peninsula. In recent years, the installation of domestic wells in the surficial aquifer has been uncommon on the Eastern Shore because of concerns about both agricultural contamination and the effects of drought.

This discussion has focused primarily on hydrogeologic factors that have influenced well depth and aquifer distribution for domestic wells and withdrawals, but many other factors likely influence the distributions. Local well characteristics also appear to be correlated with variations in family income and household value, available local well drillers and their preferences, and a variety of water-quality issues that are beyond the scope of this report.

Assumptions and Limitations Related to Assigning Domestic Wells and Withdrawals to Aquifers

The overarching assumption for this analysis was that variability in land-surface and aquifer elevations within a locality are smaller than the vertical difference between aquifer units intersected by private domestic wells. If this were completely true, a frequency analysis of collected well depths (or elevations) for each locality would have a multimodal distribution with the number of groupings equal to the number of aquifers and with distinct divisions between the aquifer groups. Examination of the histograms in figure 10 reveals that this is not usually the case. The cumulative uncertainty associated with the estimation techniques used in the analysis of the available data is large enough to cause overlap among the well groupings and complicate the determination of the aquifer associated with each well. This problem could largely be resolved with the addition of accurate well-location data or accurate well-elevation data or both. Even with the limited available data, however, the approximate validity of the assumptions allows a reasonable determination of well proportions by aquifer for most localities.

The assumptions are most valid and the analyses are more robust for localities in which aquifer units typically intersected by domestic wells are thicker and farther apart and variations in land-surface elevation are small. Thus, the relative validity of the assumptions for each locality can be used to evaluate the confidence in assigning wells to aquifers. Because of the approximation used to assign the well-screen elevation from the median elevation for a particular locality, that estimation is more valid where the locality elevation is less variable. Furthermore, the process of comparing screen elevations to hydrogeologic-unit elevations is more valid where the units are less variable and the vertical distance between them is greater. In the Virginia Coastal plain, these ideal conditions generally are more likely to be present in the eastern localities than in other areas.

In the eastern localities, such as Northumberland County, the groupings of well-screen elevations correspond nicely to aquifer elevations. In Northumberland County, the median land-surface elevation is 63 ft (table 5), the range of surface elevations is 183 ft between the smallest and largest values (tables 6, 7), the mean is 58 ft (table 8), and the standard deviation is 41 ft. This means that most elevations in the county are between 20 ft and 100 ft. The difference between the median elevations of the aquifers of interest is well over 100 ft in most cases. Furthermore, the range of elevations across the county for a given aquifer, such as the Potomac, is relatively small. Consequently, regardless of the actual land-surface elevation, a deep well drilled into the Potomac aquifer usually will be classified into the Potomac aquifer in this analysis.

In Hanover County, however, the variability in the land-surface elevation is much larger, with a range of 299 ft between the smallest and largest values (tables 6, 7), although the range of well elevations is smaller. Nonetheless, the vertical separation between the two units used for water supply, the surficial and Potomac aquifers, is large enough to distinguish the wells in each unit.

The analyses are less robust in some of the central Coastal Plain localities, such as King and Queen County, where a number of aquifers are used for water supply, but the vertical separation between the unit tops is small and the land-surface elevation is quite variable. Clearly, a much larger level of uncertainty is associated with the assignment of wells to aquifers in King and Queen County than in Northumberland County, for example. One consideration in the assignment of wells and withdrawals to closely spaced aquifers in localities like King and Queen County is that errors and uncertainties in the closely spaced assignments may balance out.

One way in which localities can be compared is by using maximum and minimum elevation values to identify the total possible variation in land surface or aquifer-unit elevation within each locality. This can be readily done with tables 6 and 7, but this approach overstates the variation because the maximum and minimum values are sensitive to outliers. Perhaps a better evaluation of the assumptions might make use of the frequency distribution of land-surface and aquifer elevations for individual localities. The mean or median value for each surface could be examined along with an error bound based on the variability of each surface. This approach was not taken for this report, but it may be useful in more detailed evaluations of domestic wells within some localities.

Despite the inherent limitations, this analysis provides at least a reasonable approximation of the aquifers used for private domestic supply in each locality and for the entire study area, which is useful for a variety of ground-water investigations. With the implementation of the domestic water-use coefficient, this analysis also provides a method for estimating self-supplied domestic ground-water withdrawals by aquifer, which previously has not been possible.

Spatial Distribution of Self-Supplied Domestic Withdrawals for a Ground-Water Model of the Virginia Eastern Shore

The spatial distribution of self-supplied domestic ground-water withdrawals on the Virginia Eastern Shore Peninsula was characterized in support of a separate effort to analyze the local ground-water flow system at a greater spatial resolution than could be supported by the previously described locality-level analyses. For an ongoing ground-water study of the mostly rural and agricultural Eastern Shore Peninsula of Virginia and a small part of Maryland, self-supplied domestic withdrawals are thought to be important. Therefore, these withdrawal estimates were needed for inclusion in a ground-water model under development for that peninsula. The well and withdrawal data for Accomack and Northampton Counties from this report initially were used, but it became apparent that applying the self-supplied withdrawals evenly across the entire county areas would produce unsatisfactory results. On the sparsely populated Eastern Shore Peninsula, much of the land area is marsh, forest, or agricultural fields, and human populations are unevenly distributed. A scheme was needed to spatially distribute domestic withdrawals in a way that would more closely simulate the population distribution and result in a more accurate representation of domestic wells and withdrawals in the ground-water model.

The methods described in this report for evaluating the proportion of private domestic wells in each aquifer and for calculating self-supplied withdrawals by aquifer provide data necessary for considering the hydrogeologic effects of domestic withdrawals. Because they rely on aggregation, by locality, of sampled well characteristics and the self-supplied population, these estimates are limited to the locality level. For many purposes, such as the Eastern Shore ground-water investigation, locality-level analysis is inadequate because it fails to capture variations in withdrawal distributions at smaller scales that are important in answering more localized questions. The example presented here demonstrates that better spatial resolution can be estimated or simulated even where water-use data are available only at the locality level. The steps involved in this analysis and their relation to the methods and results from other sections of this report are outlined in the flow chart in figure 7.

A ground-water model of the Virginia Eastern Shore Peninsula was initiated to produce an updated tool for evaluating the effects of ground-water withdrawals on the hydrogeologic system. Of particular interest was the problem of potential saltwater intrusion from the Atlantic Ocean and the Chesapeake Bay into the freshwater aquifers that provide the primary water supply for the peninsula. In order to improve on the spatial resolution of the previous Virginia Eastern Shore ground-water model (Richardson, 1994), a smaller model cell size of 1,000 ft was used with improved and updated ground-water modeling software.

The Virginia Eastern Shore ground-water model domain encompasses an area of just under 3,000 mi^2, of which about 980 mi^2 is land. All of Accomack and Northampton Counties in Virginia (totaling 674.2 mi^2) are included, along with parts of Somerset and Worcester Counties in Maryland (306.2 mi^2). The total population of the simulated area was estimated at 73,267 from 2000 census block group data, (U.S. Census Bureau, 2001), and almost 50,000 people (68 percent) are estimated to be self supplied with water from domestic wells, based on data from the USGS Water-Use Information Program (U.S. Geological Survey, 2002).

The model by Richardson (1994) did not simulate the effects of self-supplied domestic withdrawals, but water-use estimates indicate that these withdrawals may be important, especially considering that the withdrawals are mostly from the confined Yorktown-Eastover aquifer. Total withdrawals of ground-water in the Virginia Eastern Shore counties are estimated at over 7 Mgal/d in 2000, and self-supplied domestic withdrawals of approximately 2.74 Mgal/d make up about 29 percent of the total. With portions of Somerset and Worcester Counties in Maryland included within the boundary of the model, total estimated self-supplied domestic withdrawals for this area were estimated to be 3.74 Mgal/d. This total includes 2.00 Mgal/d for Accomack County, 0.74 Mgal/d for Northampton County, 0.71 Mgal/d for Somerset County, and 0.30 Mgal/d for Worcester County.

In order to estimate the distribution of domestic withdrawals, it was first necessary to estimate the spatial distribution of the self-supplied population for each county in a more realistic way using a GIS. The 2000 U.S. Census was very helpful in this respect, providing population and spatial data at the level of the census block group (U.S. Census Bureau, 2001), which is an improvement in resolution beyond the county level (fig. 11). The total population for each census block group, however, includes both the self-supplied and publicly supplied populations.

To eliminate the population in each census block group supplied with municipal drinking water, the public-supply areas were estimated by using city boundaries with additional adjustments based on limited local knowledge (fig. 11). Within these public-supply areas, point data on the publicly supplied population, available from the U.S. Environmental Protection Agency (2006), were used to subtract the publicly supplied population from the total population of the census block groups. This difference is the self-supplied domestic population for each census block group, which is zero for some census block groups in public-supply areas.

Even with the self-supplied domestic population defined by census block group, better spatial resolution was needed. Application of domestic withdrawals evenly across entire census block groups would have resulted in simulated domestic withdrawals in unpopulated areas, including marshes, forests, and agricultural fields. As a result, high-resolution spatial data on road locations were used to further constrain the population distribution.

To identify road locations, GIS data that included all roads were used, including even small unpaved roads that were found to be important to the validity of this analysis (fig. 11). From these highly detailed road data, a road-density analysis was completed using GIS software, and the road-density calculation was used to distribute the population of each census block group among the ground-water model cells that are not located in public-supply areas. This resulted in a substantially more detailed distribution of the self-supplied population than is shown in figure 11.

The self-supplied domestic water-use coefficient of 75 gal/d for Virginia was applied to the estimated distribution of the self-supplied population to approximate the distribution of self-supplied withdrawals for the Eastern Shore Peninsula (fig. 12). Self-supplied domestic withdrawals for the model domain totaled 3.74 Mgal/d. While this distribution is an approximation, it is a more detailed and realistic depiction of domestic withdrawals than is available from any other source.

Sampled domestic-well data were then used to apply the estimated self-supplied withdrawals to individual aquifers. On the Eastern Shore Peninsula, the unconfined surficial aquifer overlies the Yorktown-Eastover aquifer, which was subdivided for the purposes of more localized analysis into the upper, middle, and lower Yorktown-Eastover aquifers (Richardson, 1994). This subdivision is not necessarily supported by more recent analyses of the hydrogeology, but it was used because the Richardson study (1994) is the most current in-depth study of the hydrogeology of the Eastern Shore Peninsula of Virginia. Aquifers below the Yorktown-Eastover aquifers contain saline water and are not penetrated by any production wells.

Estimated well-screen elevations were compared to estimated aquifer elevations, as described earlier in this report, and sampled private domestic wells were assigned aquifer designations so that the spatially distributed estimated withdrawals could be applied to individual aquifers. Analyses of sampled well records in Accomack County revealed that no wells intersected the surficial aquifer, so all wells were assigned to the three aquifers of the subdivided Yorktown-Eastover aquifer. Of the sampled wells, 42 percent intersect the upper Yorktown-Eastover aquifer, 40 percent intersect the middle Yorktown-Eastover aquifer, and 18 percent intersect the lower Yorktown-Eastover aquifer. Similar analyses of well records in Northampton County indicated that 12 percent of the sampled wells intersect the surficial aquifer, 45 percent intersect the upper Yorktown-Eastover aquifer, 36 percent intersect the middle Yorktown-Eastover aquifer, and 7 percent intersect the lower Yorktown-Eastover aquifer. For the purposes of this study, the two Maryland counties were assumed to have similar well distributions as those in adjacent Accomack County.

Not surprisingly, the distribution of wells by aquifer is quite similar between Northampton and Accomack Counties. However, Northampton County appears to have a smaller

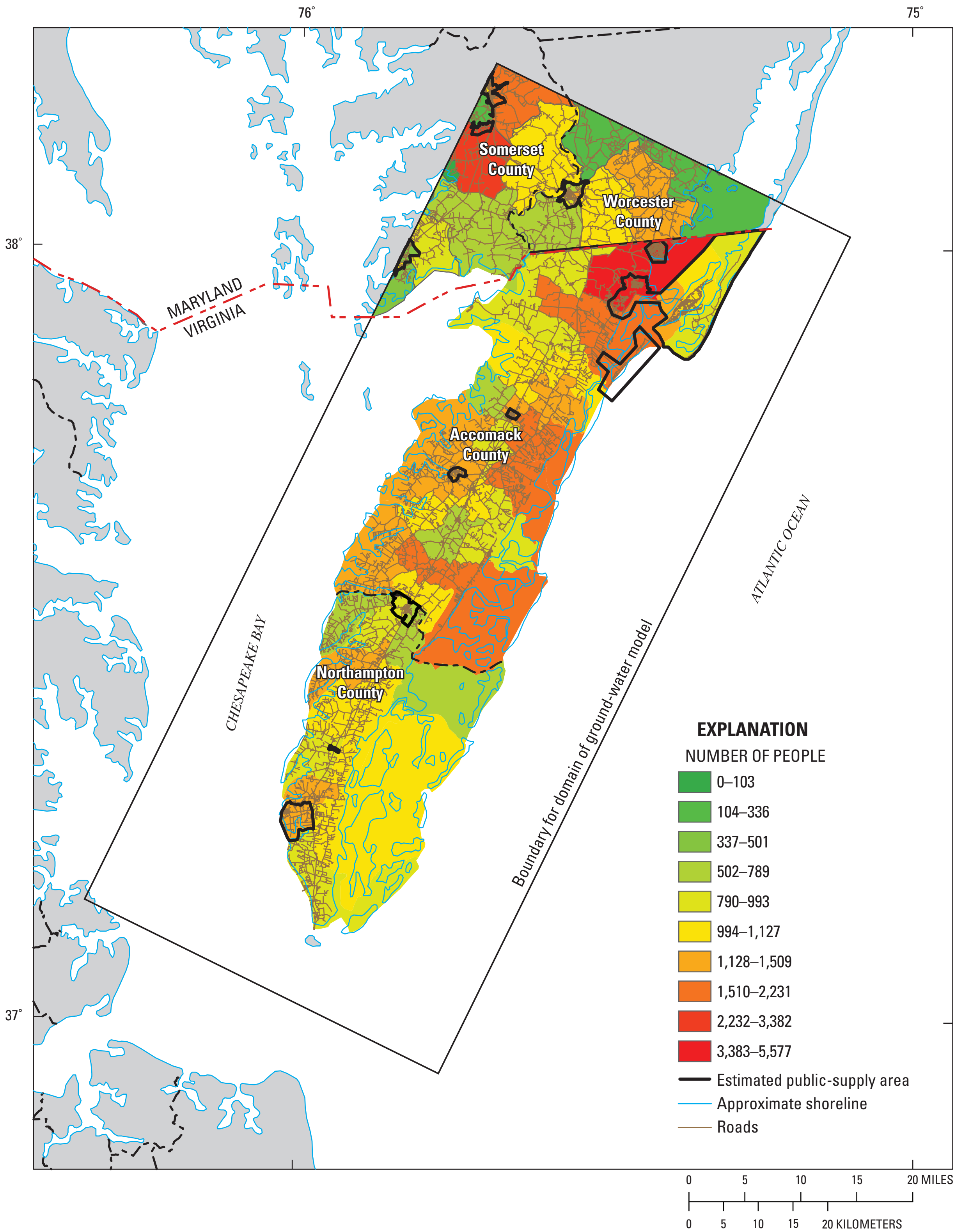

Figure 11. Population data by census block group in 2000 (derived from U.S. Census Bureau, 2001; U.S. Census Bureau, 2003a), estimated public water-supply areas, and road features in the Virginia Eastern Shore ground-water model domain.

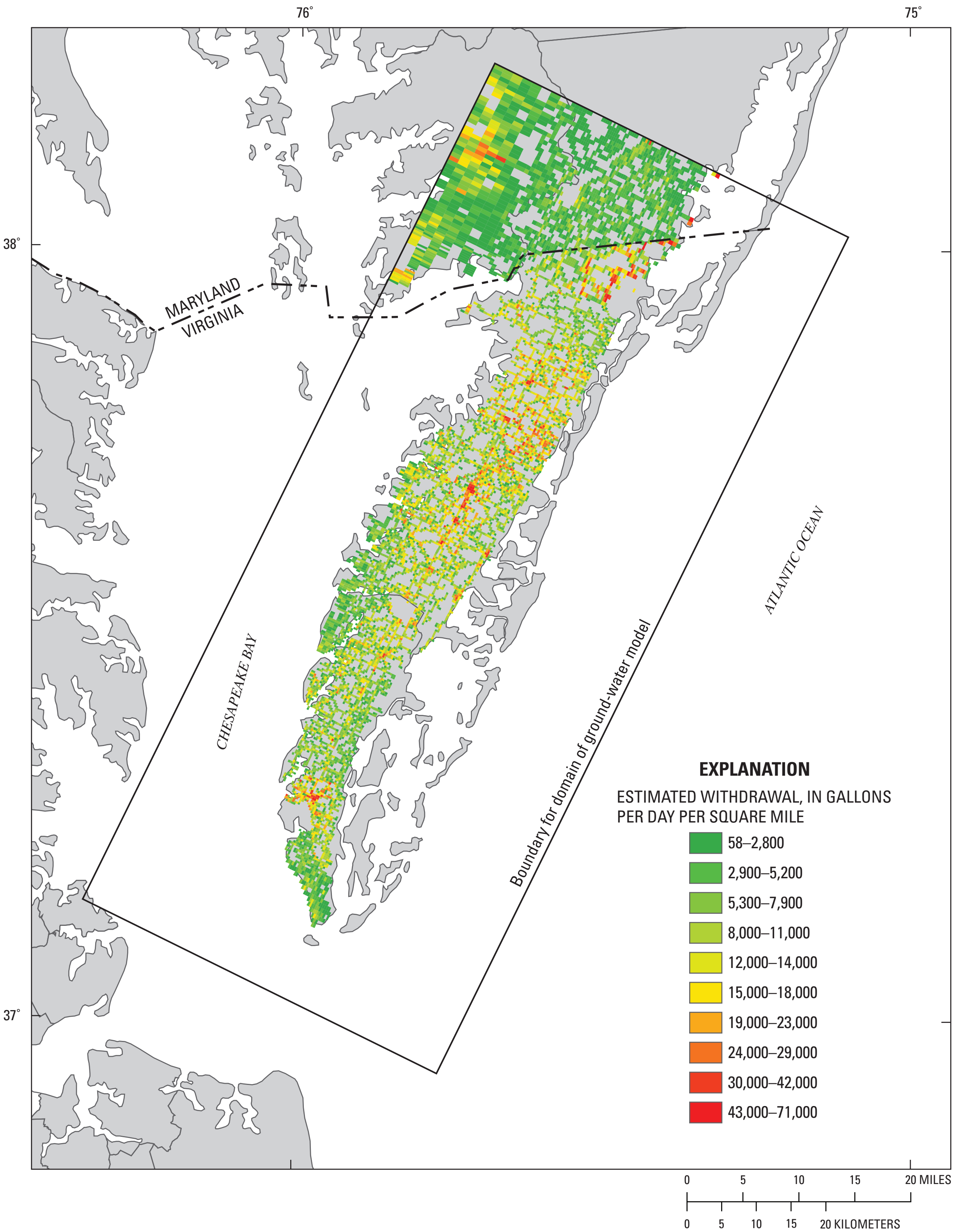

Figure 12. Estimated self-supplied domestic withdrawals of ground water in the Virginia Eastern Shore in 2000, by ground-water model grid cell.

proportion of wells in the lower part of the Yorktown-Eastover aquifer and a larger proportion of wells in the surficial aquifer. This may be the result of less fresh ground water available at depth on the southern part of the peninsula.

The estimated proportion of wells intersecting each aquifer in each county was used to estimate withdrawals from each of the aquifers for the Eastern Shore ground-water model. Total withdrawals of 3.74 Mgal/d in 2000 were composed of 0.09 Mgal/d from the surficial aquifer, 1.59 Mgal/d from the upper Yorktown-Eastover aquifer, 1.47 Mgal/d from the middle Yorktown-Eastover aquifer, and 0.59 Mgal/d from the lower Yorktown-Eastover aquifer. These withdrawals were spatially distributed in the model grid using the census block group and road density analyses described previously.

The example of the application of self-supplied ground-water withdrawals to the Eastern Shore ground-water model demonstrates how these well data, sampled by county, can be applied at greater resolution using other spatial data, such as population and road distributions. In this example, the well data were not spatially resolved beyond the county level. However, more localized studies using well data for smaller areas, such as individual tax plats, could provide even more detailed information on variations in water use by aquifer within a county. In a study in which wells could be located exactly, these analyses would be even more powerful.

Summary and Conclusions

Self-supplied domestic withdrawals of ground water, estimated to be approximately 38.5 Mgal/d for the year 2000, are a substantial portion (about 28 percent) of total ground-water withdrawals in the Coastal Plain of Virginia. Little research previously has been done to comprehensively describe the nature and distribution of these withdrawals.

Over 500,000 people, composing 15 percent of the total population of the Virginia Coastal Plain, depend on self-supplied domestic withdrawals of ground water. In some rural localities of eastern Virginia, these withdrawals provide almost all of the available water supply. Estimates based on population analyses indicate that about 200,000 private domestic wells currently may be in use in the Virginia Coastal Plain. Despite the importance of this resource, little has been known previously about the locations of private domestic wells or the aquifers from which domestic withdrawals are taken.

Previously published ground-water models of the Virginia Coastal Plain have not accounted for domestic withdrawals, because the withdrawals are difficult to measure and because of the assumption that the hydrogeologic effects of these withdrawals are insignificant. Mounting evidence indicates, however, that an understanding of the magnitude and distribution of these withdrawals may be critical to understanding ground-water flow in the Coastal Plain of Virginia.

This study included a comprehensive assessment of construction characteristics for private domestic wells based on a survey of 2,846 wells in 29 Virginia Coastal Plain localities known to have appreciable self-supplied populations. The results of this assessment indicate that the depth distribution of these wells may be more varied than previously believed. Domestic-well depths range from 14 to 865 ft below land surface in the records sampled, with a median of 141.5 ft and a mean of 202.2 ft.

A technique presented here for estimating domestic-well screen elevations in the absence of definitive elevation or location data allows these wells to be referenced to a newly revised configuration of the Virginia Coastal Plain hydrogeology and, thereby, assigned to aquifers. This estimation technique reveals that only 22 percent of the domestic wells in the Virginia Coastal Plain are completed in the unconfined surficial aquifer. On the other hand, the 78 percent of wells completed in the confined aquifers includes 33 percent in the Yorktown-Eastover aquifer or Yorktown confining zone, 8 percent in the Piney Point aquifer, 11 percent in the Aquia aquifer, and 25 percent in the Potomac aquifer and confining zone. A few remaining wells, about 1 percent, were found to intersect the Saint Marys aquifer, the Virginia Beach aquifer, or crystalline bedrock beneath Coastal Plain sediments near the Fall Line. These results directly contradict the previous assumption by some water-resources experts that domestic withdrawals are unimportant to regional ground-water flow because they are taken from the unconfined aquifer and quickly replaced by return flow through home septic systems. Based on this new information about domestic wells, withdrawals from the confined aquifers of the Virginia Coastal Plain actually make up 78 percent of the domestic total, or about 30 Mgal/d. Almost 10 Mgal/d of domestic withdrawals are from the Potomac aquifer across the Coastal Plain.

The relatively large rate of total self-supplied domestic ground-water withdrawals from the confined aquifer system indicates the importance of considering domestic withdrawals in any complete analysis of Virginia Coastal Plain ground-water resources, because these deep domestic withdrawals represent an essentially permanent removal of water from the regional flow system. The total rate of domestic ground-water withdrawals is similar to that of the large, centralized municipal and industrial withdrawals, though results of ground-water flow modeling indicate that the effects of these withdrawals may be quite different. Ongoing ground-water modeling studies that incorporate the results of this investigation may reveal more about the effect of domestic withdrawals on the regional ground-water flow system. Furthermore, substantial local variations in the distribution of domestic withdrawals by aquifer indicate that a thorough investigation of domestic wells and withdrawals is needed in any comprehensive, local, water-resources assessment.

An example of the incorporation of self-supplied domestic withdrawals to the Eastern Shore ground-water model demonstrates the application of the data and analyses presented here and introduces a GIS technique for distributing domestic withdrawals spatially based on geographic data. The importance of considering domestic withdrawals as part of the regional ground-water flow system may be revealed further by the results of ongoing modeling efforts for the Eastern Shore Peninsula and for the Virginia Coastal Plain as a whole, but the techniques for distributing estimated withdrawals spatially also could be useful in many other applications related to water-resource assessment and management.

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Pope and others—**Private Domestic-Well Characteristics and Domestic Withdrawals among Aquifers in the Virginia Coastal Plain**—Scientific Investigations Report 2007–5250

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