In cooperation with the
Maryland Geological Survey
and the
Maryland Department of the Environment

# A Science Plan for a Comprehensive Regional Assessment of the Atlantic Coastal Plain Aquifer System in Maryland

Open-File Report 2007–1205

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

**Cover.** Clockwise from upper left: [1] tidal stream in Atlantic Coastal Plain, [2] technician making ground-water-level measurement, [3] spray irrigation system with a ground-water source, and [4] large capacity pumping well. All photographs courtesy of USGS.

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By Robert J. Shedlock, David W. Bolton, Emery T. Cleaves,
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**U.S. Department of the Interior**
**U.S. Geological Survey**

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# Conversion Factors and Datums

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| inch (in.) | 2.54 | centimeter (cm) |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| | Area | |
| acre | 0.4047 | hectare (ha) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| | Volume | |
| gallon (gal) | 3.785 | liter (L) |
| | Flow rate | |
| foot per year (ft/yr) | 0.3048 | meter per year (m/yr) |
| gallon per minute (gal/min) | 0.06309 | liter per second (L/s) |
| 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) |
| | Transmissivity* | |
| foot squared per day ($ft^2$/d) | 0.09290 | meter squared per day ($m^2$/d) |

*Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

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

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

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## Abstract

The Maryland Coastal Plain region is, at present, largely dependent upon ground water for its water supply. Decades of increasing pumpage have caused ground-water levels in parts of the Maryland Coastal Plain to decline by as much as 2 feet per year in some areas of southern Maryland. Continued declines at this rate could affect the long-term sustainability of ground-water resources in Maryland's heavily populated Coastal Plain communities and the agricultural industry of the Eastern Shore.

In response to a recommendation in 2004 by the Advisory Committee on the Management and Protection of the State's Water Resources, the Maryland Geological Survey and the U.S. Geological Survey have developed a science plan for a comprehensive assessment that will provide new scientific information and new data management and analysis tools for the State to use in allocating ground water in the Coastal Plain. The comprehensive assessment has five goals aimed at improving the current information and tools used to understand the resource potential of the aquifer system: (1) document the geologic and hydrologic characteristics of the aquifer system in the Maryland Coastal Plain and appropriate areas of adjacent states; (2) conduct detailed studies of the regional ground-water-flow system and water budget for the aquifer system; (3) improve documentation of patterns of water quality in all Coastal Plain aquifers, including the distribution of saltwater; (4) enhance ground-water-level, streamflow, and water-quality-monitoring networks in the Maryland Coastal Plain; and (5) develop science-based tools to facilitate sound management of the ground-water resources in the Maryland Coastal Plain.

The assessment, as designed, will be conducted in three phases and if fully implemented, is expected to take 7 to 8 years to complete. Phase I, which was initiated in January 2006, is an effort to assemble all the information and investigation tools needed to do a more comprehensive assessment of the aquifer system. The work will include updating the hydrogeologic framework, developing a Geographic Information System-based aquifer information system, refinement of water-use information, assessment of existing water-quality data, and development of detailed plans for ground-water-flow and management models.

Phase II is an intensive study phase during which a regional ground-water-flow model will be developed and calibrated for the entire region of Maryland in the Atlantic Coastal Plain as well as appropriate areas of Delaware and Virginia. The model will be used to simulate flow and water levels in the aquifer system and to study the water budget of the system. The model analysis will be based on published information but will be supplemented with field investigations of recharge and leakage in the aquifer system. Localized and finely discretized ground-water-flow models that are embedded in the regional model will be developed for selected areas of heavy withdrawals. Other modeling studies will be conducted to better understand flow in the unconfined parts of the aquifer system and to support the recharge studies. Phase II will also include selected water-quality studies and a study to determine how hydrologic and water-quality-monitoring networks need to be enhanced to appropriately assess the sustainability of the Coastal Plain aquifer system.

Phase III will be largely devoted to the development and application of a ground-water optimization model. This model will be linked to the ground-water-flow model to create a model package that can be used to test different water-management scenarios. The management criteria that will be used to develop these scenarios will be determined in consultation with a variety of state and local stakeholders and policy makers in Phases I and II of the assessment.

The development of the aquifer information system is a key component of the assessment. The system will store all relevant aquifer data and appropriate ancillary data in a spatially referenced database. This system will be designed to serve the needs of both water managers and scientific investigators. The system, when fully developed, is envisioned as a web-based tool and will facilitate the use of ground-water management models for evaluation of a variety of water-management strategies.

# Introduction

Unconsolidated sediments that underlie the Atlantic Coastal Plain form a complex aquifer system that underlies more than half of the land area of the State of Maryland (fig. 1). Ground water is an important, and in some areas, the sole source of water supply for about 1.5 million people in this area. Except for suburban areas around Washington, D.C., this aquifer system is the sole source of water supply for most of southern Maryland and nearly all of the Eastern Shore, and is also an important water-supply source for the counties northeast of Baltimore, along the western shore of Chesapeake Bay. This system extends into neighboring states and is extensively used as a source of water supply in Delaware, New Jersey, and Virginia.

In 2004, a report by the Advisory Committee on the Management and Protection of the State's Water Resources recommended a comprehensive study of the sustainability of the entire Atlantic Coastal Plain aquifer system in Maryland (State of Maryland, 2004). In response to this recommendation, the Maryland Geological Survey (MGS) and the U.S. Geological Survey (USGS) have developed a science plan for a comprehensive assessment that will provide new scientific information and new data management and analysis tools for the State to use in allocating ground water in the Coastal Plain.

While its water balance is critical for water supply, the Coastal Plain aquifer system also provides the base flow for virtually all the streams that originate in the Atlantic Coastal Plain. Ground water from the aquifer system also discharges to Chesapeake Bay and the Atlantic Coastal Bays and to many freshwater and saltwater wetlands in the State. Water discharging from the aquifer system is critical to many ecological and aesthetic resources. The sustainability of this aquifer system, therefore, needs to be defined in terms of acceptable impacts of withdrawals on human health, the welfare of the region's population, and a variety of natural resources in this large coastal area (Alley and others 1999).

This report presents a general plan for conducting a comprehensive assessment of the Atlantic Coastal Plain aquifer system in Maryland and adjacent areas of neighboring states. The report presents the scientific and water-management issues driving this assessment, the science goals of the assessment, and an overview of the implementation plans and the timing of the general tasks in the implementation plan. This report is intended to serve as a general blueprint for a long-term comprehensive assessment with several major study components. It will be used as a guide for the preparation of more detailed proposals that will be subsequently developed for the various investigative activities described under the science goals in this report.

## Water Management Issues and Assessment Questions

> "Growing communities, industries, agriculture, energy production, and critical ecosystems depend upon water being available in adequate quantity and suitable quality." (State of Maryland, 2004).

Water and natural-resource managers in Maryland are faced with a variety of specific management issues and information needs. Officials from ground-water management and regulatory agencies as well as State and local planners need to know how much ground water is available in the different areas of the Atlantic Coastal Plain for various water demands. These demands include public and domestic water supply, as well as agricultural, industrial, and electric power generation use. Officials also need to understand where and when continued extraction of ground water may cause other problems, such as land subsidence or undesirable changes in water quality that would require additional treatment or limit the potential uses and (or) the aesthetic appeal of the water resource. Natural-resource managers need to know if withdrawals are affecting the base flow of streams or the water budgets and seasonal water levels in wetlands.

In Maryland, ground-water withdrawals are managed by the Maryland Department of the Environment (MDE) through the Water Supply Program. Although studies of individual aquifers or multi-aquifer subregions have been done, the availability of more comprehensive and interactive tools would enhance MDE's capability to make science-based management and permitting decisions in the future. Specifically, MDE needs information systems and simulation tools to evaluate the effects of increased withdrawals on the entire aquifer system in important subregions and throughout the Maryland Coastal Plain. Furthermore, these tools need to account for Coastal Plain aquifers that extend into and are being used for water supply in adjacent states.

The initial report of the Advisory Committee on the Management and Protection of the State's Water Resources (State of Maryland, 2004) emphasized the need for increased communication and interaction among water managers and State and local planners. This improved communication is designed to ensure that future water demands can be met without placing excessive stress on the quantity and quality of the available water resources. The collective community of resource managers and planners are faced with a number of issues and challenges including:

(1) Determining the impacts of future withdrawals on water levels and movement of water through confining layers from overlying and underlying aquifers in each of the pumped aquifers;
(2) Estimating water availability and demand for each aquifer to ensure that water-supply needs of local development do not exceed the actual sustainability of water in the development area;

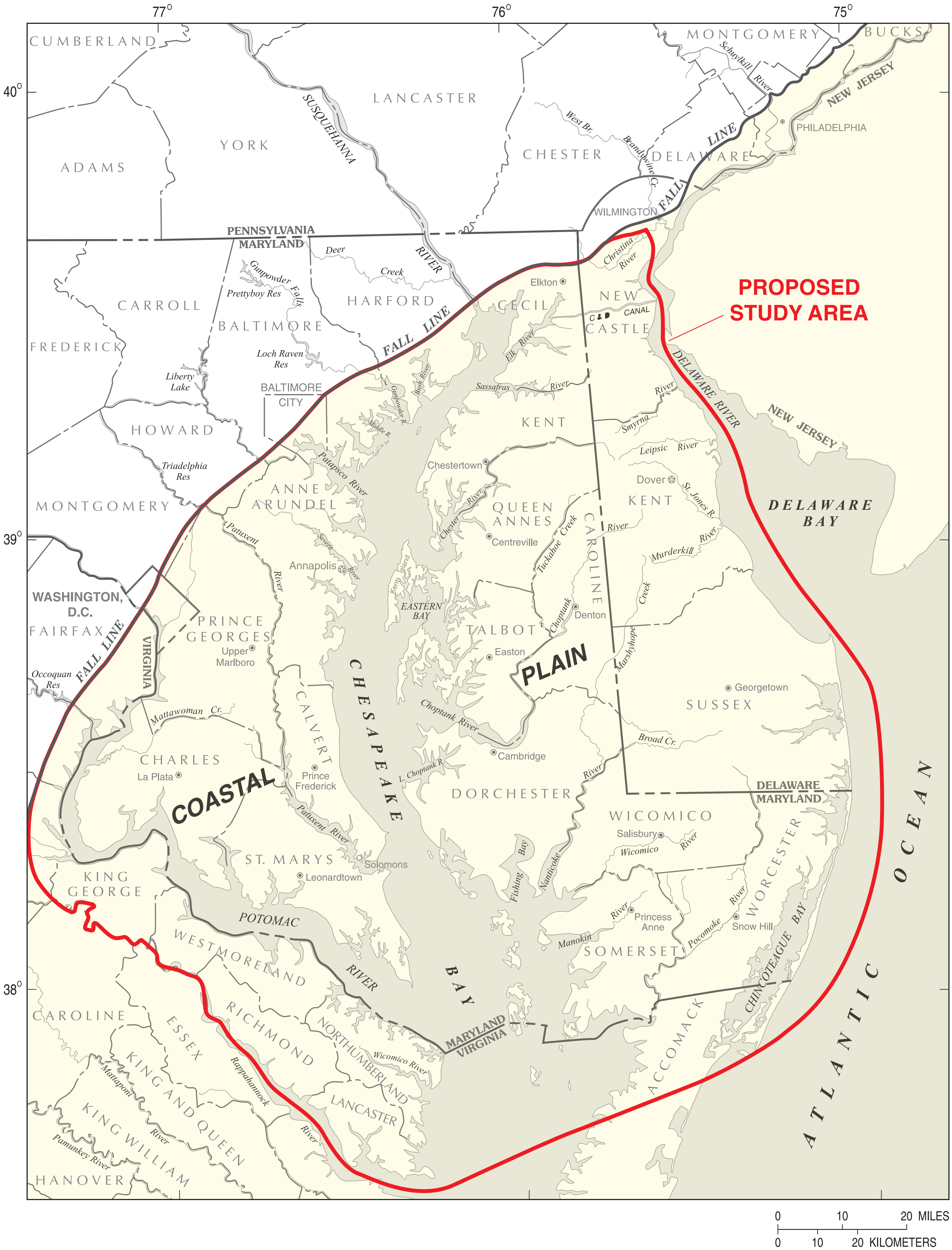


**Figure 1.** Proposed study area in Maryland and adjacent states.

(3) Understanding possible changes in water-quality patterns in aquifers induced by withdrawals;
(4) Developing source-water protection plans for confined aquifers;
(5) Incorporating water-availability estimates and source-water protection plans into water and sewer plans for local development;
(6) Understanding how significant withdrawals near state boundaries affect the availability and quality of water in adjacent states; and
(7) Understanding how withdrawals can affect the ground-water components of the water budgets of stream and wetland ecosystems.

Addressing these issues will require the development of new information and modeling tools and new data-management systems. Some of the more important developments and improvements that need to be accomplished include:

(1) A Geographic Information System (GIS)-based electronic aquifer information system for the storage, management, retrieval, and visualization of key information from boreholes, wells, aquifers, and confining layers;
(2) Improved simulation tools to manage and optimize the use of ground-water resources in the Coastal Plain aquifer system;
(3) Adequate monitoring networks for recognition of patterns and trends in ground-water levels, ground-water quality, and streamflow so that changes in the aquifer system can be observed at early stages of development;
(4) Improved information on water use that can be incorporated into the simulation models;
(5) A better information system on domestic wells to archive and retrieve location data, aquifers utilized, and consistent reporting of well abandonment; and
(6) A better understanding of the potential for saltwater intrusion from brackish tidal waters and seawater in coastal areas, and from saline formation water in the deeper parts of the aquifer system.

These new tools and information would be used primarily by water managers and scientists, but could also be used by planners and decision makers. The tools will be designed to be updated as new hydrogeologic, water-quality, and water-use data become available.

## Needs for a Comprehensive Regional Assessment

Concern over the sustainability of the Coastal Plain aquifer system for water supply in Maryland is the major driver for a comprehensive assessment of the system. This concern is motivated not only by significant declines in water levels but also by water-quality problems in parts of the aquifer system that may be exacerbated by increased withdrawals. There is also a recognition that a regional assessment will produce tools and information that can be used by resource managers and planners.

### Significant Declines in Ground-Water Levels

Water levels in confined aquifers in some parts of the Atlantic Coastal Plain in Maryland have been declining for several decades (fig. 2). The declines are especially large in southern Maryland and parts of the Eastern Shore, where the population is projected to grow significantly in the next 20 to 30 years. Ground-water levels are declining by an average of about 2 feet per year in some of these aquifers. Furthermore, the natural ground-water-flow system has been modified so that the water in large areas of these aquifers is now flowing toward production wells in the major pumping centers (fig. 3), rather than toward the natural discharge areas such as the major streams, Chesapeake Bay and Delaware Bays, Coastal Bays, and the Atlantic Ocean. In addition, the diversion of water away from natural discharge zones is likely drawing saline formation water from deeper parts of the aquifer system and from bay water and ocean water closer to the pumping centers (Achmad and Wilson, 1993; Fleck and Andreasen, 1996). In areas affected by saltwater intrusion, advanced water-treatment technologies, such as reverse osmosis and ultrafiltration, may be required to maintain the potability of the water supply.

Continued water-level declines at the current rates could affect the long-term sustainability of ground-water resources in Maryland's heavily populated Coastal Plain communities and the agricultural industry of the Eastern Shore. Water budgets and ecological resources in wetlands and coastal areas could also be affected. Furthermore, water-level declines in major withdrawal centers in each of the Mid-Atlantic States of Maryland, Delaware, Virginia, and New Jersey may extend into neighboring states, underscoring the eventual need for interstate information sharing and regional water planning.

### Compromised Water Quality in Some Areas

Several major water-quality problems exist in the Coastal Plain aquifer system. Some parts of the confined aquifers in the system have been affected by intrusion of brackish or saline water. These areas are generally along the coastlines of Chesapeake Bay and the Atlantic Ocean, but there are also concerns about encroachment of saline formation waters in the downdip parts of individual confined aquifers. Several studies (Bolton and Hayes, 1999; Bolton, 2000, 2003) have demonstrated that some zones in a few of the aquifers contain naturally occurring concentrations of trace elements including arsenic, cadmium, fluoride, and radium. Radium is present mainly in unconfined sections of the Cretaceous Age aquifers. Elevated concentrations of nitrate are a widespread problem in

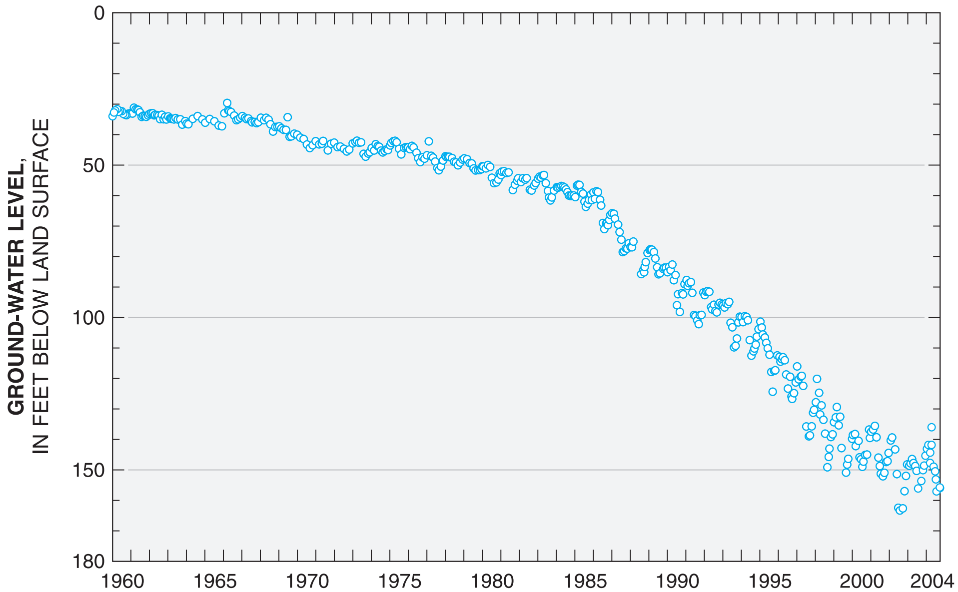


**Figure 2.** Hydrograph showing water-level decline in a well in the Aquia aquifer near Solomons, Calvert County, Maryland, 1960–2004.

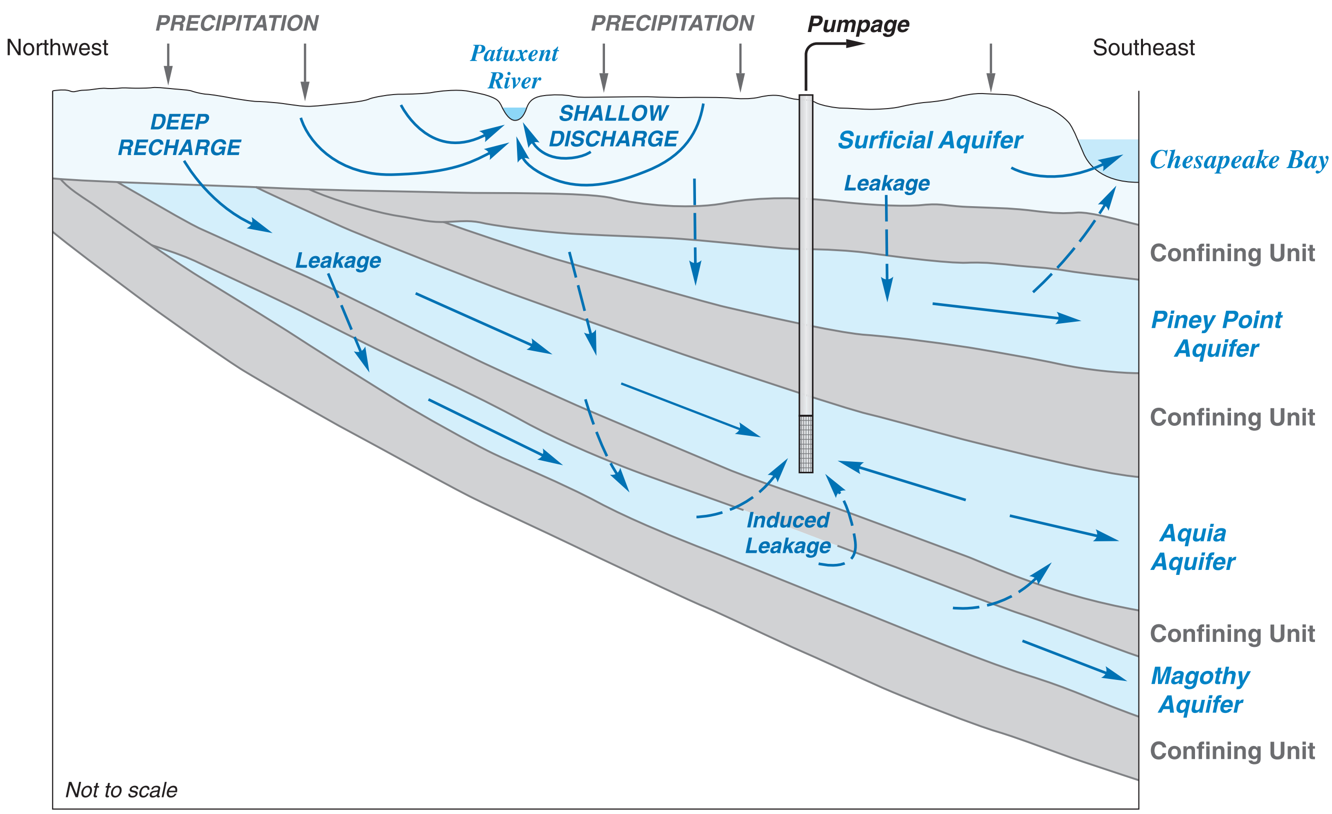


**Figure 3.** Schematic diagram of part of the Atlantic Coastal Plain aquifer system showing generalized ground-water-flow directions (length of arrows not proportional to flow rates).

the surficial aquifer in agricultural areas of the Eastern Shore. Several studies (Phillips and Bachman, 1996; Denver and others, 2004) have shown that ground water is the predominant source of nitrates in the base flow of streams in the Atlantic Coastal Plain, which is a major concern of scientists and resource managers dealing with nutrient inputs to Chesapeake Bay. Trace concentrations of pesticides and their metabolites are also found in shallow ground water and in the base flow of Coastal Plain streams (Denver and others, 2004).

### Inadequate Information Systems and Tools

While a number of detailed studies of individual aquifers or multi-aquifer subregions have been conducted for the Atlantic Coastal Plain in Maryland, there is no comprehensive information system with related visualization and summarization tools available for water managers. State and local water managers need to evaluate water-allocation plans that incorporate cumulative withdrawals at different spatial scales. In particular, state water managers need to evaluate the cumulative effects of increased pumpage on the entire aquifer system. They need new modeling tools that can be updated with new information on the aquifer system, new withdrawal data, and tools that can be used in conjunction with optimization models to evaluate different pumping strategies both locally and regionally.

# Description of the Aquifer System

The Coastal Plain sediments occur as a wedge-shaped sequence of deposits ranging in age from Jurassic to Quaternary. The western boundary of the Coastal Plain sediments is the Fall Line (fig. 1), named for the rapids and waterfalls that often occur at the contact between the unconsolidated Coastal Plain deposits and the crystalline rocks that make up the bedrock of the Piedmont Physiographic Province (fig. 1). The Coastal Plain sediments become progressively thicker south and east of the Fall Line, eventually reaching a thickness of more than 7,000 feet beneath Ocean City (Hansen, 1984; Olsson and others, 1989). Offshore, the Coastal Plain deposits reach a maximum thickness of about 50,000 feet at a distance approximately 60 miles offshore, where thick Jurassic Age sediments infill the Baltimore Canyon Trough (Grow and Sheridan, 1988).

## Hydrogeologic Framework

The Atlantic Coastal Plain aquifer system in Maryland consists of an alternating series of aquifers (generally unconsolidated sands and gravels) and confining units (finer-grained sediments such as clays and silty clays) (fig. 4).

The sediments that form the aquifers and confining units were deposited into a subsiding and faulted tectonic basin called the Salisbury Embayment that extends from southern New Jersey to northeastern Virginia (Olsson and others, 1989). These sediments range in age from Cretaceous to Quaternary. They were deposited in riverine, deltaic, estuarine, and marine depositional environments similar to those found in the Coastal Plain today, that is, in river channels and flood plains, in estuaries and in coastal, near-shore, and open-ocean environments. The sediments that form the aquifers have been interpreted in relation to cycles of rising and falling sea levels (transgression and regression, respectively). Three major transgressive-regressive sedimentary cycles have been recognized in the Maryland Coastal Plain. These cycles form a conceptual framework for understanding the hydrologic properties of the aquifers (Hansen, 1971). Maximum transmissivities typically are greater in fluvial deposits, for example, and become progressively lower in sediments of fluvio-marine and marine origin, respectively.

The Cretaceous sediments comprise the majority of the sedimentary deposits in the Maryland Coastal Plain (Olsson and others, 1989). These sediments were deposited during a major transgressive cycle (Hansen, 1972). The (Lower Cretaceous) Potomac Group, which includes the Patuxent and Patapsco aquifers (table 1), outcrops adjacent to the Fall Line in the northern and western parts of the Coastal Plain and thickens to the southeast, reaching a maximum thickness of more than 4,000 feet beneath Ocean City. These sediments were deposited in fluvio-deltaic environments, where migrating channels coalesced into complex networks of anastamosing sand bodies. Depending on the degree of connectivity of these sand bodies, the aquifers may be extensive or local. The sands are chiefly quartzose with lesser amounts of feldspars, mica, and lignite. West of Chesapeake Bay, the cumulative sand thickness is greatest in Anne Arundel County. The Upper Cretaceous Magothy Formation overlies the Patapsco Formation and was deposited in a transgressive marginal marine environment. The sands of the Magothy are generally more continuous than in the Patapsco Formation, with sand thickness greatest in central Anne Arundel County (Hansen, 1971). The Potomac Group aquifers and the Magothy aquifer outcrop over a broad region from Charles County northeast to Kent County.

The Tertiary sediments contain several major Coastal Plain aquifers. The Aquia and Piney Point aquifers are marine shelf formations that were deposited during shoaling (regressive) sea-level conditions (Hansen, 1971). The Aquia Formation is glauconitic, fossiliferous, and contains calcite-cemented sands; cumulative sand thickness is greatest beneath Queen Anne’s and Talbot Counties on the Eastern Shore (Hansen, 1974). The Aquia Formation outcrops from Charles County to Anne Arundel County west of the Chesapeake Bay and subcrops beneath the surficial aquifer in Queen Anne’s, Kent, and Cecil Counties on the Eastern Shore. In Delaware, the Aquia Formation is referred to as the Rancocas Formation.

The Piney Point Formation is similar to the Aquia Formation, although less glauconitic and fossiliferous. The Piney Point does not appear in outcrop, but rather is erosionally

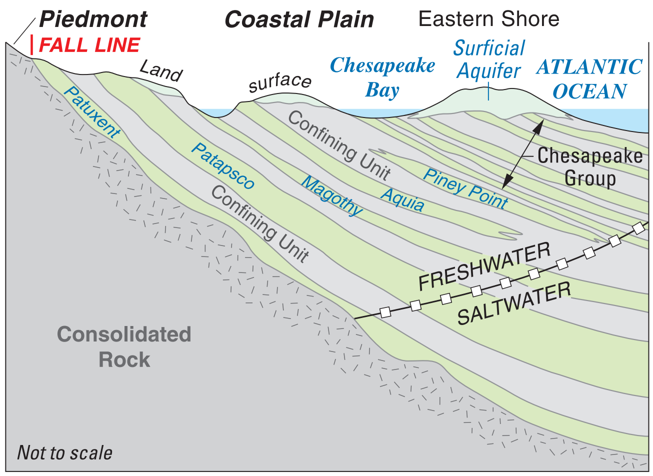


**Figure 4.** Schematic diagram of the Atlantic Coastal Plain aquifer system (relative thicknesses of aquifers and confining layers not to scale).

truncated in the subsurface by the Calvert Formation, which overlies it unconformably. Several Miocene aquifers have been identified within the Chesapeake Group (Hansen, 1972; Cushing and others, 1973). These aquifers, which are widely used on the Eastern Shore, were deposited in a marine or fluviomarine environment. On the Eastern Shore, they do not appear in outcrop but rather are erosionally truncated by generally sandy Plio-Pleistocene deposits that form an areally extensive surficial aquifer, which provides recharge to the Chesapeake Group aquifers.

The Plio-Pleistocene deposits that comprise the surficial aquifer on the Eastern Shore include (from oldest to youngest) the Pensauken, Beaverdam, Omar, and Kent Island Formations. For the most part, these formations consist of sands, gravels, silts, and clays deposited in fluvial, marine-marginal, and estuarine environments. This surficial aquifer, commonly referred to as the Columbia Aquifer (Bachman, 1984a; Wilson, 1984), is used mostly for irrigation and domestic wells. In the Salisbury, Maryland area, however, it is the main source of public water supply because the aquifer materials were deposited in a paleochannel and are up to 200 feet thick (Hansen, 1966; Andreasen and Smith, 1997).

**Table 1.** Summary of geologic units and aquifers in the Atlantic Coastal Plain of Maryland.

| TIME-STRATIGRAPHIC UNITS | | ROCK-STRATIGRAPHIC UNITS | HYDROSTRATIGRAPHIC UNITS |
|---|---|---|---|
| **System** | **Series** | **Groups and Formations** | **Major Aquifers** |
| **Quaternary** | Holocene and Pleistocene<br>? | Kent Island, Omar, Pensauken, and Yorktown Formations, Beaverdam Sand, and undifferentiated estuarine and fluvial terrace deposits on Western Shore of Maryland (Pensauken Formation interpreted as Miocene by Owens and Denny, 1979) | Surficial aquifer (referred to as Columbia aquifer in Delaware and Eastern Shore of Maryland by some authors) |
| **Tertiary** | Pliocene | | |
| | Miocene | Chesapeake Group, includes St. Mary's, Choptank, and Calvert Formations in Maryland | Pocomoke, Manokin, Frederica, Federalsburg, and Cheswold (in Delaware and Eastern Shore of Maryland) |
| | Oligocene (?), Eocene, and Paleocene | Piney Point, Nanjemoy, Aquia, and Brightseat Formations in Maryland, includes Rancocas Formation in Delaware | Piney Point in Maryland and Delaware, Aquia in Maryland (virtually the same unit as the Rancocas in Delaware) |
| **Cretaceous** | Upper and Lower Cretaceous | Severn, Monmouth, Matawan, and Magothy Formations, and Potomac Group (Patapsco, Arundel, Patuxent, and Waste Gate Formations) | Magothy, Patapsco, and Patuxent in Maryland |
| | Basement complex consisting of undifferentiated crystalline and sedimentary rocks ranging from Precambrian to Jurassic age | | None recognized |

On the Western Shore, the surficial deposits are primarily upland gravels of Miocene to Pliocene age (Krantz and Powars, 2000). The deposits are relatively thin and subject to dewatering during droughts, therefore, they are not used extensively for water supply. Nonetheless, these deposits are part of the shallow ground-water-flow system in large areas of southern Maryland and the role of this flow system in recharging the deeper aquifers needs to be investigated. This part of the aquifer system transports water and nutrients to many ecologically important parts of stream valleys and wetlands.

## Ground-Water-Flow Patterns

Water in the Atlantic Coastal Plain enters the aquifer system as rainfall and snowmelt that percolates through the soil and subsoil to the water table. Most of the infiltrating water that reaches the water table flows through the near-surface part of the aquifer system and discharges to local streams (Cushing and others, 1973). Some of the ground water in these near-surface flow systems discharges directly to larger streams and rivers. In coastal zones, some shallow ground water discharges to wetlands, major tidal rivers and open estuaries, or directly to the Atlantic Ocean. A relatively small portion of recharging water becomes part of a deeper flow system that recharges the deep confined aquifers in the western and northern parts of the Coastal Plain near the Fall Line, where the aquifers are exposed at the surface (fig. 5a). In other areas, particularly on the Eastern Shore, the aquifers are overlain by a variety of younger surficial sediments. In these settings, the confined aquifers are recharged by discrete flow paths in the surficial aquifer (fig. 5b). Some aquifers, such as the Piney Point, are recharged entirely by leakage of water from confining units. The amount of recharge from leakage from the confining units in the Coastal Plain is largely unknown.

Under natural (prepumping) conditions, the near-surface sections of the aquifer system are dominated by ground water discharging to local surface-water bodies along flow paths that typically range in length from a few thousand feet to a few miles. Those flow paths that extend into the deeper confined aquifers, however, range from a few miles to tens of miles long. Typically, these longer flow paths in the confined aquifers have been shown to discharge to Chesapeake Bay and its major tidal tributaries and to the Atlantic Ocean and associated Coastal Bays (Fleck and Vroblesky, 1996). In addition, whereas the residence time of ground water in the shallow flow systems is typically a few years to a few decades, the residence time of water in the confined aquifers in the Mid-Atlantic Coastal Plain has been inferred to range from a few decades to at least several thousands of years (Zoltan Szabo, USGS, oral commun., 2006; Aeschbach-Hertig and others, 2002) based on a variety of geochemical age-dating techniques.

Unstressed ground-water-flow systems are controlled by the geometry of the aquifer system and the head differences between the recharge zones and the discharge zones. Prior to the onset of pumping, water levels in all the freshwater aquifers were above sea level, that is, the water pressure in each aquifer was great enough to force the water in a well to rise above sea level. Over time, however, extensive pumping in several of the confined aquifers in southern Maryland has lowered the potentiometric surface (the level to which water would rise in a tightly cased well) to as much as 200 feet below sea level (Drummond, 2005). Potentiometric-surface maps of southern Maryland (Achmad and Hansen, 2001; Drummond, 2001; Curtin and others, 2005) indicate the extent to which this has occurred (fig. 6), with significant cones of depression in the Waldorf-LaPlata, Lexington Park, Easton, and Cambridge areas. The cones of depression extend over relatively large areas, ranging from approximately 300 to more than 700 $mi^2$ (square miles) where the natural ground-water-flow directions have been redirected towards these pumping centers.

## Water Chemistry and Quality

Studies of the natural chemical evolution of water in the Atlantic Coastal Plain aquifer system in Maryland show that water in the system typically evolves along regional ground-water-flow paths from recharge zones to discharge zones, forming distinct hydrochemical facies. Near the recharge areas, the water is characterized by a dilute mixture of ions typical of precipitation. As water flows away from the recharge area, calcium and bicarbonate become the dominant ions (Back, 1966). As water continues to flow deeper into the aquifer system and the residence time of the water increases, the calcium is replaced by sodium until the dominant ions are sodium and bicarbonate (Foster, 1950). In the deepest parts of the flow system, the water evolves to a sodium chloride type. Regional maps showing these variations in water type were published in Knobel and others (1998). Variations of this general scheme occur in individual aquifers in response to varying aquifer mineralogy, lithofacies, chemical composition of recharge water, and other factors. Human activity in particular can greatly affect the chemical character of the recharging water.

Water quality is a serious concern in some parts of the aquifer system used for water supply. Several communities along Chesapeake Bay have problems with intrusion of brackish water into the aquifer system. Chloride concentrations are measured in water-supply wells and observation wells to monitor intrusion of saltwater into the Coastal Plain aquifers used in Ocean City, Kent Island, and the Annapolis area (Andreasen, 2006; Bolton, 2006; Deborah Bringman, USGS, written commun., 2006). In addition, a few areas of the aquifer system have problems with high concentrations of naturally occurring trace elements that often exceed the Maximum Contaminant Levels (MCLs) set by the U.S. Environmental Protection Agency (USEPA). Contaminants include radium in the Patapsco and Magothy aquifers in Anne Arundel County, and arsenic in parts of the Aquia aquifer in Queen Anne's,

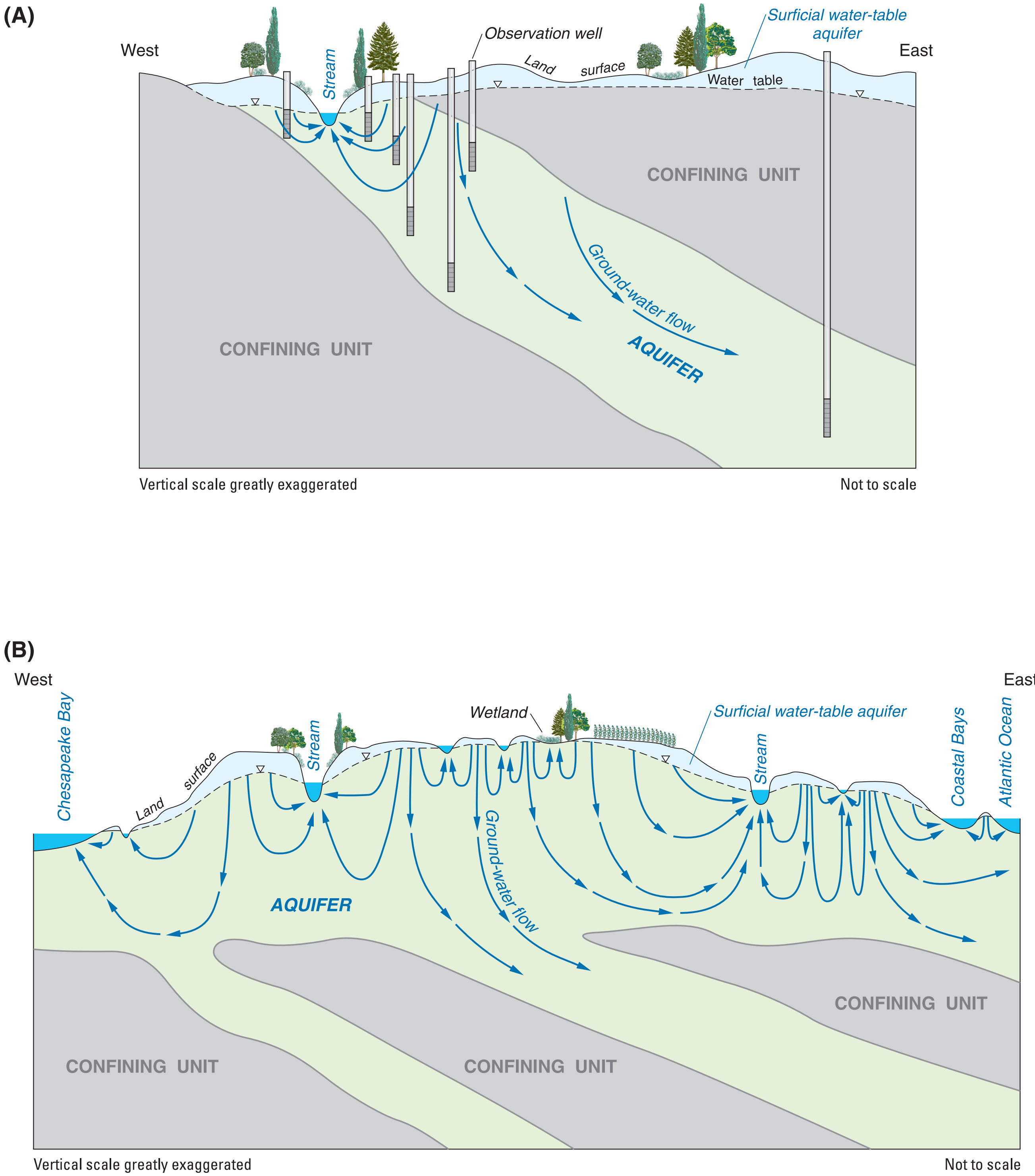


**Figure 5.** Schematic diagram showing A, ground-water-flow directions near the outcrop of an Atlantic Coastal Plain aquifer, and B, ground-water-flow directions in a setting with a surficial water-table aquifer underlain by subcropping aquifers (length of arrows not proportional to flow rates).

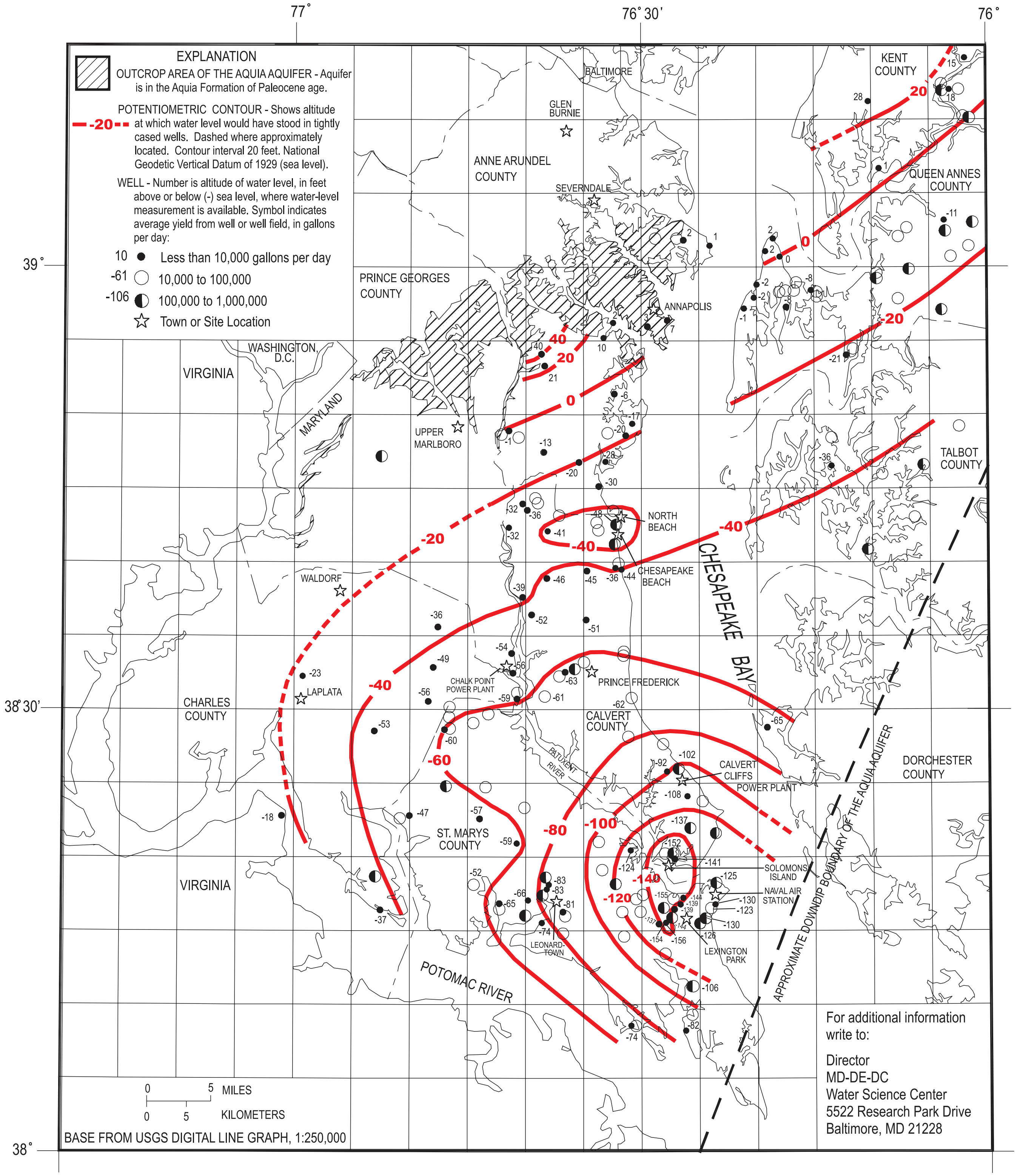


**Figure 6.** Potentiometric surface of the Aquia aquifer in southern Maryland, September 2003 (modified from Curtin and others, 2005).

Dorchester, Talbot, Calvert, and St. Mary's Counties (Bolton, 2000, 2003). The surficial aquifer on the Eastern Shore has problems with high concentrations of nitrate, especially in areas with a high percentage of agricultural land (Bachman, 1984b; Hamilton and others, 1993). Trace concentrations of many agricultural herbicides (Koterba and others, 1993) are also found in the surficial aquifer. Nitrate is the predominant anion in most of the waters with high nitrate and trace concentrations of pesticides (Shedlock and others, 1999). Hamilton and others (1993) found that the hydrochemical type of these waters (calcium-magnesium-nitrate) represents a chemical signature indicative of recharge through agricultural soils.

High concentrations of iron in several aquifers necessitate extensive treatment to make water suitable for drinking, washing, and other purposes. Naturally acidic waters in the shallow parts of the Patuxent, Patapsco, Magothy, and Aquia aquifers often require neutralizing systems to prevent corrosion of pipes in water-distribution systems. In other parts of the Aquia aquifer, the high calcium carbonate content of the aquifer results in hard water, which may require the use of water-softening systems.

# Description of Science Goals and Study Activities

Officials from scientific and resource management agencies in Maryland such as the Departments of the Environment (MDE) and Natural Resources (DNR) recognize that for this assessment to be comprehensive, the entire depth and extent of the aquifer system in Maryland must be investigated. Furthermore, the assessment must extend to technically defensible hydrologic boundaries. Therefore, the study area will extend into adjacent areas of Delaware and Virginia. An initial proposed study area that is bounded on the west by the Fall Line, on the east by the Atlantic Ocean, on the northeast by Delaware Bay, and on the south by the Rappahannock River in Virginia is shown in figure 1. The exact boundaries of the study area will be reevaluated as this assessment matures, in coordination with science and resource management agencies from Virginia and Delaware.

This comprehensive assessment has been developed on the basis of five principal "Science Goals." In this section, each goal is discussed, the need for new work explained, and the study activities necessary to achieve the goal are outlined. The five goals are:

(1) Document the geologic and hydrologic characteristics of the aquifer system in the Maryland Coastal Plain and appropriate areas of neighboring states.
(2) Conduct detailed studies of the ground-water-flow system and water budget for the Coastal Plain aquifer system in Maryland.
(3) Improve documentation of patterns of ground-water quality in all Coastal Plain aquifers, including the distribution of saltwater.
(4) Enhance ground-water-level, streamflow, and water-quality-monitoring networks in the Maryland Coastal Plain.
(5) Develop science-based tools to facilitate sound management of the ground-water resources in the Maryland Coastal Plain.

The primary information needs for this study are related to the sustainability of the ground-water resources of the Atlantic Coastal Plain aquifer system in Maryland. Considerable attention will also be devoted to water chemistry and water quality because the use of the water resource may be limited by water quality in a number of areas. Intrusion of saline or brackish water and the occurrence of both anthropogenic and naturally occurring contaminants are major concerns. The study will also include a more detailed analysis of shallow ground-water flow in the Coastal Plain aquifer system than has been done in previous studies.

This assessment has a very broad scope. Therefore, the investigators will need to develop new tools to store, summarize, and retrieve hydrologic and appropriate ancillary data. A variety of modeling approaches will be used to study the different scales of flow systems and hydrogeologic variability that exist over the study area. In order to accomplish the assessment, the following science goals have been identified. Since a significant amount of new work needs to be done to address the goals of this assessment, the work must be carefully planned, and the activities need to be staged in a logical sequence over time.

## Science Goal 1: Geologic and Hydrologic Characteristics of the Aquifer System

In order to conduct a comprehensive regional assessment of the Atlantic Coastal Plain aquifer system in Maryland, the study team will have to assemble the best information available on the geologic framework and spatial variations in hydrologic characteristics of the Coastal Plain sediments. This may lead to revisions in the hydrostratigraphic framework of aquifers and confining layers as defined in previous studies. Refinements in our understanding of the hydraulic properties of the aquifer layers are likely. Also, this new work should shed more light on the hydraulic properties of the confining layers in the aquifer system.

### Need for New Work

The hydrogeologic framework of the Maryland Coastal Plain has been evaluated and subdivided in different ways and at different scales (Hansen, 1972; Vroblesky and Fleck, 1991). As a result, aquifer names are often regionally inconsistent and sometimes include different formations in different parts of the

Coastal Plain. Some aquifer names in the literature are only of local significance. In addition, discrepancies exist in the stratigraphic delineations for the Coastal Plain among Maryland, Delaware, and Virginia.

Synthesis of available geologic, geophysical, and hydraulic property data will enable a more detailed analysis of the aquifer system than has been done in the past. Analysis and resolution of the existing discrepancies will result in more accurate regional understanding of hydrostratigraphic relations. New hydrostratigraphic interpretations can be tested with the regional ground-water-flow model proposed for this assessment. Distinctions also need to be made between geologic formations and aquifers. In some areas, for example, two or more formations with sand-on-sand contacts may function as a single aquifer. A systematic reevaluation of the hydrogeologic framework and hydraulic properties of the aquifer system would also be beneficial because much information from previous studies, particularly data including hydraulic conductivity, transmissivity, water levels, storativity, porosity, leakance, and other factors, is not located in a central repository. MDE currently uses many sources of data when making allocation and water permit decisions. A regional synthesis of this information would allow a more efficient and uniform approach.

### Proposed Study Activities

- Delineate appropriate regional and local aquifers and confining units.
- Compile geophysical, paleontological, and other appropriate geologic data.
- Establish a regional stratigraphic framework, using geologic, biostratigraphic, and geophysical data and published studies.
- Establish and document criteria for data acceptability for geologic and hydrologic data.
- Compile and assess data on aquifer properties, including pumping tests and published reports.
- Refine conceptualizations of the depositional environments and sedimentary facies that characterize the Coastal Plain aquifers, with particular emphasis on the spatial connectivity of sand layers in the Potomac Group aquifers.
- Create GIS coverages of aquifer and confining-unit properties, including information and maps showing the depth and thickness of various hydrostratigraphic units, as well as their hydraulic properties such as transmissivity, hydraulic conductivity, leakance, and porosity.
- Using appropriate formats, populate aquifer data system with geologic and hydrogeologic information compiled during the project.
- Identify areas where test wells and more data are needed to better delineate the hydrogeologic framework or to enhance the water-level networks for ground-water-flow model calibration.

## Science Goal 2: Ground-Water-Flow System and Water Budget

A sound understanding of the ground-water-flow system is fundamental to an assessment of an aquifer system, whether a water-resource or a water-quality assessment. Three major concepts are critical to understanding a ground-water-flow system. The first is knowledge of the spatial patterns in which water circulates in the system from where it is recharged to where it discharges. The second is knowledge of the rates of movement along the different flow paths, through both aquifers and confining layers. The third is knowledge of the dynamic evolution of the flow system over time, especially over the period of human appropriation of ground water. Together, these aspects are used to determine the locations and rates of fluxes in and out of the system (recharge and discharge). These types of information and knowledge are needed to allow scientists to estimate the water budget of the system, which is essential to estimating the sustainable amount of water that can be extracted.

### Need for New Work

A regional assessment of the Atlantic Coastal Plain aquifer system in Maryland and Delaware was completed by Fleck and Vroblesky (1996) as part of a larger regional study of the Northern Atlantic Coastal Plain under the USGS Regional Aquifer-System Analysis (RASA). This study included the development of a regional digital flow model in Maryland and Delaware (Fleck and Vroblesky, 1996). The RASA studies demonstrated that digital ground-water-flow models are important tools for conducting regional assessments of important aquifer systems. These models can be used to investigate the flow system and the water budget of the aquifer system and to estimate the effects of increased withdrawals on water levels in the system.

Since the Fleck and Vroblesky RASA model was completed, however, significant improvements have been made in the capabilities of digital ground-water-flow models such as the USGS MODFLOW model (Harbaugh, 2005). These improvements allow for much more detailed and more realistic representations of the hydrogeologic framework of the system as well as better representations of sources and sinks for water. The input data to these models can be changed more efficiently and local areas of interest within the regional model can be simulated with finer grid spacings (fig. 7). In addition,

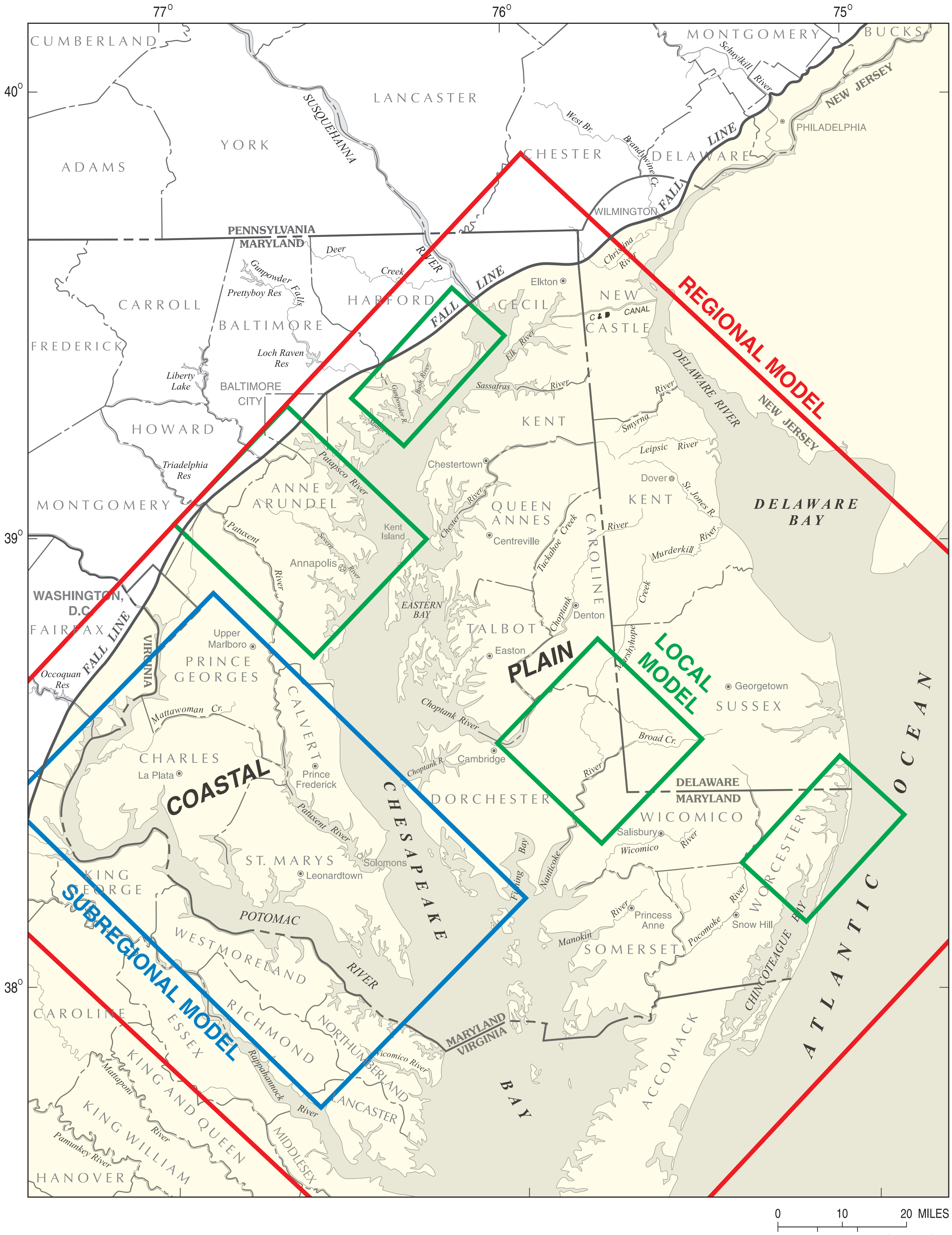


**Figure 7.** Schematic diagram showing the hypothetical nesting of localized models within a regional ground-water-flow model of the Atlantic Coastal Plain aquifer system in Maryland and parts of adjacent states and the District of Columbia.

more recent studies and data are available to develop a new and more detailed regional hydrogeologic framework than the one developed for the RASA study (Vroblesky and Fleck, 1991).

The technology of ground-water management models has also significantly improved over the last decade (Ahlfeld and Mulligan, 2000; Barlow, 2005). These models allow optimization of ground-water extraction in an area on the basis of a specific management objective and one or more management criteria that can include both scientific and economic factors. Optimization models of ground-water extraction are produced by linking ground-water-flow and management models; for example, a management model process (GWM) that runs with the USGS-MODFLOW code has recently been developed by Ahlfeld and others (2005).

A new comprehensive assessment of the ground-water-flow system in the Coastal Plain can be conducted because of the availability of new information and improvements in ground-water modeling tools. The new information and model capabilities will allow for a much needed comprehensive evaluation of all major sources and sinks of ground water, including recharge, natural discharge, and withdrawals. A new regional ground-water-flow model needs to be developed using updated computer codes that are compatible with automated data systems and GIS. The regional model needs to incorporate the best available information on the hydrogeologic framework and hydraulic properties of the aquifers and confining layers.

The regional model needs to be constructed in such a way that smaller areas of specific interest within it can be studied in more detail. Finer model grids near a major pumping center will allow more detailed information on aquifer characteristics and pumpage to be incorporated and evaluated. The capability of local grid refinement in the regional model will obviate the need to construct separate local models. In this way, the flow of ground water between the local area of interest and the rest of the model area can be simulated.

The new regional flow model needs to have a number of features and capabilities. It must be constructed with a computer code and data preprocessing programs that allow for efficient changes in input data as new information becomes available. The new model also needs to take advantage of recent advances in objective parameter estimation and uncertainty analysis. The model should also be compatible with the ground-water management model that will be used to conduct the optimization studies. In addition, the new model needs to be constructed with a spatial resolution appropriate to the ground-water management issues and problems that will be evaluated with the ground-water management modeling system.

Another critical scientific need is an improved understanding of the shallow ground-water-flow system, specifically how this system affects the spatial and temporal distribution of recharge to the confined aquifers. Thousands of small flow systems associated with water-table aquifers, as shown in figure 5a, extend across the Atlantic Coastal Plain. The only practical way to study these systems is to investigate flow in “type areas” (selected watersheds that are representative of other watersheds in the Coastal Plain); the results can then be extrapolated to similar areas. Special field studies may need to be done in some type areas, based on the connection between the water-table system and the confined aquifers. Ideally, these studies would be done in areas that will be equipped with a number of shallow observation wells, one or more streamflow gages, and a precipitation gage. The data from these wells and gages will be used in conjunction with the regional ground-water-flow model, or more detailed local flow models, to estimate the water budget for these local areas and the net influx of water from the water-table system to the underlying confined aquifer system.

Similar special studies, at both regional and local scales, are needed to better understand leakage through confining layers and how leakage affects the sustainability of the aquifer system. Flow in the confining layers was not simulated in the RASA model of Fleck and Vroblesky (1996) and many of the more localized modeling studies. Data from this part of the study will also be useful for evaluating the potential for subsidence due to compaction of the finer-grained units as the aquifer system is depressurized. Existing aquifer-test data will need to be assembled and some data may be reanalyzed. Aquifer tests and other field studies will need to be conducted in selected areas of interest. This work may include the installation of hydraulic head monitoring devices in the confining layers.

Finally, there is a need to improve the acquisition and processing of ground-water withdrawal information. This may require a thorough review and potential modification of the quality-control procedures for acquiring the raw data from water users that report pumpage. A revision of methods for estimating pumpage from self-supplied domestic and other users is also needed. These users are not required to report, but when taken in aggregate, they may greatly affect the water budget for an individual aquifer. This will also require coordination with the Maryland Office of Planning and local planners to develop better estimates of increasing water demand in areas of projected population growth.

## Proposed Study Activities

- Construct and calibrate a regional digital ground-water-flow model that is compatible with automated data systems and GIS, which can also be used as the basis for optimization models for ground-water management.
- Select several smaller areas of specific interest because of heavy development, and implement model-grid refinements that allow more detailed model analysis within the regional ground-water-flow model.

- Construct models of type areas of the surficial aquifer system to study shallow ground-water-flow patterns and ground-water/surface-water interactions.

- Design and conduct targeted field studies to improve understanding of spatial and temporal distribution of recharge to the aquifer system.

- Conduct studies in selected areas to better estimate leakage through confining layers throughout the aquifer system and the potential for land subsidence due to compaction.

- Investigate ways of improving the methods of acquiring and processing water-use data to better estimate water withdrawals from the aquifer system.

## Science Goal 3: Ground-Water Quality

Ground-water quality in Maryland's Coastal Plain aquifers varies greatly. As water flows from the outcrop areas to the deeper parts of each aquifer, the chemical and physical characteristics of ground water change as a function of recharge water quality, aquifer lithology and mineralogy, time of travel, and other factors. Water quality can vary spatially within a single aquifer, and can also differ greatly between aquifers encountered at different depths at the same site. The chemical composition of ground water can impose limitations on specific water uses in particular areas, therefore, knowledge of the occurrence and distribution of water-quality constituents throughout Maryland's Coastal Plain aquifers is a critical component of prudent ground-water management. Assessment of Coastal Plain ground-water quality will provide water users, managers, and other stakeholders with the information necessary to help guide water-use decisions.

### Need for New Work

Ground-water quality in the Maryland Coastal Plain has been studied from a regional perspective in individual aquifers or groups of aquifers (Back, 1966; Cushing and others, 1973; Chapelle and Drummond, 1983; Bachman, 1984b; Knobel and Phillips, 1988; Purdy, 1991; Appelo, 1994; Bond, 1996; Hamilton and others, 1993; Shedlock and others, 1999; Denver and others, 2004). The focus of these regional studies ranges from descriptive statistics to elucidation of geochemical processes throughout the aquifers. Ground-water studies of Coastal Plain counties published by MGS usually contain sections on water quality, which tend to be more descriptive of occurrence and distribution than of sources and hydrochemical processes. Several studies have identified ground-water contaminants in parts of several aquifers of the Maryland Coastal Plain in concentrations that either are higher than the USEPA's health-based drinking-water standards (including nitrate, radium, and arsenic) or that impart unpleasant aesthetic characteristics (iron, chloride, and pH) (State of Maryland, 2004). The MDE Water-Supply Program maintains water-quality data from wells that are tested for regulated drinking-water contaminants. County health departments often require specific water-quality testing as a condition of obtaining a certificate-of-potability for domestic wells.

Substantial amounts of water-quality data from aquifers in the Coastal Plain have been collected, analyzed, and interpreted. The data exist in different formats on different systems, however, and are not always easily accessible or even available to the organizations and individuals that need them. They have been collected in different ways, for different purposes, using different analytical methods, and are not uniformly distributed. Establishing a more comprehensive ground-water-quality data system would facilitate easier access to the data and would enable stakeholders to make more fully informed decisions.

Development of a conceptual framework for the evolution of ground-water quality is an important component of understanding the distribution of chemical constituents and for predicting water quality in areas with few data. Geochemical processes have been described for several of Maryland's Coastal Plain aquifers (Foster, 1950; Chapelle and Drummond, 1983; Knobel and Phillips, 1988). This has not been done for all aquifers, and not for all areas of all aquifers. Development of geochemical evolutionary processes establishes a framework that can be used as a predictive tool when issues arise concerning areas that have not been tested for specific contaminants.

There may also be a need to establish, modify, or enhance ongoing monitoring programs in areas where changes in ground-water quality have been documented, or where ground water may be at risk from long-term degradation with respect to drinking-water standards. Changes in ground-water quality can result from changes in land use, increased water withdrawals, and other factors. Most changes in water quality would be expected to occur relatively slowly, since ground-water-flow rates are usually on the order of feet per year, although some changes can occur quickly. In areas where changes in water quality could be reasonably expected to adversely affect the ground-water resource, water-quality monitoring can provide an early-warning system to identify situations in which management initiatives for water-quality protection are warranted. Several long-term water-quality-monitoring networks are maintained by MGS and USGS. Two of these networks, which are located in Ocean City and Kent Island, monitor annually for saltwater and brackish-water intrusion resulting from over-pumping of the aquifers. A third, statewide network whose sites are sampled at 5-year intervals, monitors unconfined-aquifer water quality for a broad suite of chemical constituents. There are other areas where water-quality monitoring programs may be warranted, including central and northern Anne Arundel County (where chloride is associated with radium and possibly other metals); additional brackish-water monitoring in areas at risk of bay- or ocean-water intrusion, based on projected areas of growth over the next 30 years; and monitoring for agricultural chemicals.

Additional questions concerning ground-water quality in the Maryland Coastal Plain remain unanswered. These include:

- Has aquifer water quality been adequately assessed in areas with high densities of private water wells?
- What is the extent and source of brackish water or saltwater in each aquifer?
- Where and to what extent can the brackish aquifers be used for water supplies given the availability and cost of advanced desalinization methods?
- How old is ground water?
- What risk is posed to downgradient water supplies from contaminants introduced in the recharge areas?

### Proposed Study Activities

- Compile existing water-quality data from available sources for all major aquifers in the Coastal Plain and incorporate the data into the aquifer data system.
- Assess the distribution of water-quality constituents for which the USEPA has established Primary or Secondary MCLs.
- Evaluate approaches for identifying sources of chloride and nitrate using geochemical, isotopic, and other methods.
- Determine the age of ground water in different parts of each aquifer.
- Develop a conceptual framework for the geochemical evolution of ground-water quality in each aquifer that accounts for major-ion chemistry with respect to aquifer composition.
- Establish or augment water-quality-monitoring networks in appropriate locations to track changes in ground-water quality.

## Science Goal 4: Monitoring Networks

The accuracy of a ground-water assessment depends to a significant degree on the quality and spatial and temporal distribution of the available hydrologic monitoring data. These data include ground-water levels in the aquifer system and streamflow measurements in the surface-water bodies that serve as the discharge or recharge zones of the aquifer system. Ground-water-flow models are typically calibrated using a combination of both ground-water levels and water-budget data. The calibration process commonly entails obtaining the best match of potentiometric or water-table surfaces while also simulating rates of discharge to the surface-water bodies that match gains or losses in streamflow from ground water. This assessment will identify needs for additional ground-water-level and streamflow information for calibration of the water budgets in the ground-water-flow models. The assessment will also identify needs for more water-quality data in areas of current or potential saltwater intrusion or in areas with other water-quality concerns.

Several networks of wells are used to monitor water levels in the confined aquifers of the Coastal Plain aquifer system in Maryland. These networks are supported by long-term monitoring projects run collaboratively by MGS and USGS. Nevertheless, there are spatial gaps of coverage in these networks, especially in the outcrop areas of the aquifers, in the surficial aquifers on both sides of Chesapeake Bay, and in the deeper downdip sections of the confined aquifers where the water has not been significantly utilized.

Several studies have been conducted to evaluate the coverage of these networks. Preston (1997) analyzed the stream-gaging network to determine the number and distribution of “core gages,” which he defined as gages at sites that are in watersheds of appropriate size and representative of the major hydrologic settings in Maryland; these gages were in watersheds in which flows were not regulated by dams or significant withdrawals. Cleaves and Doheny (2000) presented a strategy for additional gage sites to be added to the current list of core gages. This strategy was developed as the product of an interagency committee sponsored and facilitated by the Maryland Water Monitoring Council. The recommendations in this report were endorsed by the Advisory Committee on the Management and Protection of the State’s Water Resources (State of Maryland, 2004).

The Council also organized a ground-water-network evaluation team. This team reviewed the ground-water-level well networks monitored by the USGS and MGS. Some of their findings are presented in Gerhart and Cleaves (2005), which presents recommendations on additional sites needed to adequately monitor water-table aquifers throughout the State, including the Coastal Plain. The recommendations of the ground-water-level well network were also endorsed by the Advisory Committee on the Management and Protection of the State’s Water Resources (State of Maryland, 2004).

### Need for New Work

Improvements in both ground-water-level and streamflow networks are needed to increase their spatial coverage and particularly to cover important type settings such as the subcrop zones of several confined aquifers. Large areas of the Coastal Plain have no stream-gaging coverage at present. In addition, drainage in the Coastal Plain is geographically distributed among many relatively small and medium-sized drainage basins and there are currently no large “trunk” nontidal streams, particularly for the Eastern Shore. The streams in the Coastal Plain are tidal for miles to tens of miles inland, and most of the nontidal drainage areas of the largest Coastal

Plain streams are less than 100 $mi^2$. Consequently, there are major watersheds and other large areas of the Coastal Plain for which no streamflow data are available for use in water-balance calculations or ground-water-flow or watershed model calibration.

Previous studies on the adequacy of the streamflow and ground-water observation-well networks need to be reviewed with respect to the revised hydrogeologic framework. The new work not only needs to address previously identified gaps in spatial coverage, but also needs to consider monitoring essential to model calibration and coverage of all of the important hydrogeologic landscapes in the Coastal Plain.

In addition, there is a need to build more “integrated hydrologic monitoring” networks in the Coastal Plain, where streams and the aquifer systems interact strongly with each other (Achmad, 1991; Andreasen and Smith, 1997). The term “integrated hydrologic monitoring” refers to monitoring networks with co-located stream gages, monitoring wells, and meteorological measurement instruments (at a minimum, a precipitation gage). Such integrated monitoring networks will be needed to conduct more detailed studies of water budgets and to investigate the spatial and temporal distribution of recharge. Integrated networks need to be located in each of the major hydrogeologic landscapes of the Coastal Plain. These types of investigations are also needed to improve the calibration of ground-water-flow models in the Coastal Plain.

On the basis of the revised hydrogeologic framework and published landscape classifications of the surficial aquifer (Shedlock and others, 1993; Bachman and Phillips, 1996; Ator and others, 2005), type areas of the surficial aquifer can be identified for more integrated hydrologic monitoring. Transects of well sites need to be selected along shallow ground-water flow paths to monitor the water-table profile. Many of these sites should have vertical nests of wells installed so that vertical gradients in the shallow ground-water system can be determined. These well transects should be placed in watersheds with stream gages. Conversely, stream gages should be added to type areas that have existing well transects. Precipitation gages and other meteorological instruments also need to be added. These integrated hydrologic networks can serve as hydrological observatories that will be used to investigate shallow ground-water-flow patterns and recharge.

Finally, this report has presented several sets of conditions in the aquifer system that may limit the availability of water for supply purposes. For water quality, brackish or saline water intrusion is a key limiting factor in parts of the aquifer system where desalinization is impractical. In some areas, the occurrence of trace elements could limit further development of the water supply. The study team will need to identify areas of the aquifer system that will need to be monitored for water quality to provide an early warning of increased water-quality deterioration caused by or exacerbated by pumpage. Similarly, recommendations may also have to be made for enhanced monitoring of ground-water levels in key parts of the aquifer system where ground-water levels are known to be declining.

### Proposed Study Activities

- Reassess streamflow monitoring needs by examining recent network evaluations and considering additional needs for model calibration data, coverage of type areas, and integrated hydrologic monitoring.
- Reassess ground-water-level monitoring well needs, by examining recent network evaluations and considering the revised hydrogeologic framework and coverage of type areas.
- Develop integrated hydrologic monitoring networks in type areas based on the revised hydrogeologic framework and landscape classification of the surficial aquifer.
- Develop recommendations for monitoring of critical hydrologic trends in areas where ground-water levels are declining or water quality is being degraded.

## Science Goal 5: Tools for Improved Management of the Ground-Water Resources

Ground-water resource managers in Maryland need a variety of new tools to apply the best scientific knowledge available to management of ground-water resources in the Atlantic Coastal Plain. Currently (2007), water-appropriation applications are evaluated at MDE by a professional staff using data and analyses from published reports and agency sources. Many of these reports contain detailed information, usually in hard-copy format, on past, current, and projected declines in water levels caused by withdrawals from the aquifer system.

### Need for New Work

Water-resource managers have expressed the need for a computerized system that will allow them to access all the available data and summarize, graphically display, and visualize the data and interpretive information for specific areas of interest. MDE staffers need a GIS and related databases containing comprehensive ground-water information that will provide users full access to all pertinent aquifer data from a desktop. The system will need to access and collate geographical and tabular databases from various organizations including the USGS, MGS, and MDE. Initially the system would likely have a “stand-alone” design with the data stored on one or more agency computer systems. As the study progresses, a web interface would be built so that the system could be accessed and used over the internet. This system would be designed to assimilate geographical and tabular data from various independent sources.

Basic aquifer geographic datasets will need to include maps and digital coverages of the extent and thickness of each major aquifer (including sand thickness and total thickness), well locations, aquifer test locations, and geophysical log locations. MGS will provide most of these products. The aquifer base maps will be created and provided for the aquifer information system as a product of the MGS Coastal Plain hydrogeologic framework refinement effort.

GIS tools that allow the user to query these and other data and present results in useful and versatile ways will need to be developed. One tool, for example, might allow a user to create "virtual hydrogeologic logs" by clicking anywhere on the map. Such a virtual log would simply show a vertical hydrostratigraphic column at any point, based on surfaces representing the tops and bottoms of the hydrostratigraphic units that have been entered into the database of the information system. If the system is ultimately developed as a web-based application, geographic data such as well locations could be linked to internal and external tabular databases such as the USGS National Water Information System (NWIS) and the MDE Public Drinking Water Information System (PDWIS). Such an arrangement will allow automatic information updates in some cases by querying external data sources that are maintained by agencies responsible for their own data. The aquifer information system will also need to have as part of its GIS functionality an aquifer-based bibliography that allows users easy access to previously published reports, analysis, and model results. This would provide a robust base that can be extensively utilized in future ground-water models, including a ground-water management model.

Currently, ground-water managers also lack tools for determining optimal patterns and rates of ground-water withdrawals. A number of detailed published reports describe the estimated impacts of increased future withdrawal scenarios on water levels in the aquifer system, however, resource managers need improved models and tools that will help them to design optimal withdrawal scenarios under a variety of management constraints such as limitation in drawdown or capture of streamflow. The optimization of future ground-water withdrawals will have to be based on one or more hydrologic and (or) economic criteria, referred to as objective criteria. Several modeling tools will have to be developed to accomplish the optimization. The first is a regional ground-water-flow model with "local-area grid refinements" (areas with smaller model cell sizes) in areas of heavy current or projected future use. The second is an optimization model, which would be coupled with the flow model, and used to perform simulations to optimize conditions based on the stated management goals. Optimization models can solve a variety of management problems consisting of different management goals and constraints; for example, drawdown can be minimized, while meeting minimum water-supply demands (Andreasen, 2003, 2007). Economic criteria, such as the cost of well construction and pumping, can also be included in the optimization simulations. A major advantage of optimization modeling is that it eliminates the trial-and-error method used in traditional water-supply modeling and replaces it with a mathematical approach that is much less subjective. Once the management problem is solved, the model can produce optimal locations, pumping rates, and pumping periods of supply wells. As a result, the optimization model helps scientists and resource managers to better manage the aquifer system with respect to long-term sustainability of the ground-water resource.

### Proposed Study Activities

(1) Develop an aquifer-information system that will provide users full access to all pertinent aquifer data from a desktop computer.

(2) Develop the capabilities to use the aquifer-information system to obtain useful summaries and graphics of information that are directly applicable to the management of ground water in the Coastal Plain. Examples of possible outputs include:

- hydrogeologic sections;
- a well-field analysis that provides all pertinent information about a well field in map and tabular format;
- interpreted surfaces such as aquifer tops, bottoms, and potentiometric surfaces;
- existing datasets to map brackish/saline intrusion fronts; and
- portrayals of the distribution of water-quality contaminants in the aquifers.

(3) Develop optimization modeling capabilities to address ground-water management requirements.

## Implementation Plans

The science goals for this regional assessment will be accomplished in a long-term, multi-year project consisting of several phases and work activities. The project will be conducted in three phases as shown in figure 8 and table 2. Phase I activities will include planning, retrospective analysis of existing information, identification of major gaps in information and understanding, and the building of the partnerships necessary for the comprehensive assessment of the aquifer system. Phase II activities will focus on conducting investigations to address knowledge gaps and building the hydrologic models that will serve as the resource management tools. In Phase III, the ground-water-flow models will be linked with optimization models and simulations will be performed to develop a number of strategies for optimal development of ground-water resources under a variety of management goals and constraints. Phase III also will include significant outreach efforts, in the form of workshops and technical briefings, to inform all appropriate stakeholders of the results of the simulated water-management scenarios.

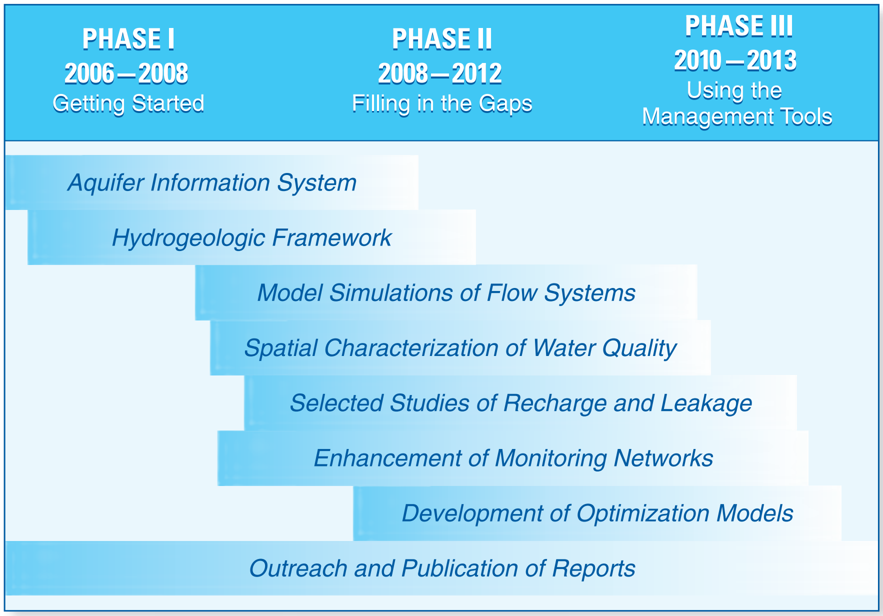


**Figure 8.** Schedule of major work activities for assessment of the Coastal Plain aquifer system in Maryland.

**Table 2.** Phases and work activities for the implementation of a comprehensive assessment of the Atlantic Coastal Plain aquifer system in Maryland (Shedlock and others, 2006).

| IMPLEMENTATION PLANS | | |
|---|---|---|
| **PHASE I (2006–2008)** *Getting Started and Building Partnerships* | **PHASE II (2008–2012)** *Filling in the Gaps and Building the Resource Management Tools* | **PHASE III (2010–2013)** *Using the Tools to Manage and Optimize the Resource* |
| • Develop an aquifer information system.<br>• Refine the aquifer framework.<br>• Determine management criteria.<br>• Identify information gaps.<br>• Develop plans for addressing gaps.<br>• Build partnerships and inform the public. | • Develop and test ground-water-flow model.<br>• Simulate flow system and conduct field studies of recharge and leakage.<br>• Enhance ground-water-level and streamflow-monitoring networks.<br>• Conduct water-quality studies. | • Develop optimization model.<br>• Link flow and optimization models to create interactive management model.<br>• Test water-management scenarios.<br>• Inform partners and stakeholders. |

### Phase I–Getting Started and Building Partnerships

In Phase I, a 3-year effort running from 2006 through 2008, the study team will do detailed planning for the assessment, build partnerships, and develop a GIS-based information system for storage, organization, and visualization of aquifer data and other appropriate data. The system is envisioned to ultimately be built with a web interface so that it can be accessed by individuals in different agencies and locations. The study team will also compile what is known about the aquifer system from previous studies and other data sources. Important gaps in data and other information will be identified in Phase 1 and plans will be developed for acquisition of appropriate new data. The regional hydrogeologic framework will be refined and updated, on the basis of recent published studies and new data, specifically geophysical data collected since the RASA study of the 1980s. Emphasis will be placed on refining the framework for the Potomac Group aquifers because of their hydrogeologic complexity and importance as sources of water supply in the Coastal Plain. In addition, plans will be developed for the design of the regional ground-water-flow model based on the revised hydrogeologic framework. Plans for the ground-water management model will also be developed. This work will include development of a list of the water management goals and constraints that will eventually be used in the optimization models to be developed in the later phases of the assessment. Improvements to the water-use database and the application of water-use data in flow and optimization models will also be made. Outreach activities in the form of fact sheets, presentations at technical meetings, and agency briefings will be conducted to inform water resource managers and other stakeholders in Maryland and adjacent states of all activities in Phase I.

### Phase II–Filling in the Gaps and Building the Resource-Management Tools

Phase II represents the major investigative part of this assessment and may overlap the final year of Phase I. The major effort in this phase will be the development and calibration of the comprehensive regional ground-water-flow model. In addition, a series of specific studies will be conducted during Phase II to investigate recharge to the aquifer system, leakage through the confining layers, gaps in understanding of the hydrogeologic framework, flow in the surficial aquifer, and water-quality patterns. These studies will address important data and information gaps identified in Phase I and during the early stages of the calibration process for the regional ground-water-flow model.

More detailed local flow-model analyses in areas of heavy pumpage or other areas of interest will also be done during Phase II. Several models of the shallow ground-water system will likely be constructed to study recharge to the confined aquifers and discharge of shallow ground water to streams. These models will likely be done in subregions of the Coastal Plain that are representative of certain hydrogeologic type settings in the surficial aquifer.

During Phase II, gaps in the hydrologic monitoring networks, primarily the ground-water-level and streamflow-monitoring networks, will be identified. Regional aquifer ground-water quality will be characterized and appropriate water-quality studies will be conducted. Ground-water-quality monitoring needs will be evaluated, with emphasis on saltwater intrusion and characterization of contaminant distribution.

During Phase II, modifications and improvements in the aquifer-information system will be made; for example, programs that allow for the periodic update of information from the source databases will be written. Additional improvements may be made in the ways data are extracted from the aquifer-information system and summarized and displayed for different user groups. Modifications will also be made to the system on the basis of feedback from these user groups, which will include scientists as well as water managers. The outreach activities during Phase II will be organized to obtain this feedback and to update the scientific and resource management communities in Maryland and adjacent states on the progress of this assessment.

### Phase III–Using the Tools to Manage and Optimize the Resource

In Phase III, the ground-water-flow models will be linked to optimization models that will be used to evaluate a number of water-management scenarios. These linked models can be used to evaluate and compare the effects of different management scenarios on the aquifer system. The models can also produce results that will give optimal locations and pumping rates of wells in specified parts of the aquifer system under a variety of management constraints. These models will essentially produce alternative water-resource management scenarios that can be evaluated by scientists, resource managers, and decision-makers from both scientific and socioeconomic viewpoints.

Phases II and III will probably overlap each other, depending on the availability of funding and the priority given to some of the specific studies mentioned in Phase II. General work plans for Phases II and III will be prepared in Phase I and modified as needed as the assessment progresses. Partners and stakeholders will be kept informed of the status of the overall project through seminars, workshops, and interim reports.

## Products and Benefits

This study will enhance the scientific community's understanding of the Atlantic Coastal Plain aquifer system. The implementation of the full range of tasks presented in this science plan will also create an enhanced understanding of the aquifer system and a number of important products and tools that will benefit scientists, water-resource managers, and decision-makers including:

(1) A computerized aquifer-information system that can be used to summarize and visualize hydrogeologic information and assist managers in making water allocation decisions;
(2) A revised hydrogeologic framework consistent with the latest data constructed in a manner that can be easily updated in the aquifer-information system;
(3) A regional ground-water-flow model, incorporating the revised hydrogeologic framework for the entire Atlantic Coastal Plain aquifer system in Maryland and appropriate areas of adjacent states;
(4) An increased understanding of water-quality patterns in the aquifer system and how water-quality problems may affect the sustainability of the aquifer system;
(5) An improved understanding of leakage in the confining layers and its impact on the sustainability of the aquifer system;
(6) An improved understanding of recharge and the relations between the unconfined and confined parts of the aquifer system;
(7) Optimization models in key areas that will produce optimal locations and pumping rates of wells for a variety of hydrologic and economic goals and constraints; and
(8) Improved liaison amongst different scientific and management agencies on water resource assessment and management.

## Program Coordination and Outreach

This assessment is a significant long-term undertaking with many study components, partners, and stakeholders. It is structured to develop several important new tools that use the results of investigative activities in order to enhance the scientific understanding of the aquifer system. The new tools and insights into the aquifer system are designed to lead to improved planning and management applications as shown in figure 9. This requires that the assessment be carefully planned and have mechanisms for tracking progress and maintaining appropriate technical coordination among the participating science and management agencies, especially MGS, USGS, and MDE. Interagency coordination will also be required to secure the funding needed for the assessment and for informing all stakeholders of significant findings, new tools, and future plans. This report describes an overall plan for the assessment, however, additional work needs to be done to finalize and prioritize plans for detailed investigations on regional flow analysis, recharge, leakage, and water-quality patterns during Phase II. Similar plans will need to be developed for the ground-water-flow and optimization models to be done in Phases II and III.

The program coordination process has already been initiated with the formation of several interagency teams for a) planning, staffing, and funding, b) scientific coordination, c) hydrogeologic framework and ground-water modeling, and d) water use. These teams have been meeting to prioritize initial work and to develop plans for work in ensuing years. Team members currently include individuals from MGS, USGS, and MDE. However, agencies and organizations involved in municipal planning, agriculture, and management of ecological resources should also be included. The study team will need feedback from a variety of stakeholders on the sustainability of the aquifer system. In addition, the study team will need feedback from a diverse group of stakeholders to develop a reasonable set of management goals and constraints for the optimization models.

The planning, staffing, and funding team will also need to maintain a close relationship with the Advisory Committee on the Management and Protection of the State's Water Resources.

Interstate coordination will also be important for this assessment. Because the study area extends into neighboring states, there is a critical need to exchange information and ideas effectively with science and natural resource agencies in Delaware and Virginia, as well as appropriate agencies in the District of Columbia. There will also be a need to engage other Federal agencies that manage lands and natural resources in the study area such as the U.S. Fish and Wildlife Service, the National Park Service, and a number of Department of Defense agencies.

The coordination with partners and stakeholders will be accomplished in a variety of ways. Much of the information transfer with the science partners will be done by the teams described earlier. Presentations and posters at local and regional technical meetings will also be used to describe study plans, report interim findings, and solicit feedback from a variety of stakeholders. A number of reports published by the MGS and USGS will be generated during the course of the assessment. Major reports will be written on (1) the hydrogeologic framework, (2) the aquifer-information system, (3) model analysis of the regional ground-water-flow system, (4) major water-quality patterns in the aquifer system, and (5) optimization model results. Opportunities may also emerge for joint publications with agencies in Virginia and Delaware. Smaller reports or articles in scientific journals will also be published and many interim findings will be presented at scientific meetings.

## Concluding Remarks

The plans for this comprehensive program of study are directed primarily toward assessing the sustainability of the Atlantic Coastal Plain aquifer system in Maryland over the

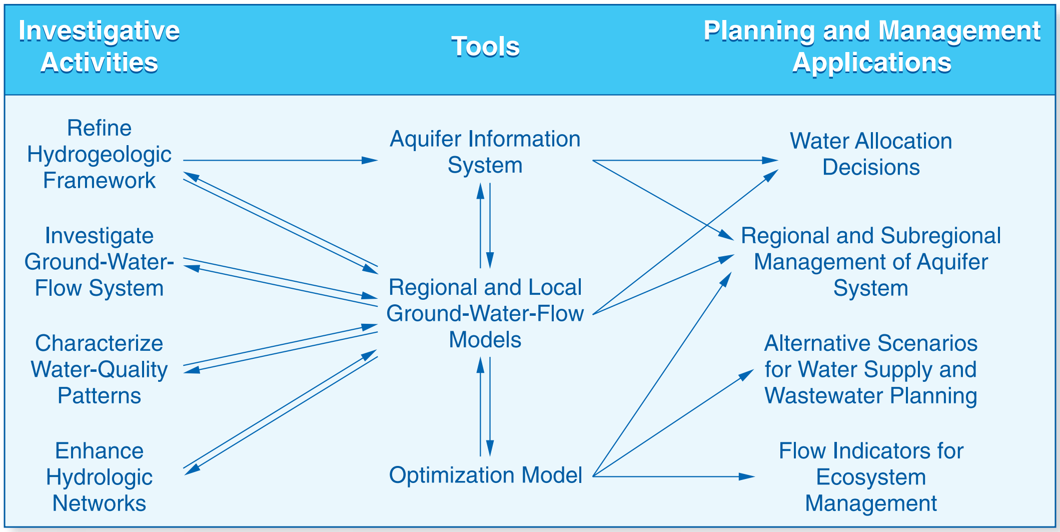


**Figure 9.** Relations among investigative activities, tools, and planning and management applications.

next few decades. Many other important questions, however, will likely emerge in the future about the aquifer system. What will the effects of sea-level rise be on the sustainability of the aquifer system? Will the climate of the region or land-use patterns change enough over the next few decades to significantly alter spatial patterns and rates of recharge to the aquifer system? How will changes in climate and sea level affect patterns of ground-water discharge to streams and wetlands? Will areas of brackish-water intrusion expand and will desalinization of the ground water in these areas be economically feasible?

As withdrawals increase and ground-water levels continue to decline in some parts of the aquifer system, the possibility of injecting treated surface water into the aquifer system to mitigate ground-water-level declines and supplement water supplies may be seriously considered. Many hydrogeologic and water-quality issues will need to be considered and studied before aquifer storage and recovery are significantly implemented.

This report has not addressed the study of these emerging issues; however, this assessment will build the knowledge base and create tools that will provide the scientific basis for addressing these and other important emerging issues in the future.

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