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The Maryland Coastal Plain Aquifer Information System: A GIS-based tool for assessing groundwater resources

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ABSTRACT

Groundwater is the source of drinking water for ~1.4 million people in the Coastal Plain Province of Maryland (USA). In addition, groundwater is essential for commercial, industrial, and agricultural uses. Approximately 0.757×10^9 L d^{-1} (200 million gallons/d) were withdrawn in 2010. As a result of decades of withdrawals from the coastal plain confined aquifers, groundwater levels have declined by as much as 70 m (230 ft) from estimated prepumping levels. Other issues posing challenges to long-term groundwater sustainability include degraded water quality from both man-made and natural sources, reduced stream base flow, land subsidence, and changing recharge patterns (drought) caused by climate change. In Maryland, groundwater supply is managed primarily by the Maryland Department of the Environment, which seeks to balance reasonable use of the resource with long-term sustainability. The chief goal of groundwater management in Maryland is to ensure safe and adequate supplies for all current and future users through the implementation of appropriate usage, planning, and conservation policies. To assist in that effort, the geographic information system (GIS)–based Maryland Coastal Plain Aquifer Information System was developed as a tool to help water managers access and visualize groundwater data for use in the evaluation of groundwater allocation and use permits. The system, contained within an ESRI ArcMap desktop environment, includes both interpreted and basic data for 16 aquifers and 14 confining units. Data map layers include aquifer and confining

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unit layer surfaces, aquifer extents, borehole information, hydraulic properties, time-series groundwater-level data, well records, and geophysical and lithologic logs. The aquifer and confining unit layer surfaces were generated specifically for the GIS system. The system also contains select groundwater-quality data and map layers that quantify groundwater and surface-water withdrawals. The aquifer information system can serve as a pre- and postprocessing environment for groundwater-flow models for use in water-supply planning, development, and management. The system also can be expanded to include features that evaluate constraints to groundwater development, such as insufficient available drawdown, degraded groundwater quality, insufficient aquifer yields, and well-field interference. Ultimately, the aquifer information system is intended to function as an interactive Web-based utility that provides a broad array of information related to groundwater resources in Maryland's coastal plain to a wide-ranging audience, including well drillers, consultants, academia, and the general public.

INTRODUCTION

Groundwater resources, both in Maryland (USA) and worldwide, are at risk from overdevelopment, contamination, and changing climatic conditions (Morris et al., 2003; State of Maryland, 2004). As populations grow and economies expand, the demand for fresh drinking water will increase, placing further stress on groundwater and surface-water resources. Data frequently used by water-resource professionals (such as hydrogeologists, planners, engineers, government, and academia) in the analysis and assessment of groundwater resources are often scattered amongst numerous and disparate databases, publications, and paper files. As a result, well-informed decisions related to critical issues of water supply and water quality may be hampered by the inability to find or access the most current and reliable information. Basic and interpretive data pertaining to groundwater systems, such as the hydrogeological framework (aquifer geometry and hydraulic properties), rates and distribution of water withdrawals, groundwater levels and trends, and groundwater quality, may be absent or outdated, leading to poorly informed management decisions. To help ensure sustainable, long-term water security, more robust water-management tools need to be developed. A fundamental factor for the effective management of groundwater resources is to have readily accessible, high-quality scientific data in a user-friendly interface. A critical capability in identifying potential problems and trends is the ability to overlay and relate multiple information layers in the same interface.

Over the past several decades, the increasing use and development of geographical information systems (GISs) and data models have provided means by which groundwater data from multiple sources can be compiled for spatial, temporal, and relational analysis (Strassberg et al., 2007, 2010). While the potential exists for the creation of comprehensive aquifer information systems, few have been developed at regional scales. The absence of such systems may in part be a result of the difficulties related to the standardization of aquifer framework and nomenclature, database formatting and access, adequate funding and staffing, and effective collaboration across multiple agencies, organizations, and political boundaries.

This paper describes the effort made in Maryland in developing a GIS-based aquifer information system for evaluating groundwater allocation and use permits (GAPs). The paper includes a discussion of issues facing groundwater supply in Maryland, the conceptualization, content, and development of the system, and its use in water-supply management. We also discuss how the system can be leveraged as a foundation for groundwater-flow and management modeling, and in assessing constraints to water supply.

BACKGROUND

The majority of Maryland's Coastal Plain Province (Fig. 1) derives its freshwater supply from groundwater. In Maryland, ~1.38×10^9 L d^{-1} (364 million gallons per day [Mgal d^{-1}]) have been appropriated for use from the coastal plain aquifers (Robert Peoples, 2014, written commun.) to supply the drinking-water needs of ~1.4 million people, as well as the water demands of industry, agriculture, and energy production (Maupin et al., 2014). Maryland jurisdictions that withdraw groundwater from the Coastal Plain Province include Anne Arundel, Baltimore, Calvert, Cecil, Charles, Caroline, Dorchester, Hartford, Kent, Prince George's, Queen Anne's, St. Mary's, Somerset, Talbot, Wicomico, and Worcester Counties, and Baltimore City. Approximately 0.757×10^9 L d^{-1} (200 Mgal d^{-1}) were pumped from coastal plain aquifers in 2010 (Maupin et al., 2014). Between 2002 and 2030, population is expected to grow by 44% (Maryland Department of the Environment, 2013). Long-term stress on the aquifers, resulting from more than a century of withdrawals, has caused a significant decline in groundwater levels. In some coastal plain aquifers, groundwater levels have declined up to 2.1 m yr^{-1} (7 ft yr^{-1}) (Staley, 2014). Continued declines at this rate could affect the long-term sustainability of the groundwater resource, potentially leading to well failures, saltwater intrusion, and water-use restrictions. Degradation of stream aquatic life may occur as withdrawals

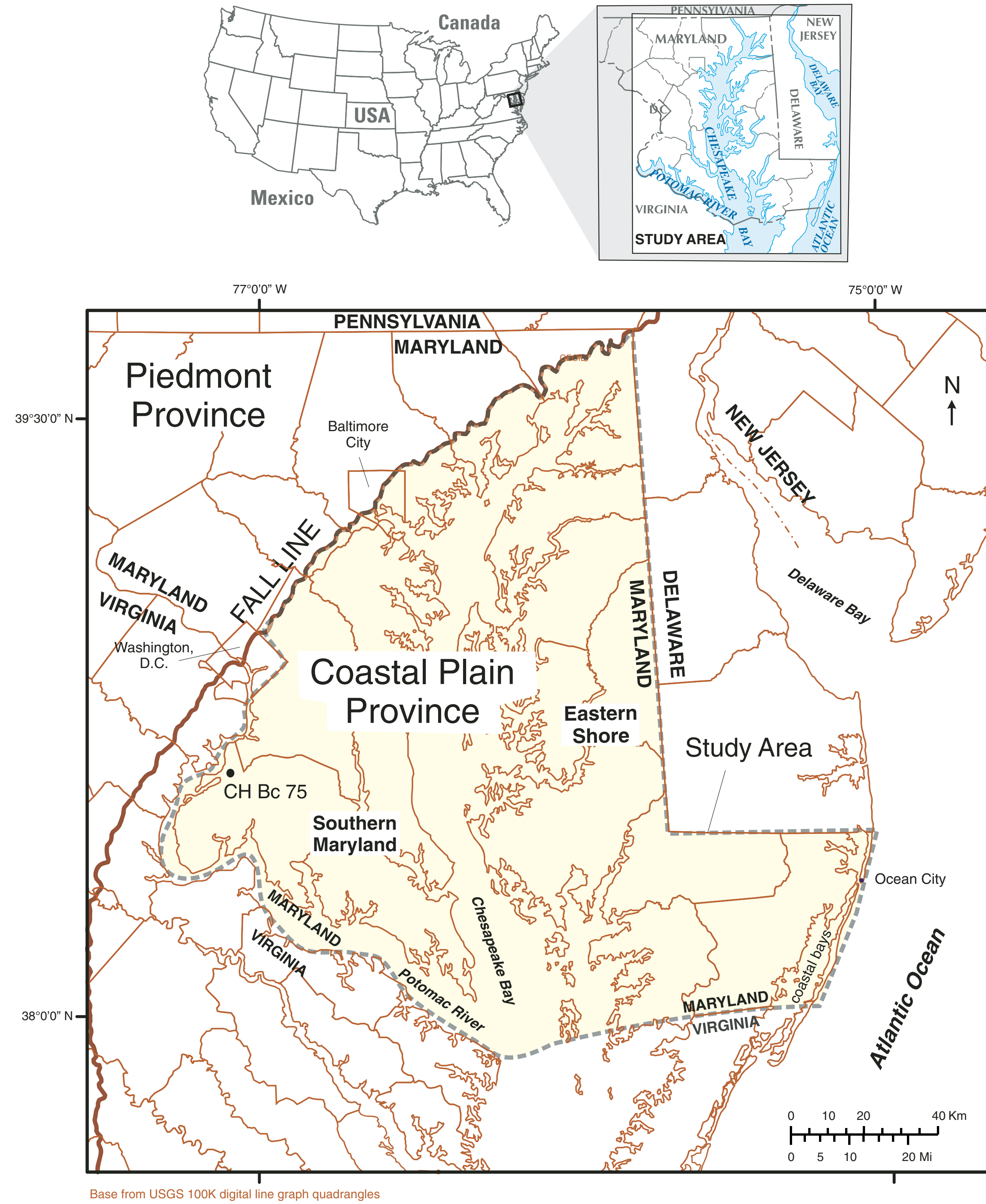

Figure 1. Location of study area.

alter the groundwater budget by diverting a portion of base flow to deep aquifer recharge, thereby reducing stream flow. Economic impacts may also result as wells need to be drilled deeper into the aquifer system, or more costly alternative water supplies need to be developed, such as surface-water reservoirs, desalinization of brackish or salty water, and wastewater reclamation.

Water and natural resource sector managers, regulators, and planners need to be informed of the quantity of groundwater available and the current water demands in the different areas of the coastal plain. The ability to evaluate where and when continued or increased groundwater extraction may cause economic, water security, or natural resource problems is necessary so that such risks can be managed and avoided.

Concerns regarding excessive use of the groundwater resource, accentuated by a severe drought during the early 2000s, prompted the formation of an advisory committee to address improvements in the management and protection of Maryland's water resources and to develop a comprehensive approach to water management in the state (State of Maryland, 2004). In response to recommendations from the committee, the Maryland Geological Survey (MGS) and the U.S. Geological Survey (USGS), with input from the Maryland Department of the Environment (MDE), developed a plan to provide new scientific information and new data-management and analysis tools for the state to use in allocating groundwater in the Coastal Plain Province (Shedlock et al., 2007). A similar effort was undertaken in the fractured rock area in the central and western portion of Maryland (Fleming et al., 2012). The primary objective of this effort was the development of the GIS-based Maryland Coastal Plain Aquifer Information System (MCPAIS), a desktop tool used by water regulators and managers for accessing basic groundwater data for the assessment of GAPs.

Hydrogeologic Setting

The MCPAIS includes the entire section of coastal plain strata, consisting of a series of wedge-shaped sedimentary units that thicken in an east-southeast direction from the fall line or line of contact with the consolidated, crystalline rocks of the Piedmont Province. The fall line strikes approximately northeast, passing through Washington, D.C., and the city of Baltimore (Fig. 1). The coastal plain sediments consist of interstratified layers of unconsolidated sand, gravel, silt, and clay of varying extent and thickness. Changes in sea level since Cretaceous time resulted in alternating nonmarine (fluvial-deltaic), fluvio-marine, and marine sedimentary environments, forming a complex array of layered deposits. The sediments range in age from Early Cretaceous to Holocene and deepen to the east-southeast within a structural depression known as the Salisbury embayment (Richards, 1948). The thickness of the coastal plain sediments increases from a feather edge near the fall line to as much as 900 m (3000 ft) along the southwestern margin of Chesapeake Bay, and more than 2300 m (7500 ft) at the Atlantic Ocean coastline (Fig. 2). The majority of coastal plain sediments (~70%) within the Salisbury embayment are of Cretaceous age (Glaser, 1968).

The geologic setting controls the occurrence, movement, and quality of groundwater. The lithology, permeability, and structure of the sediments define the geologic setting and provide the framework for the groundwater-flow system. Aquifers exist in sand and gravel layers capable of yielding water to wells, while fine-grained layers such as silts and clays impede the flow of water and form confining units. In the Maryland coastal plain, 16 aquifers (or aquifer systems) and 14 confining units are recognized (Table 1; Andreasen et al., 2013). Fourteen of the aquifers are confined, and two are water-table aquifers. The sequence of hydrogeologic units varies across the study area as geologic units pinch out, truncate, or change to nonaquifer facies. Each aquifer is used for water supply to varying degrees in different parts of the coastal plain, with the exception of the Waste Gate aquifer, which contains briny water.

The confined aquifers are gently inclined to the east-southeast at ~1.5–20 m km^{-1} (8–110 ft mi^{-1}; Andreasen et al., 2013). In updip areas, the aquifers are either exposed (outcrop) at the surface or underlie thin veneers of unconsolidated sediments that are predominantly Quaternary in age. Under prepumping conditions, the aquifers were recharged by infiltration of precipitation within the aquifer outcrop belts. Prior to groundwater development in the late 1800s to early 1900s, water in the deep confined aquifers discharged to overlying layers and ultimately to the Atlantic Ocean, Chesapeake Bay, or tidal estuaries and surface-water bodies. Under modern-day pumping regimes, groundwater-flow directions and rates have changed dramatically from predevelopment or prepumping conditions as a result of a significant portion of the water being captured by wells (Andreasen, 2007; Drummond, 2007).

Groundwater Management

Groundwater use in Maryland is managed primarily by the MDE Water Supply Program. The Water Supply Program utilizes an inclusive and comprehensive approach to water management through the coordination and collaboration with state agencies and stakeholders including the Maryland Department of Natural Resources, local governments, scientific organizations such as the MGS and USGS, and the general public. The mission of the Water Supply Program is to ensure that public-drinking water systems provide safe and adequate water to all current and future users in Maryland, and that appropriate usage, planning, and conservation policies are implemented. Maryland's water management policies strive to conserve, protect, and use water resources of the state in accordance with the best interests of the people of Maryland through the issuance of water allocation and use permits for both surface water and groundwater. Water allocations in Maryland are governed by the common law doctrine of reasonable use, which states that all landowners have the opportunity to make a reasonable use of the water associated with their property, limited only by the rights of other landowners.

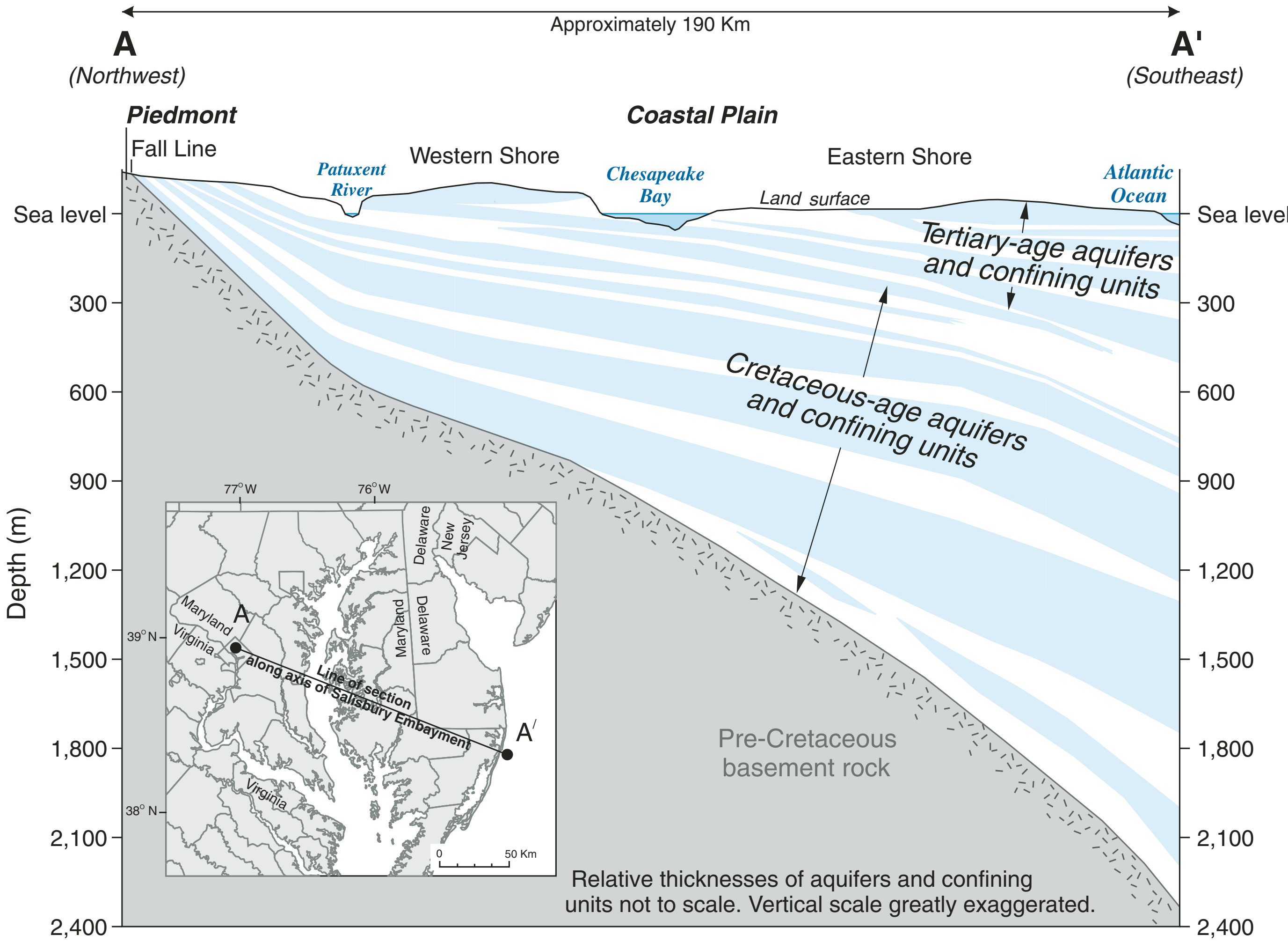

Figure 2. Schematic cross section of the Maryland coastal plain aquifer system extending downdip from the fall line to the Atlantic Ocean.

There are ~9600 active GAPs in Maryland, of which more than 2900 are permitted to withdraw more than 37,854 L d^{-1} (0.01 Mgal d^{-1}). Increasing water use to supply a growing population and an expanding agricultural sector is placing continued stress on the aquifer systems. Between May 2012 and April 2013, ~83% of new GAPs issued statewide for average annual withdrawals greater than 37,854 L d^{-1} (0.01 Mgal d^{-1}) were for agricultural purposes; ~89% of these were for groundwater withdrawals, and the remainder of the permits were for surface-water withdrawals (Maryland Department of the Environment, 2013).

Issues Facing Water Managers in Maryland

Groundwater is the most readily available and cost-effective source of freshwater in Maryland's Coastal Plain Province. Many of the coastal plain aquifers have a sufficient quantity of high-quality water to supply current and projected use; however, some aquifers in certain areas face a number of issues that require careful management.

Declining groundwater levels. Groundwater levels in many confined aquifers in Maryland have experienced accelerated rates of decline resulting from well withdrawals causing large cones of depression. Groundwater levels in some aquifers have exceeded predefined management levels. In Maryland, water levels in confined aquifers are not allowed to fall below a predefined management level to prevent aquifer dewatering. The management level is defined as 80% of the difference between the prepumping water level and the top of the aquifer. Declining water levels also have occasionally resulted in saltwater intrusion and the failure of small-diameter telescoping domestic wells, which prevent deeper pump placement.

Groundwater levels in some of the major confined aquifers in Maryland's coastal plain have declined by as much as ~70 m (230 ft) from estimated prepumping levels in response to water withdrawals (Drummond, 2007). Water-level declines up to 2.1 m yr^{-1} (7 ft yr^{-1}) have been recorded in the confined aquifer system (Fig. 3; Staley et al., 2014). Groundwater use, and the subsequent lowering of groundwater levels, has resulted in restrictions on the

TABLE 1. LIST OF HYDROGEOLOGIC UNITS (AQUIFERS AND CONFINING UNITS) INCLUDED IN THE MARYLAND COASTAL PLAIN AQUIFER INFORMATION SYSTEM

Surficial aquifer
Surficial Upland aquifer
Upper Chesapeake confining unit 1
Pocomoke aquifer
Upper Chesapeake confining unit 2
Ocean City aquifer
Upper Chesapeake confining unit 3
Manokin aquifer
St. Mary's confining unit
Choptank aquifer
Lower Chesapeake confining unit
Calvert aquifer system
Calvert confining unit
Piney Point aquifer
Nanjemoy confining unit
Marlboro Clay confining unit
Aquia aquifer
Severn confining unit
Monmouth aquifer
Matawan confining unit
Matawan aquifer
Matawan-Magothy confining unit
Magothy aquifer
Magothy-Patapsco confining unit
Upper Patapsco aquifer system
Patapsco confining unit
Lower Patapsco aquifer system
Arundel Clay confining unit
Patuxent aquifer system
Waste Gate aquifer
Pre-Cretaceous basement rock

use of certain aquifers in some locations. Special water management areas, known as Water Management Strategy Areas, have been established by the MDE to address the problem of excessive drawdown in the Upper and Lower Patapsco aquifer systems in the Indian Head area of Charles County and in the Magothy aquifer in the Waldorf area of Charles County (Maryland Department of the Environment, 2013).

Degraded groundwater quality. Degraded groundwater quality can limit use of aquifer resources. The use of some Maryland coastal plain aquifers for drinking water, in certain areas, has been constrained by the presence of naturally occurring arsenic (Drummond and Bolton, 2010), radionuclides (Andreasen and Bolton, 2015; Bolton, 2000), and chloride from saltwater intrusion (Achmad and Wilson, 1993; Chapelle and Kean, 1985; Drummond, 1988; Fleck and Andreasen, 1996; Hiortdahl, 1997; Meisler, 1989; Werkheiser, 1990; Fig. 4). Water Management Strategy Areas have been established by the MDE to address the problem of saltwater intrusion in the Aquia aquifer on Kent Island and Annapolis Neck, the Upper and Lower Patapsco aquifer systems in the Indian Head area, and the Surficial aquifer beneath Ocean Pines in Worcester County (Maryland Department of the Environment, 2013). Man-made sources (diffuse and point source) of water contamination also can constrain the use of groundwater in Maryland's Coastal Plain Province in the shallow water-table aquifer. Farm fertilizer application and animal waste (nitrate), and pesticide and herbicide application in agricultural areas are a major concern in the Surficial aquifer on Maryland's Eastern Shore (Ator and Denver, 2015; Denver and Ator, 2012; Maryland Department of the Environment, 2013).

Reduced stream base flow. The health of stream and wetland biota can be sensitive to alterations in natural flow regimes.

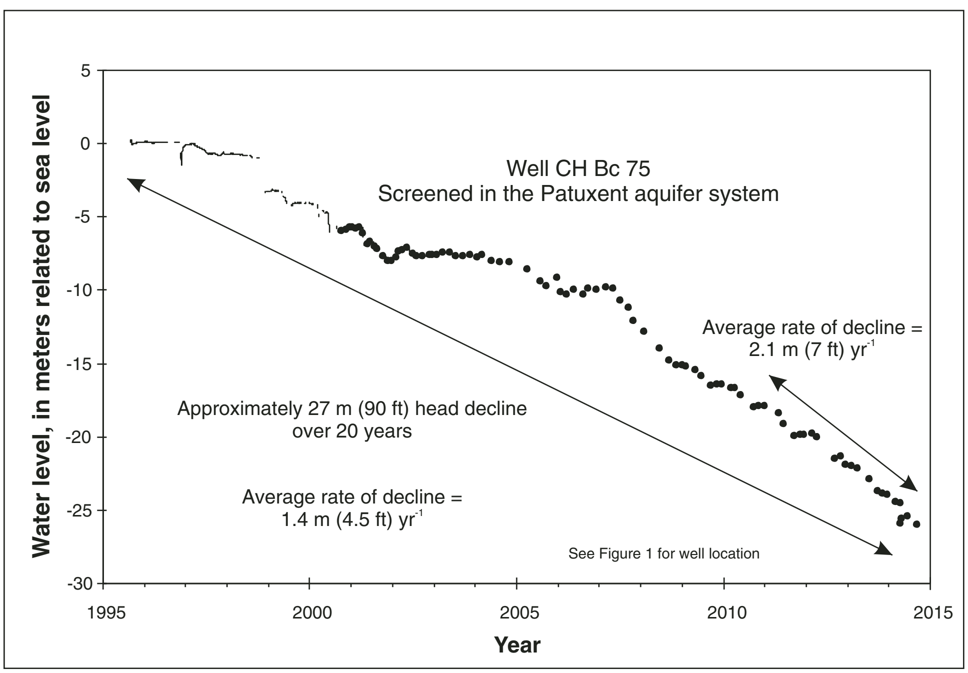

Figure 3. Hydrograph showing effect of water withdrawals on water levels in the Patuxent aquifer system in southern Maryland.

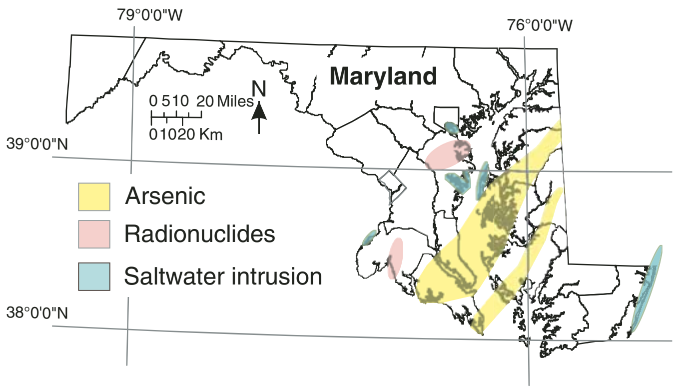

Figure 4. Areas where aquifer water quality is degraded by naturally occurring contamination.

Although not a widespread problem, groundwater withdrawals in Maryland's Coastal Plain Province have resulted in significant stream base-flow depletion at local scales (Achmad, 1991). Withdrawals on a regional scale may also have the potential to reduce base flow to streams; however, interaction between the two has not been quantified. Preserving adequate base flow for healthy stream habitat is an integral part of achieving a sustainable water supply; it is critical that water managers understand what effect withdrawals are having on the water budget of the entire aquifer system.

Land subsidence. Excessive groundwater withdrawals can result in land subsidence in unconsolidated sediments in coastal plain settings (Gabrysch, 1969; Davis, 1987; Davis and Rollo, 1969), compounding the problem of sea-level rise associated with climate change (Boesch et al., 2013). While land subsidence has not yet been observed in Maryland's Coastal Plain Province, the potential for subsidence caused by heavy withdrawals does exist. In neighboring Virginia, land subsidence at rates of 1.5–3.7 mm yr^{-1} in coastal plain sediments similar to those in Maryland has been attributed to large groundwater withdrawals (Eggleston and Pope, 2013).

Climate change. Climate change in Maryland could potentially alter groundwater budgets as precipitation patterns change, evaporation increases as temperatures warm, and demand for drinking water, irrigation, and power production increases (State of Maryland, 2004). Air temperature in Maryland is likely to increase ~4.4 °C by 2100, and precipitation during the winter and spring is likely to increase ~10%–15%, mostly as heavy rainfall events, while the likelihood of droughts will increase during summer and fall (Boesch, 2008).

MARYLAND COASTAL PLAIN AQUIFER INFORMATION SYSTEM

The MCPAIS was created to increase the accessibility of critical groundwater information used in the management of water supply in Maryland's Coastal Plain Province utilizing scalable data visualization and summarization tools. While individual studies of select aquifers or multi-aquifer subregions have provided valuable information in the past, a more robust and comprehensive information system was needed to help enhance management and permitting decisions. The MCPAIS incorporates geographical map layers consisting of both interpreted and basic data and tabular data from the USGS, MGS, and MDE databases.

Conception and Development

The MCPAIS was conceived as a means to provide critical groundwater information compiled from various sources (reports, maps, file data, and databases) in an easily accessible form for routine use in the evaluation of groundwater withdrawals. In a conceptual model of the system, information flow begins with data entered from a large, established knowledge base consisting of the vast volume of groundwater data and interpretative reports spanning multiple decades (Fig. 5). As information enters the system, it flows to a wide array of users (local government, academia, well drillers, consultants, and the general public) and to state officials responsible for managing and regulating the resource. Data can also flow back and forth between the MCPAIS and groundwater-flow simulation models. Groundwater-flow models can be coupled with management (optimization) models to solve specific water-supply objectives through input from water-resource managers.

Development of the system required a collaborative and focused process incorporating input from end users (MDE). Decisions regarding system functionality, data layers, and interactive tools were some of the more difficult steps in the development process. Legitimate, and sometimes competing, interests coupled with the desire to create a streamlined and intuitive information system meant that not all functionality and data sets could be included. Developers relied on close communication and consultation among all team members to determine which data sets and related tools functions to include.

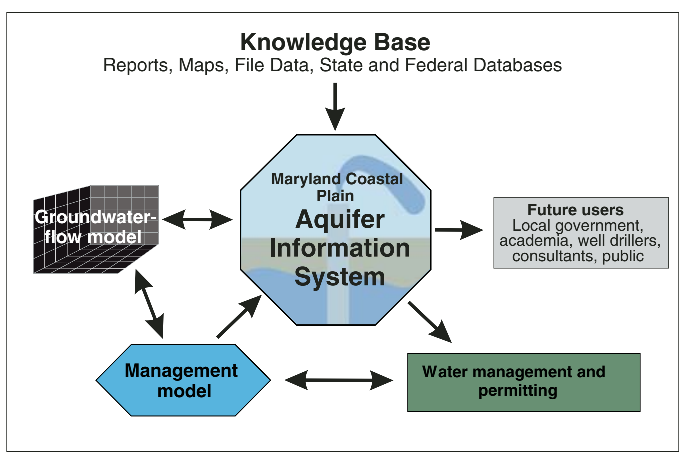

Figure 5. Conceptual diagram of the Maryland Coastal Plain Aquifer Information System.

A critical factor in the development of any GIS is proper quality assurance and control (QA/QC), and creation of the supporting metadata. All data contained within the MCPAIS required various levels of quality assurance to ensure consistency and data integrity. Additionally, data in different formats required analysis, processing, and formatting before they could be included in the MCPAIS.

Serving the MCPAIS through a Web-based interface was the final objective; however, the current version (version 2.0) is limited to individual installations on desktop personal computers for use by agencies of Maryland State.

Data Layers

Data layers available in the MCPAIS include aquifer and confining unit structure (layer surfaces), borehole data, hydraulic properties of hydrogeologic units, groundwater levels, well records, water-use data, and select groundwater-quality data. The MCPAIS contains surface elevations of 16 aquifers, 14 confining units, and the crystalline pre-Cretaceous basement rock. The hydrogeologic framework is the foundation on which the MCPAIS is built. It encompasses the geometric structure of the land surface, aquifers, confining units, and the crystalline basement rock. A description of the hydrogeologic framework contained in the MCPAIS is given in Andreasen et al. (2013).

Site information for the 901 boreholes used to develop the framework structure (surface elevation) of the aquifers and confining units is included in the MCPAIS. Information available in this data set includes borehole identification, hydrogeologic unit contacts (hydrostratigraphy), and data-reference source for interpretations of hydrostratigraphy. In total, 692 geophysical and 215 lithologic logs from the boreholes used to compile the framework are included in the MCPAIS. Geophysical log types contained in the system consist mostly of gamma, multipoint resistivity, and single-point resistance.

Aquifer tests performed on wells throughout the state provide data to derive the hydraulic properties of aquifers. Hydraulic properties, including transmissivity, hydraulic conductivity, and storage coefficient, were compiled from published reports and are included in the MCPAIS. Additional analyses were made for 307 wells using unpublished data on file at the MGS and MDE. Hydraulic properties for a total of 603 wells are included in the system.

The USGS Ground-Water Site-Inventory (GWSI) System is a groundwater data storage and retrieval system that is part of the National Water Information System (NWIS). In total, 15,582 wells from the GWSI database were vetted for geographic accuracy and are included in the MCPAIS. Information contained in these records includes local well identification, locational information, land surface elevation, well depth, aquifer in which the well is screened, as well as a hyperlink to the NWIS Web site. This set of data includes 1372 wells with long-term records (more than 14 water levels) and 8925 wells with short-term records (less than 14 water levels).

The MCPAIS includes a prototype groundwater-quality layer consisting of published maps showing arsenic concentration point data and contour maps for the Aquia and Piney Point aquifers (Drummond and Bolton, 2010).

The MCPAIS includes a static prototype data set of reported monthly withdrawal rates from 1980 to 2005 for permits located in the western portion of the Coastal Plain Province and the eastern portion of the Piedmont Province (Ries et al., 2010). The data consist of 361 GAPs and 172 surface-water allocation and use permits, and it was developed as a subset of data stored in the USGS Site-Specific Water-Use Data System (SWUDS). The GAPs are linked to monthly withdrawal data disaggregated by individual well.

Tools

The MCPAIS includes five tools used to access and query data layers. The tools provide functionality for creating virtual hydrostratigraphic logs, and displaying groundwater levels, borehole information, and hydraulic property data, as well as retrieving water-use data. There are also tools for determining land surface elevation at a selected point and a "help" button linked to a user's guide and other information. Standard ArcMap tools also can be used to access MCPAIS content. The standard ArcMap tools include the ArcMap hyperlink tool to access data files (text and Excel formats) and image files (portable document format [pdf] format) for logs and hydraulic properties, and the ArcMap HTML popup tool to access well-site information, groundwater levels, and water-quality data from the USGS's National Water Information System Web server.

MCPAIS tools were created using customized programming for the desktop environment and built on ESRI's ArcMap and ArcObjects. Visual Basic .NET was used as the programming language.

Use in Water-Supply Management

Groundwater users in Maryland who wish to use more than 18,927 L d^{-1} (0.005 Mgal d^{-1}) on an annual average basis are required to apply for a GAP. Some water uses, such as domestic supply and firefighting and small agricultural uses of less than 37,854 L d^{-1} (0.01 Mgal d^{-1}), are exempt. The MDE Water Supply Program must evaluate each GAP application to ensure that the use is compliant with state laws, is reasonable, and does not adversely impact the resource or other users of the resource. Evaluation of a GAP consists of determining whether the requested withdrawal rate is consistent with the particular use, identifying the depth and hydraulic properties of the target aquifer, quantifying the amount of drawdown associated with the desired withdrawal rate, and determining whether there is sufficient available drawdown and whether nearby users will be adversely impacted.

Presently, the MDE Water Supply Program uses the MCPAIS as an integral part of its groundwater-allocation evaluation process. Permit writers routinely access the system to obtain the required information. Since its introduction, the MCPAIS has greatly improved the efficiency and integrity of permitting decisions. Additionally, the MCPAIS has allowed water managers to view individual water use in a more comprehensive manner, and to visualize hydrogeological trends on larger scales.

USE OF THE AQUIFER INFORMATION SYSTEM IN ASSESSMENT OF WATER-SUPPLY SUSTAINABILITY AND LIMITATIONS

The current application of the MCPAIS is for evaluation of GAPs by water-resource regulators; however, the system has the potential to be used for many additional applications related to water-supply planning, development and sustainability, and evaluation of limitations to water supply.

Groundwater-Flow and Management Modeling

Currently, groundwater management is conducted on a permit-by-permit basis by the MDE, while general long-range, water-supply planning is conducted by local government at 10 yr intervals as part of the state-mandated Water and Sewer Plans. Part of the recommendations of the water resource advisory committee was for a more comprehensive approach to water management (State of Maryland, 2004). Specifically, the MDE and local governments need tools to help evaluate the long-term effects of increased withdrawals on the entire aquifer system throughout Maryland's Coastal Plain Province, including water supply in adjacent states. The MDE also must determine the reasonableness of use and potential conflicts of proposed water-use projections amongst the local jurisdictions.

The MCPAIS can be leveraged to provide the information needed for tools, such as the development of a regional groundwater-flow model of the coastal plain aquifer system (Shedlock et al., 2007). The numerical modeling tool would have the ability to simulate groundwater flow and the cumulative effect of withdrawals in the entire coastal plain aquifer system in Maryland, as well as the neighboring states of Delaware and Virginia. The model also could provide an improved understanding of the hydrogeologic processes that control groundwater availability and identify areas in need of greater observational data.

Understanding of the groundwater-flow system is fundamental to assessing water resources (water supply) and water-quality issues of aquifer systems. There are several major components critical to understanding groundwater-flow systems. The first is knowledge of the spatial patterns of water circulating from recharge to discharge areas within the aquifer system. The second is knowledge of the rates of groundwater movement through both aquifers and confining units, and the third is knowledge of the dynamic evolution of the flow system over time, especially over the period of human appropriation of groundwater. Together, this information can be used to determine the locations and rates of fluxes in and out of the aquifer system, knowledge needed by water managers to estimate water budgets and sustainable withdrawal rates.

Specific uses of a groundwater-flow model could include estimating sustainable yield for coastal plain aquifers, assessing the impacts of groundwater withdrawals on streams, and evaluating impacts of withdrawals in shallow portions of confined aquifers constrained by relatively small amounts of available drawdown. In order to accomplish these tasks, the model would require an active water-table layer capable of simulating shallow hydrologic processes, such as recharge, base flow to streams, submarine groundwater discharge, and evapotranspiration, as well as active layers representing both confined aquifers and confining units. Because of the relatively large area of Maryland's coastal plain aquifer system and number of aquifer and confining unit layers to be simulated, a regional groundwater-flow model would have to be refined using local grid refinement techniques (Mehl and Hill, 2006; Raffensperger et al., 2010) to simulate hydrogeologic conditions at finer scales.

Currently, groundwater planning in Maryland lacks tools for determining optimal and sustainable patterns and rates of groundwater withdrawals that take into account system constraints such as available drawdown and minimum required streamflow (base flow). To provide this important function, an optimization (or management) model coupled with a groundwater-flow model, could be developed (Ahlfeld et al., 2005; Ahlfeld and Mulligan, 2000). An optimization model could determine optimal well-withdrawal rates that satisfy long-term planning goals and strategies for sustainable use of the resource. Optimization models can solve a variety of management problems with different management goals and constraints; for example, drawdown can be minimized while meeting minimum water-supply demands (Andreasen, 2004, 2007). Economic criteria, such as the cost of well construction and pumping, also can be included in the optimization simulations. A coupled groundwater-flow and optimization model also could greatly benefit local governments responsible for developing long-range, water-supply plans and making necessary infrastructure investments.

Both groundwater-flow and optimization models could be linked to the MCPAIS system (Fig. 5). Coupling of GIS databases and groundwater-flow models or model-processing interfaces can be an effective means of model construction and manipulation (Gogu et al., 2001; Strassberg et al., 2011). Conceptually, data such as the aquifer framework, hydraulic properties, and groundwater levels stored in the MCPAIS could provide input for parameters used in construction and calibration of groundwater-flow models. Groundwater levels and water budgets output from groundwater-flow and optimization models could be returned to the MCPAIS for visualization and analysis.

Water-Supply Constraints

Many factors, both natural and anthropogenic, can constrain the use of fresh groundwater in the confined aquifers of

Maryland's Coastal Plain Province. Constraints include insufficient available drawdown, degraded groundwater quality (such as saltwater intrusion, arsenic, and radionuclides), low aquifer yields, and well-field interference. Identification of constraints on groundwater availability is a critical component in water allocation, and in local and state growth and development planning. In Maryland, adoption of local comprehensive growth plans must include assurances that adequate water supplies are available to meet current and future population growth. Failure to identify known or potential water-quality or water-supply problems can potentially result in high economic costs when wells need to be redrilled to different aquifers or when other sources of freshwater supply need to be developed. Expansion of the current aquifer information system to include constraints to groundwater use for drinking water for the major coastal plain aquifers in Maryland could provide useful information in water-supply planning, development, and management.

Known or Potential Saltwater Intrusion

Saltwater intrusion, while not an extensive problem in Maryland's coastal plain aquifer system, can be a significant constraint on water supply in localized areas of some aquifers. Sources of saltwater intrusion include Chesapeake Bay, coastal bays, the Atlantic Ocean, and tidal rivers. The extent of saltwater intrusion has been mapped in the Patuxent aquifer system in the Baltimore City area (Chapelle and Kean, 1985), the Patuxent and Lower Patapsco aquifer systems at Indian Head (Hiortdahl, 1997), the Aquia aquifer on Kent Island (Drummond, 1988), the Aquia aquifer on Annapolis Neck and Mayo Peninsula (Fleck and Andreasen, 1996), the Manokin aquifer in Somerset County (Werkheiser, 1990), and the Manokin and Ocean City aquifers at Ocean City (Achmad and Wilson, 1993). At a regional scale (Northern Atlantic Coastal Plain Province), Meisler (1989) mapped the transition zone between freshwater and saltwater in a series of maps showing the depths-to-chloride concentrations ranging from 250 to 18,000 mg L^{-1}.

Mapped areas of saltwater intrusion converted to GIS layers (points, lines, polygons, or rasters) could be included in the MCPAIS database and displayed as layers within the ArcMap project. The depth to the freshwater-saltwater interface also could be displayed along with the hydrogeologic framework within the Virtual Log tool.

Aside from the mapped areas of saltwater intrusion, areas of potential saltwater intrusion also could be developed by comparing the location of saltwater bodies to aquifer outcrops and subcrops along with aquifer head gradients. Areas where conditions are favorable for saltwater intrusion (saltwater entry point into an aquifer and landward head gradient) could be incorporated into the MCPAIS as polygons. Since sea-level rise resulting from climate change is predicted to inundate significant areas bordering Maryland's Chesapeake Bay and Coastal Bays (Boesch et al., 2013), the polygons could be expanded to account for higher sea-level stands.

Groundwater Contamination

Groundwater contamination in some of Maryland's coastal plain aquifers constrains the use of those aquifers in certain areas. Of particular concern is the presence of naturally occurring arsenic in the Aquia and Piney Point aquifers (Drummond and Bolton, 2010) and radionuclides in the Patapsco aquifer system (Andreasen and Bolton, 2015; Bolton, 2000). The distribution of arsenic in the Aquia and Piney Point aquifers currently is included in the MCPAIS; however, any additional areas of elevated arsenic could be included along with areas of elevated radionuclides. Those areas could be converted to GIS layers (points, lines, polygons, or rasters) and displayed as layers associated with individual aquifers within the ArcMap project.

While not a health risk, elevated iron concentrations are often present in Maryland's coastal plain aquifer system. Iron at high concentrations can be costly to treat and, therefore, may constrain water use in affected aquifers, particularly for domestic use. Elevated iron concentrations can cause discoloration of plumbing fixtures and laundry. The distribution of elevated iron concentrations could be converted to GIS layers (points, lines, or polygons) and displayed as layers associated with individual aquifers within the ArcMap project.

Many types of groundwater-quality data are collected throughout Maryland by local, state, and federal agencies and organizations. Incorporating these disparate databases into the MCPAIS for key water-quality parameters could greatly enhance the ability to effectively manage the resource. Collectively, these data could be used to determine where groundwater use may be constrained by the presence of naturally occurring contaminants. A recent GIS project in Garrett County, Maryland, that mapped the concentration distribution of arsenic, chloride, manganese, and radon using water-quality data from five separate databases could serve as a prototype for a similar effort using the MCPAIS (David Bolton, Maryland Geological Survey, 2014, written commun.). That project incorporated data from the Garrett County Health Department, MDE, MGS, and USGS water-quality databases.

Limited Available Drawdown

Groundwater withdrawals in confined aquifers in Maryland's Coastal Plain Province are managed such that water levels are not allowed to fall below a designated management level. The management level, intended to prevent dewatering of the confined aquifer, is defined as 80% of the difference between the prepumping water level and the top of the aquifer. Areas with a relatively small amount of remaining available drawdown for a particular aquifer may be limited in the additional use of that aquifer. Those areas naturally occur near aquifer outcrops where the depth of the aquifer is relatively shallow, and in areas where there is excessive drawdown caused by pumping. Maps showing areas of limited available drawdown could be created and included in the MCPAIS as polygons.

High Stress from Withdrawals

Groundwater withdrawals have stressed many aquifers in Maryland's coastal plain aquifer system, resulting in deep cones of depression and significant drawdown over time. Identifying areas of greatest stress could help water managers achieve a more balanced distribution of water withdrawals across the available aquifers, preventing or alleviating excessive drawdown. Maps highlighting areas of high stress from appropriated and domestic groundwater withdrawals could be incorporated into the MCPAIS as GIS layers (polygons).

Low Aquifer Productivity

Groundwater supply is obviously constrained by aquifer productivity. Aquifer productivity, in part, is a function of the hydraulic conductivity and thickness of the permeable sediment that forms the aquifer. Aquifer productivity can vary significantly within individual aquifers across the coastal plain related to the depositional environment in which the geologic unit was deposited. For example, stacked channel deposits of highly permeable sand and gravel deposited in a high-energy, braided-channel stream environment can change facies to thin, muddy, discrete sand layers of relatively low permeability deposited in a low-energy meandering stream environment. The coastal plain aquifer system is characteristically heterogeneous and anisotropic. In some aquifers, hydraulic conductivity and sand thickness can vary significantly over even relatively short distances. In areas where sufficient data are available, GIS layers (polygons) showing areas of relatively low aquifer productivity (low hydraulic conductivity and sand thickness) could be constructed and included in the MCPAIS.

In many locations, hydraulic conductivity (determined mainly from aquifer tests) and sand thickness (determined from geophysical logs) are insufficient to discern trends and patterns in aquifer productivity. As an alternate method for estimating aquifer productivity, well specific capacity could be compiled to estimate aquifer transmissivity using the relative abundance of specific-capacity data contained in the MDE's well-permit database.

CONCLUSION

Informed, expedited, and cost-effective decision making is a necessary step to successfully manage groundwater resources, especially considering the economic and environmental impacts of increasing water demands and climate change. The Maryland Coastal Plain Aquifer Information System (MCPAIS) was developed as a scalable tool to help water managers access and visualize groundwater data for use in the evaluation of groundwater allocation and use permits. Long-term stress on the aquifer system caused by more than a century of withdrawals has resulted in significant declines in groundwater levels, which could affect the long-term sustainability of the groundwater resource, potentially leading to well failures, saltwater intrusion, water-use restrictions, and land subsidence. Degradation of stream aquatic life also may occur as withdrawals alter the groundwater budget by diverting a portion of base flow to deep aquifer recharge, thereby reducing stream flow. Additionally, high economic costs may result as wells are forced to deeper aquifers or if alternate water supplies, such as surface-water reservoirs, desalinization of brackish or salty groundwater or surface water, and reclaimed wastewater, need to be developed.

The current application of the MCPAIS is for evaluation of groundwater allocation and use permits by water-resource regulators; however, the system has the potential to be used for many additional applications related to water-supply planning, development and sustainability, and evaluation of limitations to water supply. The MCPAIS can be leveraged to provide the information needed for tools such as the development of a regional groundwater-flow model and coupled management model of the coastal plain aquifers. Coupled flow and management models could assist water users, managers, and regulators to plan long-term use of the resource, and these models could provide an improved understanding of the hydrogeologic processes that control groundwater availability. Additionally, expanding the current aquifer information system to include constraints to groundwater use for drinking water for the major coastal plain aquifers in Maryland could provide useful information in water-supply planning, development, and management.

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