The Virginia Coastal Plain Model: Implications of New Simulation Features for Ground-water Management

Charles Heywood
U.S. Geological Survey, cheywood@usgs.gov Richmond, VA, USA

ABSTRACT

A new transient, three-dimensional variable-density ground-water flow model of the Virginia Coastal Plain aquifer system has been developed and calibrated to simulate aquifer-system behavior in response to 113 years of ground-water withdrawals beginning in the late 1800's. A USGS RASA model of the aquifer system developed in 1990 is currently used as a regulatory tool by the Virginia Department of Environmental Quality. Significant changes to the hydro-geologic framework, including the discovery of the Chesapeake Bay Impact Crater, and advances in flow-modeling techniques motivated the development of the new CPM2006 model. State and municipal water management authorities intend to replace the RASA model with the CPM2006 as a regional water management tool. The Virginia regulatory evaluation procedure is based on the RASA-era framework, and will therefore require refurbishment as the CPM2006 is adopted. The new features of the CPM2006 result in different simulated aquifer-system response compared to the RASA model, which was quasi-three-dimensional. Explicit representation of thick, low-permeability hydrogeologic units prolongs response time to changes in pumping stress, while current regulatory evaluation procedures assume that steady-state conditions are substantially attained after several years. The CPM2006 should be used for transient simulations, and potential users should consider the nature of the transient response in formulating ground-water management schemes.

HYDROGEOLOGIC SETTING

The Coastal Plain aquifer system in Virginia consists of an eastward-thickening wedge of unconsolidated marine and fluvial-deltaic sediments, which attain a thickness of over 4000 feet near the Atlantic coast. Consolidated lower Mesozoic rift-basin and older crystalline bedrock of the Piedmont underlie the coastal plain sediments. Annual precipitation over the Virginia Coastal Plain averages 45 inches per year, and potential evapotranspiration is about 32 inches. Recharge water that infiltrates shallow aquifer sediments near the western extent of the Coastal Plain (the Fall Line) may flow about 100 miles before discharging upward to the Atlantic Ocean near a freshwater-saltwater transition zone. The ground-water flow pattern and salinity distribution near this transition zone are influenced by the Chesapeake Bay Impact Structure, the remnant of a mid-Eocene comet or asteroid collision (McFarland and Bruce, 2005). The Cretaceous fluvial-deltaic Potomac formation is the deepest aquifer in the system, from which 75% of the Coastal Plain ground-water usage is withdrawn. Several large river systems, as well as the Chesapeake Bay and Atlantic Ocean, are the principal ground-water discharge areas where they are hydraulically connected to shallow aquifers.

VIRGINIA GROUND-WATER WITHDRAWAL REGULATION

Ground-water withdrawals in the Virginia Coastal Plain increased significantly since World War II, and have resulted in regional cones of depression, with drawdown currently exceeding 200 feet in some areas. The Virginia Ground Water Management Act of 1992 empowered a State Water Control Board to create Ground Water Management Areas (GWMA), within which ground-water withdrawals greater than 300,000 gallons per month must be permitted by the Department of Environmental Quality (DEQ). The south-east two-thirds (approximately) of the Virginia coastal plain are currently a declared GWMA. Among the criteria for ground-water withdrawal permit issuance is the evaluation of the "area of impact" of a withdrawal, and an assessment of the probable additional groundwater drawdown resulting from the proposed withdrawal. A regional ground-water flow model (Harsh and Laczniak, 1990) that was developed by the U.S. Geological Survey (USGS) Regional Aquifer Systems Analysis (RASA) program is utilized for these evaluations. The "area of impact" on each aquifer is defined as that inside the one-foot drawdown contour of the proposed withdrawal. The additional drawdown in each aquifer resulting from the proposed withdrawal is constrained such that the simulated water-level potentiometric surface of the aquifer may not fall below a level representing 80% of the distance between the simulated pre-development water level and the top of that aquifer. This evaluation is made at a point halfway between the withdrawal location and the one-foot drawdown contour, "based on the predicted stabilized effects of the proposed withdrawal" (Virginia Administrative Code, 2005). The evaluation simulations incorporate historical withdrawals for non-permitted withdrawals, and the maximum legally allocated withdrawals for all permitted users within the GWMA. The maximum allocated withdrawals have been about 60% greater than the actual reported withdrawals from the Virginia coastal plain. As such, these "maximum permitted withdrawal" simulations are intended to represent a "worst case" scenario for evaluating whether a prospective withdrawal will result in violation of the 80% drawdown criterion. Using the USGS RASA model (Harsh and Laczniak, 1990), the Virginia DEQ determined that the simulated effects of withdrawals stabilized after several years, and later modified the RASA model to perform drawdown evaluations using steady-state simulations. The RASA model (Harsh and Laczniak, 1990) utilized 10 layers to simulate flow in each recognized coastal plain aquifer, but did not simulate flow within or release of storage water from the intervening confining beds.

GROUNDWATER FLOW MODEL – CPM2006

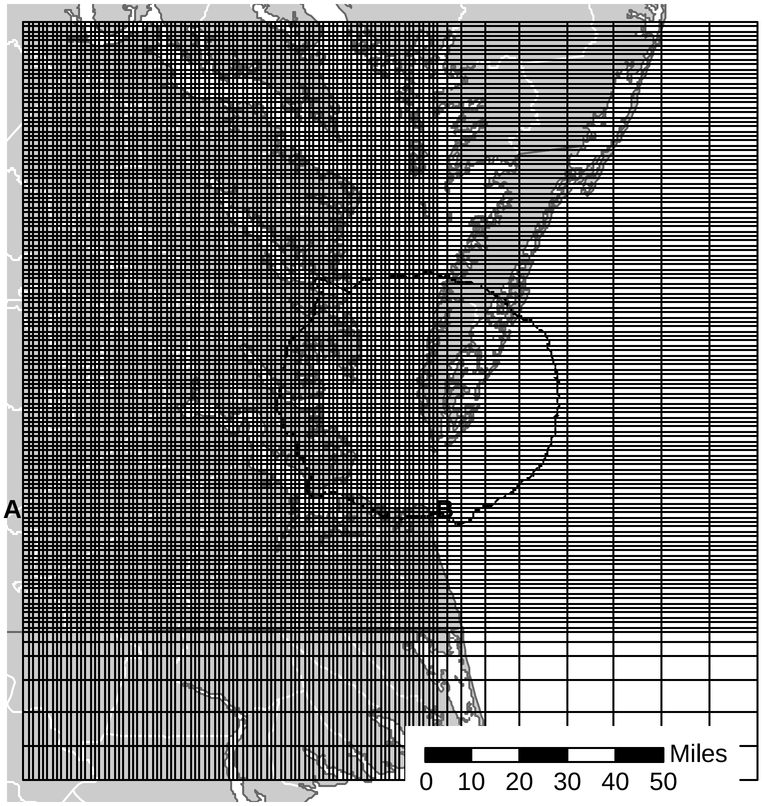

Figure 1. Finite-difference model grid over Virginia and adjacent parts of Maryland and North Carolina, location of Chesapeake Bay Impact Crater (B) and cross section.

The new finite-difference ground-water model grid (Figure 1), composed of 134 rows, 96 columns, and 60 layers, was developed using SEAWAT-2000 (Langevin and others, 2003) to provide good spatial resolution on a regional scale while retaining acceptable computer execution time. Most of the model domain is covered with a one-square mile grid cells, but the cell spacing increases to maximum dimensions of 7 and 10 miles in North Carolina and east of mainland Virginia, respectively. The vertical thickness of the upper 48 layers is uniformly 35 feet, and increases through 50 feet to a maximum of 100 feet (figure 2). This relatively fine vertical discretization was needed both to faithfully represent the hydro-stratigraphic framework, and to simulate the slope of the saltwater transition zones within aquifers. Land surface elevations and bathymetric depths obtained from digital elevation models (DEMs) defined the uppermost active layer in a particular row and column. The 24,486 mi^2 area encompassed by the grid extends from the Fall Zone in the west toward the continental shelf-slope break in the east, and from 31 miles south of the Virginia – North Carolina state line to about 25 miles north of Point Lookout in Maryland. The grid-covered area is almost twice the area of the Coastal Plain in Virginia (13,000 mi^2), although areas on the continental shelf and in North Carolina have wide column and row spacing, respectively, and therefore did not significantly increase execution times. The eastern continental-shelf grid extension was required to investigate the evolution of the salt-water transition zone through a series of Pleistocene glaciations (Heywood, 2003). The North Carolina extension avoids model-boundary effects near large simulated withdrawals in southern Virginia, and enables specification of North Carolina withdrawals which influence regional water levels. The 113-year historical transient simulation was time-discretized into 34 stress periods of various lengths. A time-step multiplier of 1.4 was chosen so that the initial time-step length of each stress period was approximately 33 days.

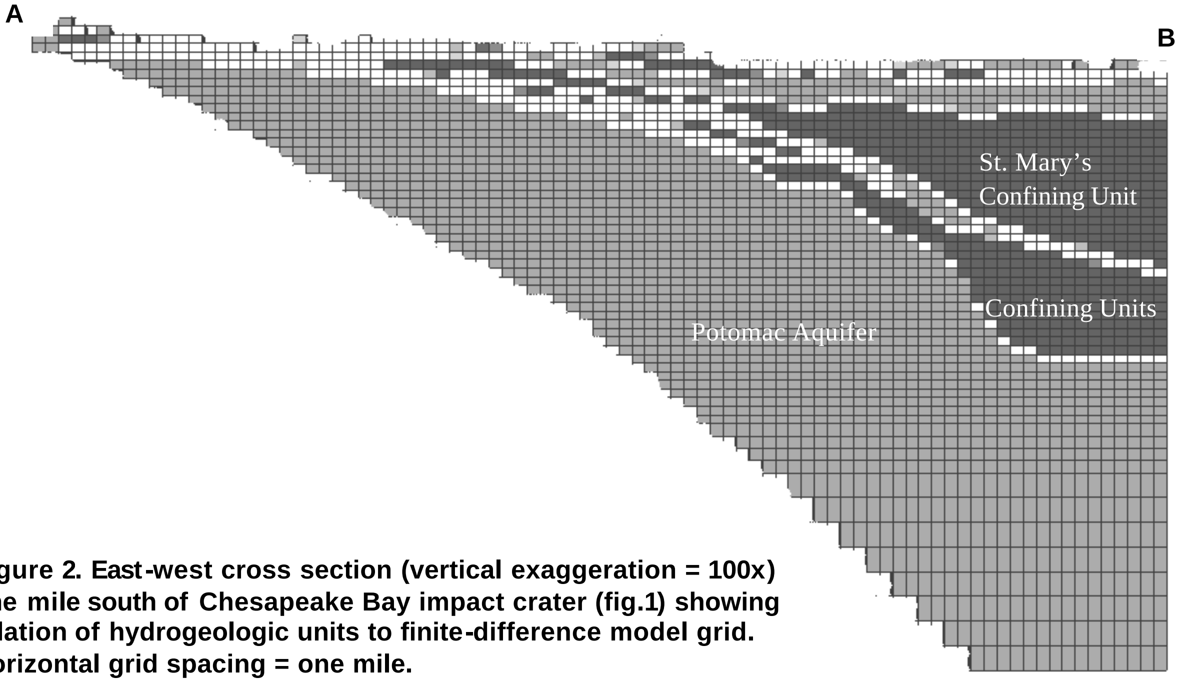

Figure 2. East-west cross section (vertical exaggeration = 100x) one mile south of Chesapeake Bay impact crater (fig.1) showing relation of hydrogeologic units to finite-difference model grid. Horizontal grid spacing = one mile.

McFarland and Bruce (2006) utilized borehole electric logs with core and drill-cutting samples to delineate the horizontal extent and depth of Virginia Coastal Plain hydro-stratigraphic units. During the course of model development, several interim versions this framework were built from Geographic Information System (GIS) coverages of unit-top elevations of the 19 constituent hydro-geologic units. Because unit-top elevations specified for the Hydrogeologic Unit Flow package (Anderman and Hill, 2000) are independent of the vertical layering of the finite-difference model grid, these separate and distinct frameworks could be incorporated and tested without modifying the model grid, or the specification of boundary conditions representing pumpage, recharge, evapotranspiration, rivers, or leakage through the Chesapeake Bay or Atlantic sea floor. The final hydro-stratigraphic framework incorporated in the model will be documented by McFarland and Bruce (2006). Reported ground-water withdrawals from 866 wells in Virginia and the portions of Maryland and North Carolina within the model domain were simulated with the Multi-Node Well Package (Halford and Hanson, 2002). Unreported domestic withdrawals comprise about 25% of the groundwater use in the Virginia Coastal Plain. Pope (2006) sampled domestic well completion records from every Virginia Coastal Plain county to statistically determine the spatial distribution of domestic ground-water withdrawals from each aquifer. Decadal census data were used to simulate the temporal increase of domestic groundwater withdrawals with the FHB package (Leake and Lilly, 1997). The effect of ground-water withdrawals in Maryland was simulated as an increasing flux out of the north side of the model domain. The chloride-concentration distribution in the CPM2006 was generated by a separate 108,000-year simulation of Pleistocene fresh-water flushing around the Chesapeake Bay Impact Crater during transient sea-level changes (Heywood, 2003). The spatially variable ground-water density distribution associated with this chloride concentration distribution was assumed constant in time because little temporal concentration data is available to indicate changes in ground-water salinity. UCODE-2005 (Poeter and others, 2005) was used to calibrate hydraulic conductivity, storage, and boundary-flux model parameters to 7183 historical ground-water level observations from Virginia, Maryland, and North Carolina.

COASTAL PLAIN MODEL DIFFERENCES AND REGULATION

Several of the differences between the original RASA and CPM2006 models of the Virginia Coastal Plain aquifer system have resource-management implications. In addition to representation of the Chesapeake

Bay Impact Crater, the hydro-geologic framework of CPM2006 includes a different conceptualization of the fluvial-deltaic Potomac aquifer system. In the RASA model, the Potomac formation was conceptually divided into lower, middle, and upper aquifers that were separated by confining units. It is not possible, however, to identify significant regionally-extensive fine-grained layers within the Potomac formation, and it is difficult to correlate low-resistivity signals between electric logs separated by more than several thousand feet. This indicates that regionally-extensive confining units within the Potomac formation do not exist, and suggests that numerous low-permeability clay interbeds have horizontal extents on the order of several hundreds of feet. The Potomac aquifer system is currently conceptualized as a three-dimensional fluvial-deltaic network of anastomosing sandy river channels and fine-grained overbank deposits. It is represented in the model as a single hydrogeologic unit, which incorporates up to 40 finite-difference cells vertically (figure 2). The discontinuous low-permeability interbeds are implicitly represented by a vertical hydraulic conductivity approximately 2 orders of magnitude less than the horizontal hydraulic conductivity. Because of this vertical hydraulic conductivity anisotropy, pumping stresses in the transient flow simulation produce vertical hydraulic head gradients within the Potomac aquifer system. The Virginia Coastal Plain ground-water regulatory scheme currently designates Potomac withdrawals from either the lower, middle or upper Potomac aquifers (or some combination) according to the RASA-era hydrogeologic framework. The Virginia Water Control Board must consider how to adapt the ground-water drawdown criteria of the withdrawal evaluation process to the new framework in order to use the CPM2006 model as a management or regulatory tool. Because existing withdrawals must be re-permitted every 10 years, the equitable transition to a new regulatory evaluation scheme may be challenging.

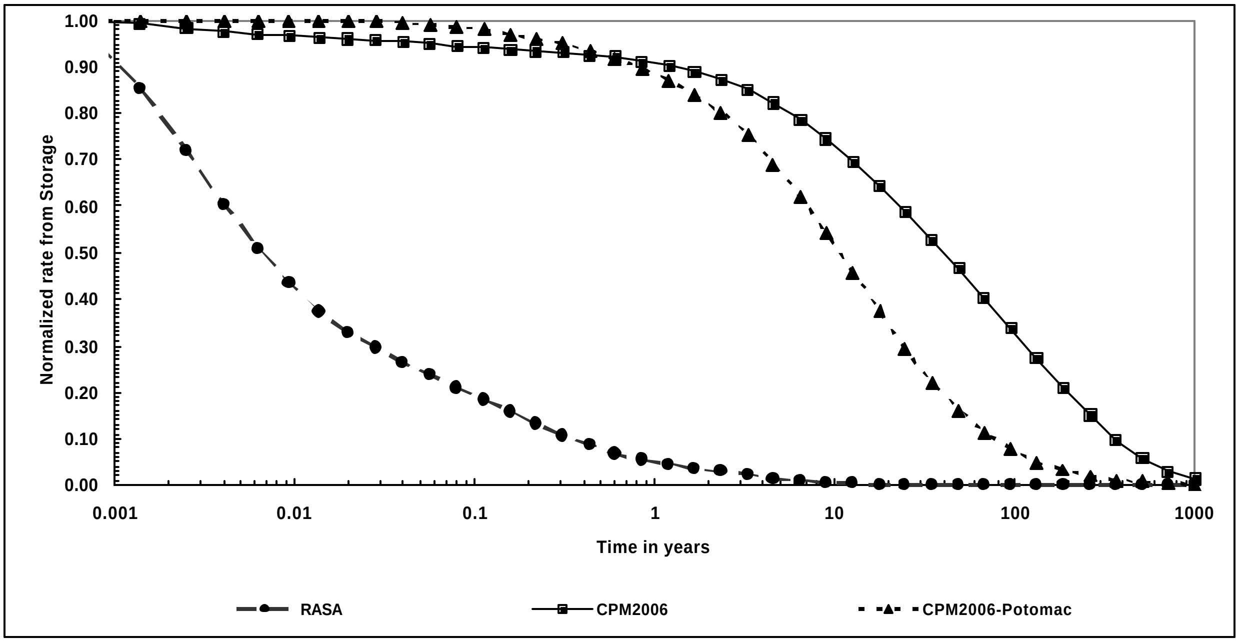

Figure 3. Normalized storage response of Virginia Coastal Plain ground-water flow models.

As a ground-water system approaches steady-state, or “stabilized conditions”, the change in ground-water storage approaches zero. In a model of a ground-water system, the rate of change in release of water from storage can be used as a measure of its proximity to steady-state conditions. Figure 3 illustrates the transient aquifer-system responses for the two Coastal Plain models in response to a large pumping stress imposed in a “maximum permitted withdrawal” simulation. Because the RASA and CPM2006 models employ different units and encompass different domains, the curves have been normalized to their respective storage release rates 5 hours after imposition of the “maximum permitted withdrawal” stress. These curves characterize the simulated aquifer-system relaxation time to a stress change in each model. Of interest are the curve inflections and the time to asymptotically approach the abscissa, indicating the time required to approach steady-state conditions. The RASA model characteristic curve shows that steady-state conditions are approached after approximately 10 years. The curve for CPM2006, in contrast, shows that more than 1000 years are required to approach steady-state conditions. This difference is primarily due to the simulation of slow drainage from low-permeability confining beds in the CPM2006 model. A secondary cause of the response-time difference is the representation of the water table as a constant-head boundary in this implementation of the RASA model, which hastens equilibration of heads in the underlying aquifers. The third characteristic curve, labeled CPM2006-Potomac, illustrates the simulated response for the relatively permeable "aquifer" materials in the CPM2006 model, including portions of the Potomac formation relatively far from the applied pumping stresses. Although the hydraulic properties of this aquifer material are similar to those specified for aquifers in the RASA model, the simulated system dynamics require over 100 years for this aquifer to approach steady-state conditions. In the real world, Coastal Plain aquifer system heads are constantly adjusting to "natural" stresses: seasonal changes in recharge, annual to decadal variations in climate (drought, for example), and centennial to millennial changes in base sea level. Approximation of the ultimate drawdown attributable to a proposed ground-water withdrawal with a steady-state solution removes consideration of time from the evaluation. Where a long response time is characteristic of the system, "stabilized conditions" may not be achievable in a relevant time frame. In that case, it may be preferable to determine the relevant time frame, through which the evaluation of simulated transient drawdown effects is made with appropriate regulatory limits.

REFERENCES

Anderman, E.R., and Hill, M.C., 2000, MODFLOW-2000, The U.S. Geological Survey modular ground-water model – documentation of the hydrogeologic-unit flow (HUF) package: U.S. Geological Survey Open File Report 00-342, 89 p.

Halford, K.J., and Hanson, R.T., 2002, User guide to the drawdown-limited, multi-node well (MNW) package for the U.S. Geological Survey's modular three-dimensional finite-difference ground-water flow model, versions MODFLOW-96 and MODFLOW-2000: U.S. Geological Survey Open File Report 02-293, 33 p.

Harsh, J.F., and Laczniak, R.J., 1990, Conceptualization and analysis of ground-water flow system in the Coastal Plain of Virginia and adjacent parts of Maryland and North Carolina: U.S. Geological Survey Professional Paper 1404F, 100 p.

Heywood, C.E., 2003, Influence of the Chesapeake Bay impact structure on ground-water flow and salinity in the Atlantic Coastal Plain aquifer system of Virginia in MODFLOW and More 2003: Understanding Through Modeling, International Ground Water Modeling Center, p. 871-875

Langevin, C.D., Shoemaker, W.B., and Guo, W., 2003, MODFLOW-2000, The U.S. Geological Survey modular ground-water model - documentation of the SEAWAT-2000 version with the variable-density flow process (VDF), and the integrated MT3DMS transport process (IMT); U.S. Geological Survey Open File Report 03-426, 43 p.

Leake, S.A., and Lilly, M.R., 1997, Documentation of a computer program (FHB1) for assignment of transient specified-flow and specified-head boundaries in applications of the modular finite-difference ground-water flow model (MODFLOW): U.S. Geological Survey Open File Report 97-571, 50 p.

McFarland, E.R., and Bruce, T.S., 2005, Distribution, origin, and resource-management implications of ground-water salinity along the western margin of the Chesapeake Bay impact structure in eastern Virginia: Chapter K of: Studies of the Chesapeake Bay Impact Structure-The USGS-NASA Langley Corehole, Hampton, Virginia, and Related Coreholes and Geophysical Surveys, U.S. Geological Survey Professional Paper 1688, 32 p.

McFarland, E.R., and Bruce, T.S., 2006, The Virginia coastal plain hydrogeologic framework, U.S. Geological Survey Professional Paper XXXX, (in review)

Poeter, E.P., Hill, M.C., and Banta, E.R., Mehl, Steffen, and Christensen, Steen, 2005, UCODE_2005 and six other computer codes for universal sensitivity analysis, calibration, and uncertainty evaluation: U.S. Geological Survey Techniques and Methods 6-A11, 283 p.

Pope, J., 2006, Domestic wells and ground-water withdrawals in the coastal plain of Virginia, U.S. Geological Survey Scientific Investigation Report XXXX (in review).

Virginia Administrative Code, 2005, Title 9: Environment, Agency 25: State Water Control Board, Chapter 610: groundwater withdrawal regulations, Section 110: Criteria for issuance of permits, Part H (9VAC25-610-110).