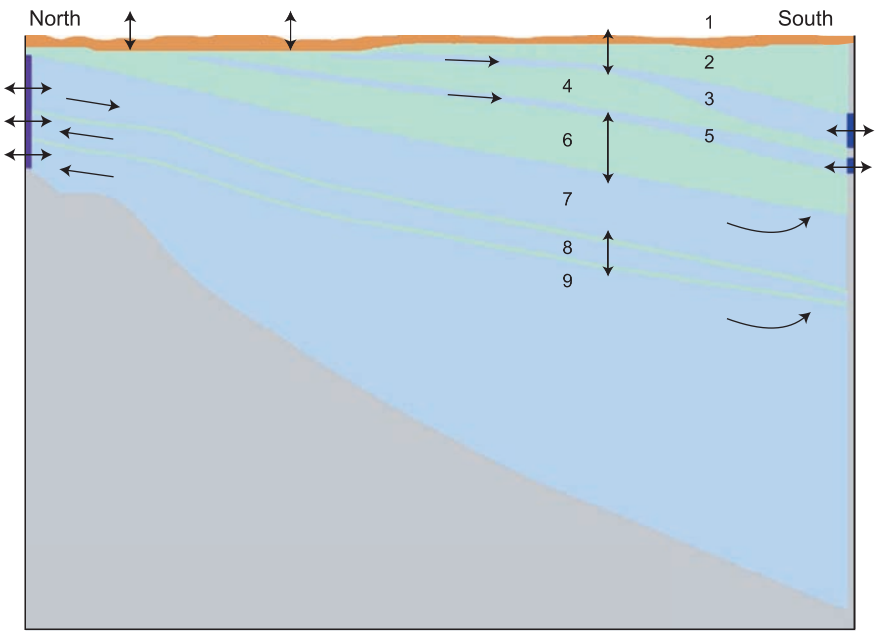
State of Delaware
DELAWARE GEOLOGICAL SURVEY
John H. Talley, State Geologist

REPORT OF INVESTIGATIONS NO. 77

SIMULATION OF GROUNDWATER FLOW IN SOUTHERN NEW CASTLE COUNTY, DELAWARE

By

Changming He and A. Scott Andres



University of Delaware
Newark, Delaware
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Acknowledgements

Reviews of the manuscript by Jim Boyle, Tom McKenna, and John Talley resulted in significant improvements and are gratefully appreciated.

Conversion factors:

Multiply	By	To obtain
meter (m)	3.28	foot (ft)
cubic meter per day (m^3/d)	264.17	gallons per day (gal/d)

Use of trade, product, or firm names in this report is for descriptive purposes only and does not imply endorsement by the Delaware Geological Survey.

SIMULATION OF GROUNDWATER FLOW IN SOUTHERN NEW CASTLE COUNTY, DELAWARE

ABSTRACT

To understand the effects of projected increased demands on groundwater for water supply, a finite-difference, steady-state, groundwater flow model was used to simulate groundwater flow in the Coastal Plain sediments of southern New Castle County, Delaware. The model simulated flow in the Columbia (water table), Rancocas, Mt. Laurel, combined Magothy/Potomac A, Potomac B, and Potomac C aquifers, and intervening confining beds. Although the model domain extended north of the Chesapeake and Delaware Canal, south into northern Kent County, east into New Jersey, and west into Maryland, the model focused on the area between the Chesapeake and Delaware Canal, the Delaware River, and the Maryland-Delaware border. Boundary conditions for these areas were derived from modeling studies completed by others over the past 10 years.

Compilation and review of data used for model input revealed gaps in hydraulic properties, pumping, aquifer and confining bed geometry, and water-level data. The model is a useful tool for understanding hydrologic processes within the study area such as horizontal and vertical flow directions and response of aquifers to pumping, but significant data gaps preclude its use for detailed analysis for water resources management including estimating flow rates between Delaware and adjacent states. The calibrated model successfully simulated groundwater flow directions in the Rancocas and Mt. Laurel aquifers as expected from the conceptual model. Flow patterns in the Rancocas and Mt. Laurel aquifers are towards local streams, similar to flow directions in the Columbia (water table) aquifer in locations where these aquifers are in close hydraulic connection.

Water-budget calculations and simulated heads indicate that deep confined aquifers (Magothy and Potomac aquifers) receive groundwater recharge from shallow aquifers (Columbia, Rancocas, and Mt. Laurel aquifers) in most of the study domain. Within shallow aquifers, groundwater moves toward major streams, while in the deep aquifers, groundwater moves toward major pumping centers.

INTRODUCTION

Southern New Castle County (SNCC) and northern Kent County (NKC) (Fig. 1) are undergoing rapid development. The Delaware Population Consortium (2005) estimates that the population will more than triple between the years 2000 and 2030 thereby increasing the total number of residents to more than 95,000. The sole source of drinking water for residents in this area comes from groundwater, and groundwater is a major source of water for agricultural and commercial concerns (Delaware WSCC, 2006).

Recent and projected increases in water demand have raised concerns about potential impacts on water availability and water quality in the aquifers of SNCC and NKC and the effects of declining groundwater levels on stream flow, wetlands, and other ecologically sensitive areas. A better understanding of the hydrogeologic system is essential in making proper and informed management decisions concerning groundwater use in this area.

Given the complexity of aquifer characteristics and development patterns, a numerical groundwater flow model not only helps in understanding and conceptualizing the current groundwater flow system, but also provides a quantitative evaluation of changes in groundwater levels under current and projected water use conditions.

Purpose and Scope

Similar to many flow model studies, the purpose of this work was to simulate flow and groundwater levels due to pumping, predict changes in flow and groundwater levels due to changes in pumping, and evaluate the completeness and suitability of existing hydrogeologic data. This report documents development of the model, the results of model calibration, and analysis of a simulated water budget and simulated flow directions.

Previous Work

In addition to SNCC and NKC, the study area for data evaluation included portions of New Castle County north of the Chesapeake and Delaware (C&D) Canal, portions of Kent County extending to the Leipsic River, portions of Maryland extending westward to Chesapeake Bay, and portions of New Jersey extending several miles from the New Jersey shore of the Delaware River (Fig. 1).

Dugan et al. (2008), the most recent compilation of existing hydrogeologic information for the study area, was the primary source of hydrologic information for this study. Interested readers are directed to that report for more detailed descriptions of geologic units and their hydrologic functions.

This study divides the Coastal Plain into six aquifers and three confining units. Further, we used the interpretation of three subunits (A, B, and C; Benson and McLaughlin, 2006) (Table 1) within the Potomac that were used in recent modeling work by the U.S. Army Corps of Engineers (USACE) (USACE, 2007). These subunits will, in some cases, be collectively referred to as the Potomac aquifers. Because the Rancocas and Mt. Laurel aquifers occur at shallower depths and their hydraulic and chemical properties are suitable for water supply, they have been the primary source of water for nearly all domestic wells and many public supply wells.

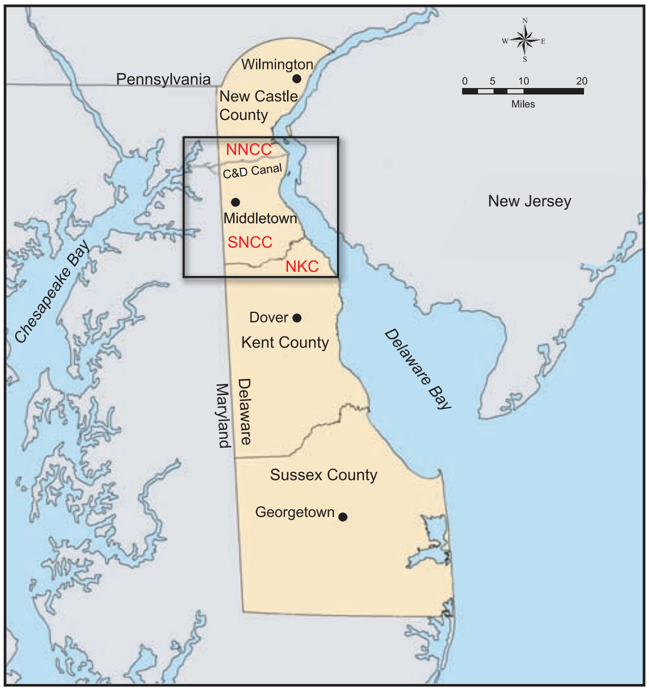

Figure 1. Location of study area. NNCC = northern New Castle County; SNCC = southern New Castle County; NKC = northern Kent County. Boxed area is the model domain.

Barring major pollution problems, it is likely that these aquifers will continue to be the major groundwater sources in this area. Over much of the study area, the Magothy and Potomac aquifers occur hundreds of feet deeper than the Rancocas and Mt. Laurel aquifers. Due to the greater cost of well construction associated with deeper drilling, only a small number of public supply wells pump water from these aquifers.

Spatial models of thicknesses and elevations of hydrogeologic units and hydraulic characteristics reported in Dugan et al. (2008) and McLaughlin and Velez (2006) are the bases of our understanding of the hydrogeologic framework of SNCC and NKC. For areas adjacent to our area of interest, additional information from groundwater simulation reports (USACE, 2007; Martin, 1998; Voronin, 2003; and Drummond, 1998, 2001) were reviewed and reconciled with those from Dugan et al. (2008). Information includes hydraulic properties and geometries of the tops and bottoms of aquifers and confining beds.

Several local-scale groundwater simulation studies have been conducted in this area. Baxter and Talley (1996) conducted a steady-state analytical modeling study and estimated water yield by aquifer. Their study did not explicitly consider flow between aquifers. Ground Water Associates (1997) conducted a MODFLOW simulation of groundwater flow in the upper Potomac aquifer and included effects of newly constructed and proposed pumping wells. This model did not explicitly model flow within the overlying aquifers and assumed vertical flow from overlying units to the upper Potomac aquifer. Using a finite-element model, the USACE conducted a study of groundwater flow in the Potomac aquifers for an area focused on New Castle County north of the C&D Canal (USACE, 2007). The model included parts of SNCC; however, the elements were too large to use in a detailed analysis of conditions in SNCC. Application of the USACE model results to SNCC is limited because the model represented aquifers and confining beds above the Potomac aquifers as a single layer of elements.

Regional-scale groundwater simulations conducted in the area include models of the New Jersey Coastal Plain (Martin, 1998; Pope and Gordon, 1998; Voronin, 2003) and of the Maryland and Delaware Coastal Plain (Fleck and Vroblesky, 1996). A key element of these models is the position of the interface between fresh and saline (total dissolved solids greater than 10,000 mg/L) waters in each of the major aquifers. Advanced modeling codes that can simulate density-dependent groundwater flow can explicitly calculate the position of this interface; however, this interface is typically represented as a no-flow boundary when density-dependent flow is not simulated. The location of the no-flow boundary can have significant impacts on simulated flow directions.

SIMULATION OF GROUNDWATER FLOW

Groundwater Flow Model

Groundwater flow was simulated using Visual MODFLOW (Schlumberger Water Systems, 2008), a 3D finite-difference groundwater modeling program. This software is an implementation of Modflow-2000, developed by the U.S. Geological Survey (USGS).

Data limitations require that model implementation be fairly simplistic. After compilation and review of groundwater-level data for the study area, we found that the distribution of wells having water-level observations extending over a sufficient length of time is very sparse. There are very few data from aquifer tests that could be used to determine storage coefficient and storativity and only one long-term streamflow monitoring site exists in the study area. The available hydrologic data are not adequate to support construction of a transient, groundwater flow model and impose serious limitations on implementation and calibration of a steady-state model.

Wells with hydraulic properties determined from reliable pumping test data are sparse in number and spatial distribution (Dugan et al., (2008), Drummond (1998), Martin (1998), Voronin (2003), and USACE (2007)). Specific capacity (Sc) data, however, are more widely available (Dugan et al., 2008). To improve initial estimates of hydraulic conductivity (K) and transmissivity (T), we used Sc to derive hydraulic conductivity from an empirically determined regression relationship between Sc and T. Usually, the correlation is better between log-transformed values of T and Sc, and the linear relationship can thus be expressed as

$$T = A * Sc^{B}$$

where A and B are regression coefficients of the power relationship (Rotzoll and El-Kadi, 2008). We used the results of this regression analysis, spatial models of aquifer thickness (b), and the relationship between hydraulic conductivity (K) and T (K= T x b) to compute point estimates of K. These values along with K values from Dugan et al. (2008) were

Table 1. Groupings of lithostratigraphic units for groundwater model layers, layer thicknesses, and elevations of layer bottoms. Confining unit names are those proposed by Dugan et al. (2008). Hydraulic properties of the Potomac aquifers are adapted from USACE (2007).

Lithostratigraphic Units (Delaware nomenclature)	Hydrostratigraphic Function	Model Layer	Thickness range (meters)	Elevation of layer bottom (meters NAVD 1988)
Scotts Corners, Lynch Heights, Columbia	Columbia aquifer	1	1 to 42	17 to -15
Calvert, Shark River, Manasquan	Blackbird confining unit	2	1 to 187	10.0 to -197
(Manasquan), Vincentown, (Hornerstown)	Rancocas aquifer	3	1 to 77	8.0 to -218
Hornerstown, Navesink	Armstrong confining unit	4	1 to 54	6.0 to -230
Mt. Laurel, (Marshalltown)	Mt. Laurel aquifer	5	1 to 35	4.0 to -257
Marshalltown, Englishtown, Merchantville	Summit confining unit	6	1 to 75	-0.6 to -260
Magothy/upper Potomac	Magothy/Potomac A aquifer	7	1 to 215	-12 to -467
middle Potomac	Potomac B aquifer	8	8 to 80	-20 to -533
lower Potomac	Potomac C aquifer	9	31 to 473	-80 to -983

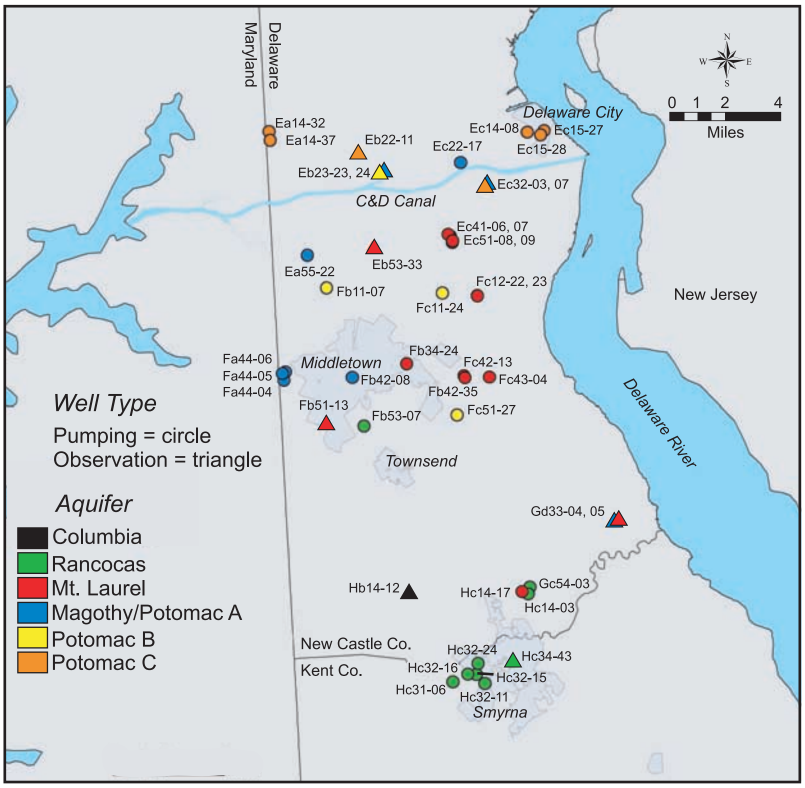

Figure 2. Locations of pumping and observation wells used in the study.

interpolated using the ordinary kriging method in Surfer (Golden Software, 2008) to estimate grids of K values for aquifer units within the study area. The K grids were then spatially averaged and grouped into conductivity zones (K zones) with similar ranges of values, adapted to the model grid, and assigned as the initial K values to begin testing and calibration of the model.

The model was calibrated by comparing model-predicted heads to heads measured in observation wells (Fig. 2) and by comparing model-predicted water budgets to previous estimates of long-term recharge rates (Johnston, 1973). Sensitivity analysis is a procedure that evaluates model response to variations in the input parameters. In one set of tests, conductance values assigned to general-head boundaries (GHBs) were varied by a factor of four. A second test evaluated the effects of altering the vertical hydraulic conductivity of the confining layer overlying the Magothy/ Potomac A aquifer on model-calculated water budgets.

To further characterize and quantify flow within the model, water-budget zones were defined for each model layer and for the boundaries along the edges of the model domain. The output of the calibrated model was used to calculate inflow to and outflow from each zone by using the Zone Budget package of Visual MODFLOW (Schlumberger Water Systems, 2008). Because our model is a steady-state model, changes in aquifer storage are not computed.

Additional Hydrologic and Geospatial Data

Groundwater-level data from Delaware were extracted from published (Martin and Andres, 2005, 2008) and unpublished in-house sources. Additional groundwater-level data from adjacent Maryland and New Jersey were extracted from the USGS NWIS Web site (http://waterdata.usgs.gov/

Table 2. Correlation of hydrostratigraphic units between states.

Model Layer (this study)	Delaware Unit	Maryland Unit	New Jersey Unit
1	Columbia	Columbia	Water table
2	Blackbird confining	Confining	Confining
3	Rancocas	Aquia	Vincentown
4	Armstrong confining	Confining	Confining
5	Mt. Laurel	Monmouth	Mt. Laurel
6	Summit confining	Confining	Confining
7	Magothy/Potomac A	Patapsco	PRM upper
8	Potomac B	Arundel (confining)	PRM middle
9	Potomac C	Patuxent	PRM lower

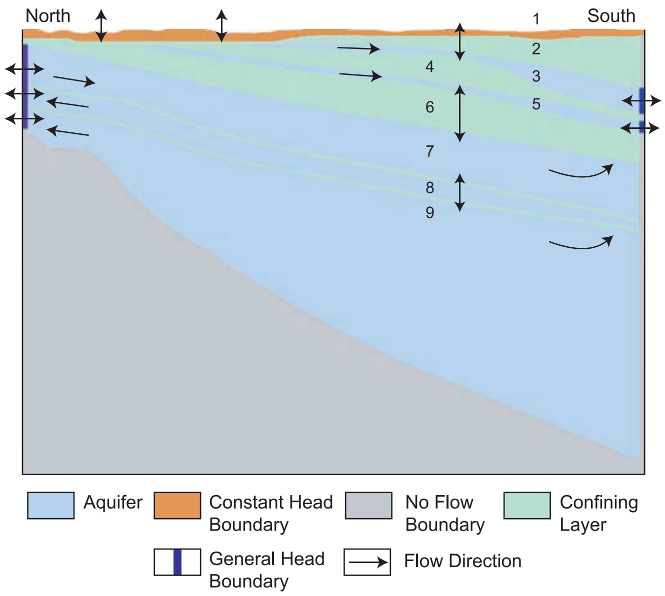

Figure 3. Conceptual model showing aquifer and confining bed geometries, boundary conditions, and groundwater flow directions. Numbers indicate model layers.

usa/nwis) and used to determine heads for constant-head boundaries in model cells located in those states.

Groundwater pumping data were obtained from the Water Allocation Branch of the Delaware Department of Natural Resources and Environmental Control (DNREC) (S. Lovell, written commun.) and supplemented with information reported by the Delaware Water Supply Coordinating Council (2006). Well locations are shown in Figure 2.

Maps produced using Visual MODFLOW were modified for publication using ArcGIS v9.2 (ESRI, 2007). Maps created in Visual MODFLOW were exported as x, y coordinate pairs along with the values of hydraulic head, elevation, etc. in ASCII format. These data were then converted to ESRI format grids for display. Smoothing algorithms in ESRI (2007) were used in the final rendering of the contour lines and color fill patterns to reduce pixelation. Base map data were downloaded from the Delaware Data MIL (http://datamil.delaware.gov) in February 2009.

Conceptual Model and Model Implementation

The regional hydrogeologic framework of SNCC has been defined by a model grid consisting of 400 columns, 320 rows, and 9 vertical layers. Each cell has dimensions of 150 m by 130 m, resulting in a total of 1,152,000 cells (681,345 active cells). The model consists of a layered sequence of six aquifers and three confining units. In general, these units thicken and dip to the southeast (Figs. 3, Figs. 4a-4i on Plate 1, and Table 1). We have presented thickness data in tabular format because there is little variation in thickness within most model layers compared to the range in thickness of the model layer representing the Potomac C aquifer. Correlations of names of our model units to those used in Maryland (Drummond, 1998, 2001) and New Jersey (Martin, 1998; Voronin, 2003) are shown in Table 2.

Because we are using a finite-difference flow modeling code, individual model layers are required to be continuous over the entire domain (Anderson and Woessner, 1992). In general, individual model layers correspond to individual aquifers and confining units. However, several of the geologic and aquifer units are truncated toward the north and west, and in some stream valleys. We followed recommendations of Reilly (2001) and assigned a minimum thickness (1 m) to areas where the aquifer(s) or confining bed(s) are missing. The spatial distributions of hydraulic properties of these layers are described in a later section.

Layer 7 includes the combined Magothy and Potomac A aquifers, which are referred to as the Magothy/Potomac A aquifer and is included in the general category of Potomac aquifers. The Magothy/Potomac A aquifer is simulated as a single model layer because of the discontinuous nature of Magothy sands and the absence of data to describe the thickness and extent of the intervening confining unit in the study area.

Representation of the water-table and surface-water features in the model is complicated by the fact that cross-cutting relationships between land surface, water table, and hydrogeologic units cause surface-water features (streams, swamps, and marshes) and the water table to intersect the five uppermost hydrogeologic units and the model layers that are used to represent them. This is a problem for numerical modeling because in some areas the water table occurs in hydrogeologic units beneath the Columbia aquifer and the

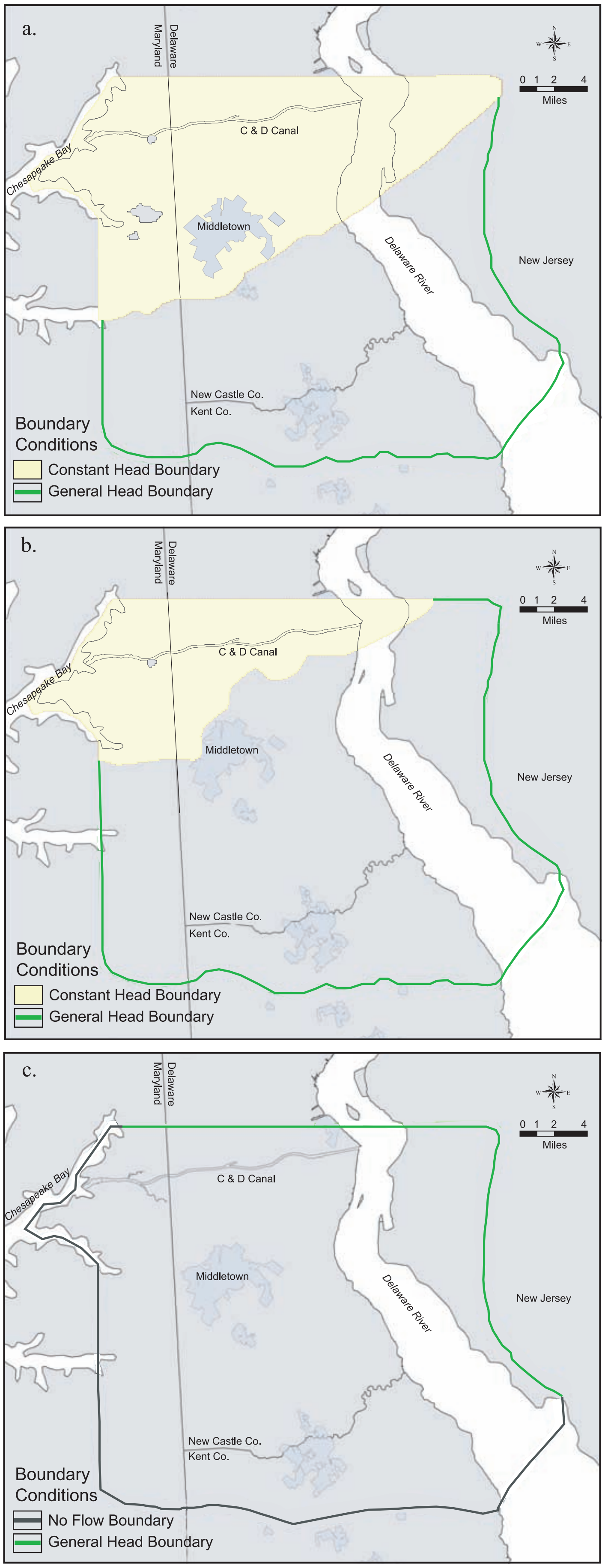

Figure 5. Boundary conditions for (a) layer 3 (Rancocas aquifer), (b) layer 5 (Mt. Laurel aquifer), and (c) layers 7, 8, and 9 (Potomac aquifers).

Columbia aquifer is unsaturated. In order to avoid known problems with numerical instability and non-convergence in the model caused by unsaturated model cells, we represent the water table as a constant-head layer. In areas where the water table occurs below the base of the Columbia aquifer, constant-head nodes representing the water table were placed in the uppermost saturated layer which, depending on location, would be in the Rancocas aquifer or Mt. Laurel aquifer (Figs. 5a and 5b). A similar strategy was employed to place constant-head nodes representing bodies of surface water in the proper model layer.

General-head boundaries (GHB) were used to represent many of the boundaries along the edges of the model domain (Figs. 5a-5c). A uniform value of 1000 m^2/day was initially set as conductance of the GHB cells. This value was changed during calibration.

Head values for GHB cells in the Rancocas (Fig. 5a) and Mt. Laurel aquifers (Fig. 5b), located along the eastern and western boundaries, were estimated from Martin (1998) and Drummond (1998), respectively. Setting head values for GHB cells in the Rancocas and Mt. Laurel aquifers for the southern boundary proved to be problematic. With only one observation well in the Rancocas aquifer in the area, head values for the boundary were estimated from a few sparsely distributed water-level measurements abstracted from well completion reports.

GHB head values for the Potomac aquifers (layers 7, 8 and 9) along the northern and eastern boundaries were derived from the models of USACE (2007), Martin (1998), and Voronin (2003). No-flow boundaries were defined for Potomac aquifers along the western edge of the model domain because no data were available to define the heads, and the distance to the boundary is great enough to limit boundary effects (Fig. 5c). A no-flow boundary is specified on the bottom of the model domain to represent crystalline basement rock and overlying saprolite. A no-flow boundary was set around the edge of the model for all confining units (layers 2, 4, and 6).

A no-flow boundary was set on the southern boundary of the model for the Potomac aquifers (Fig. 5c) to represent the occurrence of an interface between saline (total dissolved solids greater than 10,000 mg/L) and fresh waters in the Potomac aquifers as postulated by Meisler (1981) and Pope and Gordon (1998). The interface between fresh and saline water is commonly modeled as a no-flow boundary (Reilly, 2001).

Model Input

Head values for cells representing the water table and surface-water features were derived from the digital water-table model of Martin and Andres (2005) and from Drummond (1998) and Martin (1998). These data were then adapted to the model grid (Fig. 6) and conceptual model.

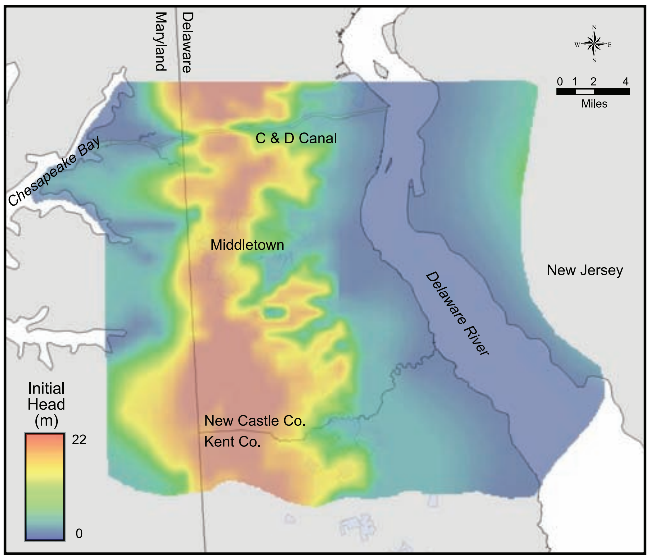

Figure 6. Constant-head values used for uppermost saturated layer.

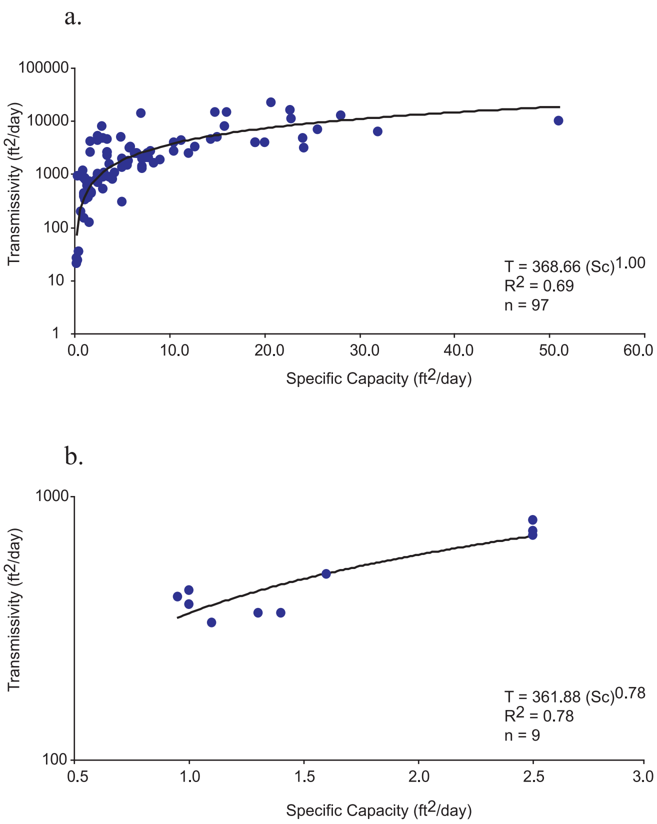

Figure 7. Relationships between specific capacity and transmissivity (a) using all available data, and (b) using data from the Mt. Laurel aquifer.

The results of regression analysis of T and Sc for all the available data are shown in Figure 7a, and the results of regression analysis using data from the Mt. Laurel aquifer are shown in Figure 7b. The spatial distributions of horizontal hydraulic conductivity within model layers was determined by gridding observations and estimates of K, spatial averaging of results into zones of similar K values, and conditioning by calibration for all nine layers, which are illustrated in Figures 8a - 8g (Plate 2).

Sedimentary deposits typically exhibit anisotropic hydraulic properties – specifically, they are more permeable in the horizontal direction than they are in the vertical direction (Anderson and Woessner, 1992). The magnitude of anisotropy is poorly understood for the study area. As a result, an initial value of 10:1 was selected for the starting vertical anisotropy ratio of K (horizontal K : vertical K). This initial anisotropy value was adjusted during the calibration process.

Hydraulic conductivity for layers representing confining units (layers 2 and 4) vary from very low values in the southeast to higher values in the northwest. Areas with lower K values represent locations where confining units are thick; areas with higher K values represent locations where an individual confining unit is missing due to erosional truncation or stratigraphic pinch out. To avoid numerical instability due to sharp changes of K, several transition zones were added in which K values vary gradually (Figs. 8b, 8d).

Simulation of groundwater pumped by wells (Fig. 2) from confined aquifers was limited to those wells having reported water use in the DNREC water use database (S. Lovell, personal communication). Simulated pumping rates (Table 3) are averages of those reported in this database. Because the Columbia aquifer was modeled as a constant-head boundary, pumping wells located in this layer were not simulated in our model.

Calibration and Sensitivity Analysis

Model calibration for head falls within acceptable ranges, that is, root mean square error is less than 10 percent of the difference between minimum and maximum head (Table 4, Fig. 9). The primary changes made to K during calibration were adjustments to values assigned to individual K zones, rather than adjustments to the spatial sizes and shapes of the zones. It is worth repeating that more observation wells in each aquifer are required to improve the accuracy of the model.

Rigorous model calibration cannot be done with the current model design and data limitations. A rough check on the ability of the model to accurately simulate flow volumes was done through evaluations of water budgets. The model-computed water budget for the Columbia aquifer, derived from summing all water added by constant-head nodes, indicated a recharge rate of 20.6 cm/yr, or roughly 50 to 80 percent of recharge rates estimated from hydrograph separation analysis (Table 4, Johnston, 1973). The difference between predicted and observed recharge rates may be partially due to the fact that a constant-head boundary was used to represent the Columbia aquifer. The difference between predicted and observed recharge rates may also be partially explained by the specific streams used by Johnston (1973) and uncertainty due to estimation procedures. When data become adequate to support more sophisticated models, we expect that flow calibrations can be improved by explicitly computing heads in the Columbia aquifer.

In this study, several simplifications and assumptions about boundary conditions and parameter values were made

Table 3. List of production wells and pumping rates used in steady-state model. Rates are averages reported in DNREC water-use database. Note: gpm = gallons per minute.

Aquifer	DGSID	Pumping Rate (gpm)	Pumping Rate increased by 170% (gpm)
Rancocas	Fb53-07	39	105
	Gc54-03	81	219
	Hc14-03	123	332
	Hc31-06	1	3
	Hc32-15	41	111
	Hc32-16	14	38
	Hc32-24	44	119
	Hc33-11	33	89
	Total	**377**	**1018**
Mt. Laurel	Ec41-05	1	3
	Ec41-06	88	238
	Ec41-07	3	8
	Ec41-25	143	386
	Ec51-08	1044	2819
	Ec51-09	506	1366
	Fb34-24	175	473
	Fc12-22	12	32
	Fc12-23	33	89
	Fc42-13	27	73
	Fc42-35	1	3
	Fc43-04	32	86
	Hc14-17	31	83
	Total	**2096**	**5659**
Magothy/ Potomac A	Ea55-22	71	192
	Ec22-17	189	510
	Fa44-04	1	3
	Fa44-05	16	43
	Fa44-06	16	43
	Fb42-08	4	11
	Total	**297**	**802**
Potomac B	Fb11-07	155	419
	Fc11-24	13	35
	Fc51-27	8	22
	Total	**176**	**475**
Potomac C	Ea14-32	423	1142
	Ea14-37	662	1787
	Ec15-27	92	248
	Ec15-28	91	246
	Ec14-08	680	1836
	Total	**1947**	**5257**

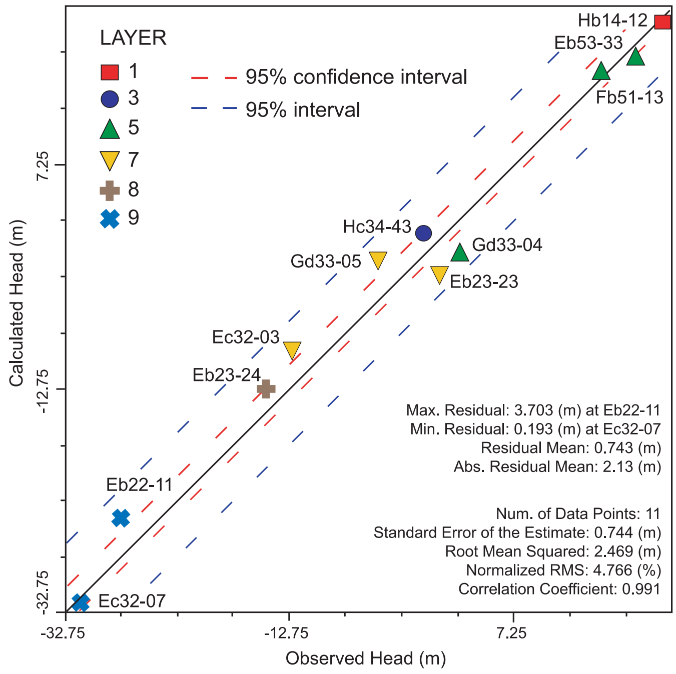

Figure 9. Comparison of calculated vs. observed head: steady state.

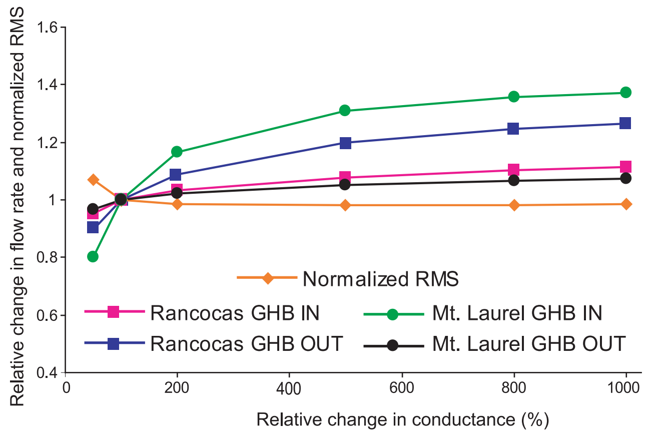

Figure 10. Results of sensitivity analysis comparing relative changes in simulated flow and head RMS error to relative changes in conductance of general-head boundaries.

because of limited data. This has, of course, consequences for the accuracy of the results and for the reliability of the model. To evaluate the sensitivity of the model (e.g., flow directions and flow rate between different layers) to changes in conductance values of GHBs, conductance values were decreased by 50 percent below, and increased up to 1,000 percent above the calibrated parameter value during the sensitivity analysis (Fig. 10). Results indicated that the changes in magnitude of model flux responses were less than the changes in magnitude applied to GHB conductance values. RMS errors behaved similarly to fluxes.

Water Budget and Flow Directions

Results of water-budget calculations (Fig. 11a) indicate that there is significant inflow to the Rancocas aquifer and Mt. Laurel aquifer from the water-table constant-head boundary, and most inflow occurs where these aquifers are

Table 4. Model calibration results. Note: min = minimum; max = maximum; water levels measured in the last ten years were used to calculate minimum, maximum, and average values.

DGSID	Layer	Aquifer	Observed Head Min (m)	Observed Head Max (m)	Observed Head Average (m)	Simulated (m)
Eb22-11	9	Potomac C	-23.72	-30.09	-27.93	-24.22
Eb23-23	7	Potomac A	1.97	-1.36	0.49	-2.57
Eb23-24	8	Potomac B	-12.69	-18.08	-15.03	-12.71
Eb53-33	5	Mt. Laurel	17.39	18.85	17.97	16.91
Ec32-03	7	Potomac A	-9.01	-14.88	-12.62	-9.26
Ec32-07	9	Potomac C	-26.32	-34.30	-31.52	-31.71
Fb51-13	5	Mt. Laurel	14.73	15.06	14.85	15.65
Gd33-04	5	Mt. Laurel	3.15	1.66	2.30	-0.57
Gd33-05	7	Magothy	-3.36	-6.49	-4.92	-1.32
Hb14-12	1	Columbia	19.34	21.85	20.28	19.86
Hc34-43	3	Rancocas	-0.08	-1.74	-0.95	1.10

located directly beneath and in hydrologic contact with the Columbia aquifer. Water-budget calculations also show that a majority of this flow exits the model through constant-head nodes in the Columbia, Rancocas, and Mt. Laurel aquifers (Fig. 11b), which is consistent with the conceptual model for the area; however, this finding highlights a shortcoming of the model. Because the water-table aquifer is represented as a constant-head boundary, the model cannot predict the effects of pumping from the Columbia aquifer on flow to and from the underlying aquifers.

Due to the interaction between aquifer and confining bed geometries, topography, bodies of surface water, and pumping wells, groundwater flow directions exhibit complex spatial variability in the vertical direction. Head differences between the Rancocas and Mt. Laurel aquifers illustrate this finding (Fig. 12). In general, the Mt. Laurel aquifer is replenished in the subcrop area in the northern portion of the model domain in topographically high areas where the constant-head water-table boundary is coincident with the Mt. Laurel aquifer or by vertical flow from the Columbia aquifer to the Mt. Laurel aquifer. In areas within stream valleys, groundwater flows upward from the Mt. Laurel aquifer to water-table constant-head boundaries in the Rancocas aquifer or the Columbia aquifer, indicating that the Mt. Laurel aquifer contributes to streamflow. In the southern part of the model domain, head differences indicate the potential for upward flow from the Rancocas aquifer to the Mt. Laurel aquifer, with the flow rate dependent on the head differences and the hydraulic properties of the intervening confining unit.

Complex interactions between aquifer geometries, topography, bodies of surface water, and pumping wells also create complex spatial variability in horizontal flow directions. Flow directions within the Rancocas and Mt. Laurel aquifers are directed from cells underlying topographically high areas toward cells representing streams, the C&D Canal, and marshes fringing tributaries to Chesapeake Bay and the Delaware River (Figs. 13a, 13b).

Throughout most of the model domain, predicted heads in the Rancocas and Mt. Laurel aquifers are above sea level. Due to heads in GHB cells, predicted heads in these aquifers are below sea level in the southeasternmost portion of the model domain. This prediction cannot be verified because the heads below sea level in this area were derived from a few driller-reported water levels abstracted from well completion reports. If the head predictions in the southeastern portion of the model domain are correct, they indicate the potential for downward flow of salty water from the overlying marsh and tidal streams to the Rancocas aquifer. This finding underscores a recommendation from Dugan et al. (2008) for exploratory drilling and new monitoring wells to be located in this area.

Water-budget results indicate that the GHB cells on the edges of the model domain are the primary source of water for the Magothy/Potomac A aquifer rather than vertical leakage from overlying layers (Figs. 11 and 14). Data are not sufficient to document locations where most of the vertical flow is occurring; however, the maximum head differences between the Mt. Laurel aquifer and the Magothy/Potomac A aquifer (Fig. 15) are coincident with the area of highest head within the Mt. Laurel aquifer (Fig. 13b).

Model simulations show that flow rate between the Mt. Laurel aquifer and the Magothy/Potomac A aquifer is sensitive to increases in K of the Summit confining unit (layer 6) (Fig. 14). An increase in the value of vertical K for the Summit confining unit increases the amount of vertical leakage into the Magothy/Potomac A aquifer from above and decreases the amount of flow into this aquifer from GHB cells along the northern boundary of the model. Results indicate that the source of the added water moving downward is the water-table constant-head boundary rather than other boundary cells (Figs. 11, 14).

The significant dependence of flow rates on vertical K values indicates the need for obtaining data on the hydraulic properties of the Summit confining unit. If the rate of vertical flow is small, then pumping in the study area will induce flow from areas north of the C&D Canal where pumping has already caused water levels to be drawn down far below sea level. If the rate of vertical flow is large, then increased pumping in the Potomac aquifers will induce flow from the overlying layers, thus reducing the amount of water available for shallower wells and maintaining streamflow.

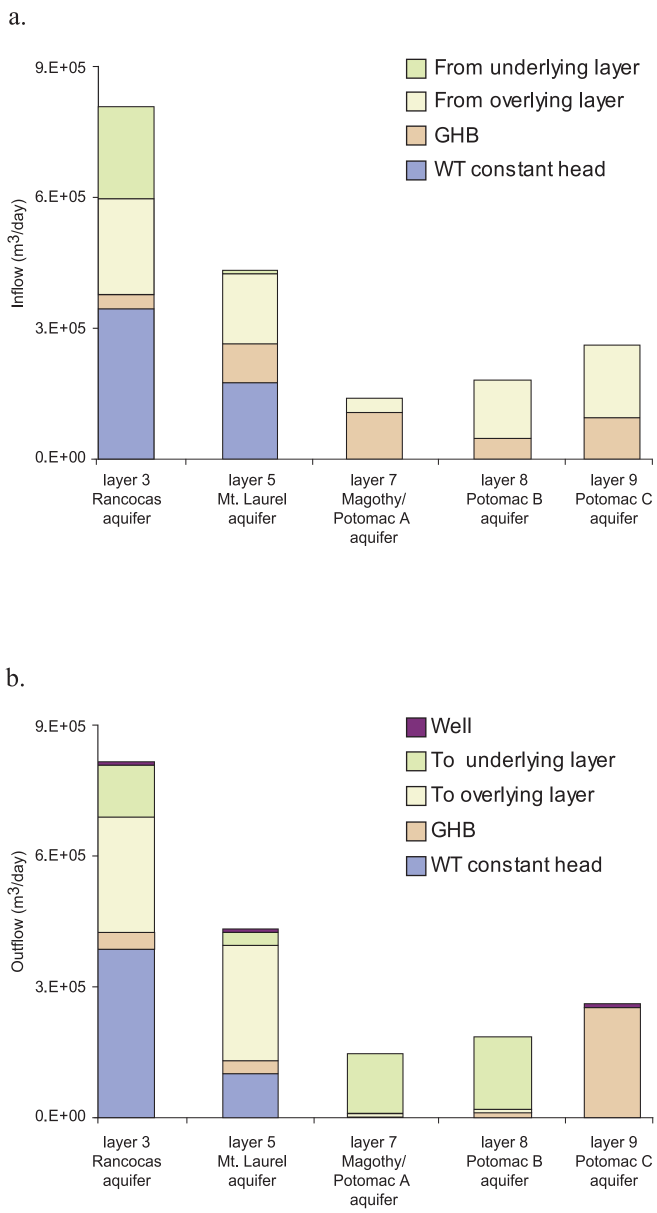

Figure 11. Simulated water budgets - comparison of (a) inflow and (b) outflow rates between aquifers and surface-water boundaries. GHB = general head boundary; WT = water table.

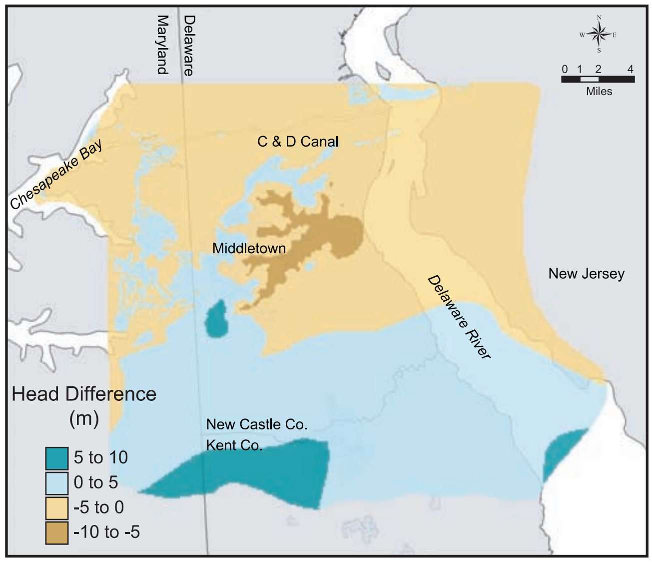

Figure 12. Predicted difference in head between layer 3 (Rancocas aquifer) and layer 5 (Mt. Laurel aquifer). Positive value indicates head value in the Rancocas aquifer is greater than in the Mt. Laurel aquifer.

Model-computed water budgets indicate that the vast majority of water in layers 8 and 9 (Potomac B and C aquifers) is derived from vertical flow from layer 7 (Magothy/Potomac A aquifer) (Fig. 11a). The model predicts that this water exits the model domain through GHB cells in layer 9 (Fig. 11b). Contour maps of head indicate that the majority of water is leaving the model domain along the northern boundary of the model area (Figs. 16b, c) in layers 8 (Potomac B) and 9 (Potomac C).

Flow directions in the Magothy/Potomac A aquifer (layer 7; Fig. 16a), are directed toward wells pumping water from that layer. Similar relationships between flow directions and pumping wells are observed in the Potomac B (layer 8) and Potomac C (layer 9) aquifers. Consistent with findings of USACE (2007) and long-term monitoring data, the model predicts that minimum heads in all of the Potomac aquifers are below sea level over large portions of the area south of the C&D Canal. In considering these findings it is important to note that GHB conditions for the northern boundary of the model strongly influence flow directions in the Potomac aquifers.

Predicted Effects of Increased Pumping

The Delaware Water Supply Coordinating Council (Delaware WSCC, 2006) projected that the demand for public water supply in southern New Castle County will increase by approximately 170 percent between 2006 and 2030. To understand how this increased pumping may affect groundwater flow and water budgets, we assumed that this increased demand will be supplied by existing wells (Fig. 2, Table 3), and simulated the increased water demand by increasing concurrently the pumping rate for all current production wells by 170 percent (Table 3). Because it is certain that new wells will be installed to meet the increased demand, and because the locations of these new wells cannot be predicted, the results are highly speculative. GHB conditions for the northern boundary were not changed for this simulation.

Comparison of predicted water levels during increased pumping to previous model-simulated results (Figs. 17a-17e on plate 2) indicates that the maximum head decline in the Rancocas aquifer will be approximately 2.5 meters (8.2 ft) (Fig. 17a), which occurs at the wells serving the James T. Vaughn Correctional Center located northeast of Smyrna. The maximum head decline (about 4 meters or 13.1 ft) in the Mt. Laurel aquifer (Fig. 17b) occurs between Middletown and Odessa, with additional areas of decline coincident with the wells serving the James T. Vaughn Correctional Center and an additional area west of Clayton.

Effects of increased pumping in the Potomac aquifers indicate maximum additional drawdown to be in the range of

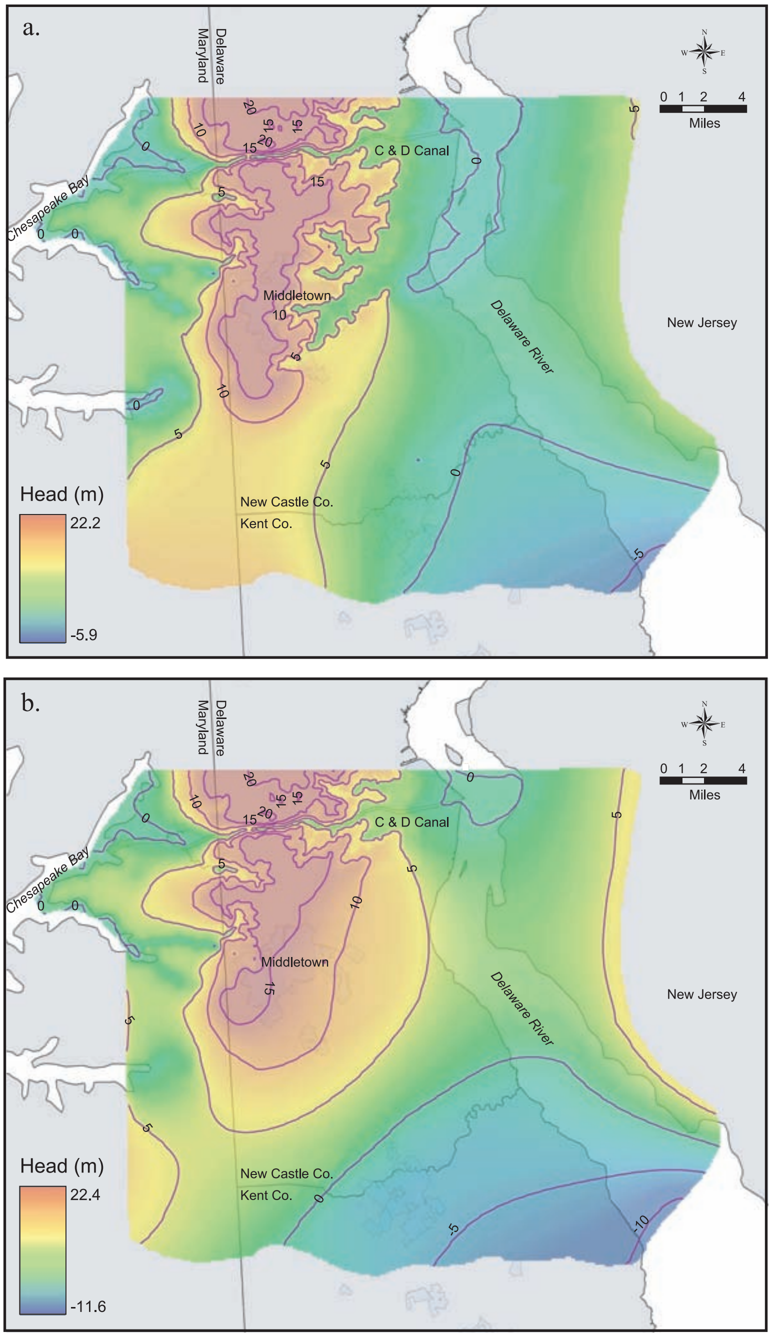

Figure 13. Model computed heads for (a) layer 3 (Rancocas aquifer) and (b) layer 5 (Mt. Laurel aquifer).

a few meters (Figs. 17c-17e on Plate 2). Given that there are little field data with which to evaluate how reasonable these predictions are, and that new wells are likely to be installed by water utilities at additional locations, these results are useful only for illustrative and discussion purposes, rather than planning purposes.

CONCLUSIONS

Water-budget calculations and predicted head differences between aquifers indicated significant flow between the Rancocas, Mt. Laurel, and Columbia aquifers, especially in updip areas where the confining unit between the aquifers is thin. Farther to the south, where confining units between the Rancocas, Mt. Laurel, and Columbia aquifers are thicker, flow paths and water budget calculations indicated that flow is towards the Delaware River, a regional hydrologic boundary.

The model predicted head patterns in the Magothy/Potomac A, Potomac B, and Potomac C aquifers that are similar to those in previous modeling studies. Pumping in the Magothy/Potomac A aquifer from wells located in southern New Castle County has lowered heads and is directing flow to the pumping center near Delaware City. Pumping from wells in the Potomac B and Potomac C aquifers in New Castle County has lowered heads in these aquifers both north and south of the canal and causes flow to be directed north towards northern New Castle County pumping centers.

Water-budget calculations indicated that there is significant movement of water from the Magothy/Potomac A aquifer downward to the Potomac B and Potomac C aquifers. The predicted flow of water from the Columbia, Rancocas, and Mt. Laurel aquifers to the deeper Magothy/Potomac A, Potomac B, and Potomac C aquifers is highly dependent on the hydraulic properties of the confining bed between the Mt. Laurel aquifer and the Magothy/Potomac A aquifer. This finding supports the need for hydraulic data from the confining layer and indicates the potential for pumping from Potomac aquifers to impact groundwater and streams in southern New Castle County.

Groundwater simulations performed by numerical models are now the state of the practice for professional and research assessments of groundwater availability and determination of sustainable water use for an area. Model predictions are only as good as the information used to construct and calibrate models. In this regard, there are several improvements to numerical models that could make results more useful for water management.

As noted in previous sections, there are very few locations in the study area where groundwater - level and streamflow observations have been made. Without suitable water-level data to compare to model output, it is not possible to determine how well the model simulates flow and head distributions within and between multiple aquifers. This is a clear indication that more monitoring locations are needed. Proposed locations for new wells are described by Dugan et al. (2008).

Groundwater pumping rates used in this model are averages computed from incomplete water-use records. These data are inadequate for future work that simulates time-dependent responses of aquifers to seasonal and annual changes in climate and pumping. Accurate and complete water pumping records for large capacity water wells are needed to allow any model to simulate field conditions of head and flow.

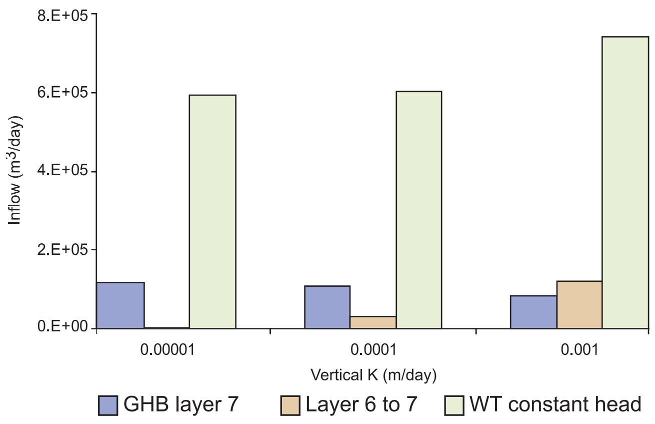

Figure 14. Comparison of flow rates from upper aquifers to layer 7 (Magothy/Potomac A aquifer) and flow rates between Potomac aquifers by varying hydraulic conductivity (K) of layer 6 (overlying confining layer). GHB = general head boundary; WT = water table.

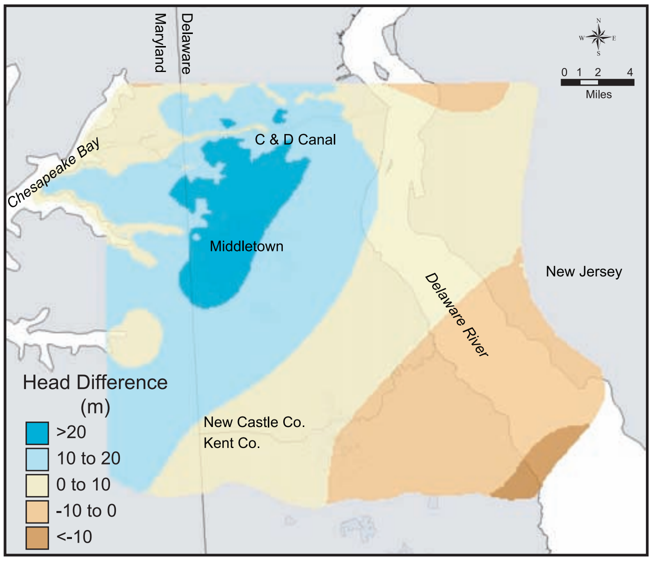

Figure 15. Predicted differences in head between layer 5 (Mt. Laurel aquifer) and layer 7 (Magothy/Potomac A aquifer). Positive value indicates head value in the Mt. Laurel aquifer is greater than the Magothy/Potomac A aquifer.

Aquifers in the Potomac Formation provide a large portion of water currently being pumped and represent the largest potential additional source of water for the area, yet data required to accurately portray the geometry, hydraulic properties, and head distribution of aquifers and confining beds within the model domain are absent. This lack of information highlights a critical need for additional information required to support planning of future water supplies and wastewater disposal, and management of water-dependent environmental resources.

RECOMMENDATIONS

We recommend that the current model continue to be modified and updated as more data become available. The general plan for modifications is as follows:

1. Following collection and analysis of additional groundwater level and streamflow data, model the water-table aquifer as a dynamic layer (e.g., without constant-head boundary condition).
2. Following collection and analysis of additional groundwater level, aquifer hydraulics, and pumping data for the Rancocas and Mt. Laurel aquifers, construct a transient model to evaluate seasonal and annual climate and pumping effects on groundwater and stream flow.
3. Following collection and evaluation of additional groundwater level and aquifer hydraulics data for aquifers in the Magothy and Potomac Formations, and hydraulics data for intervening confining units and the overlying Summit confining unit, reconstruct the model and conduct steady state simulations.

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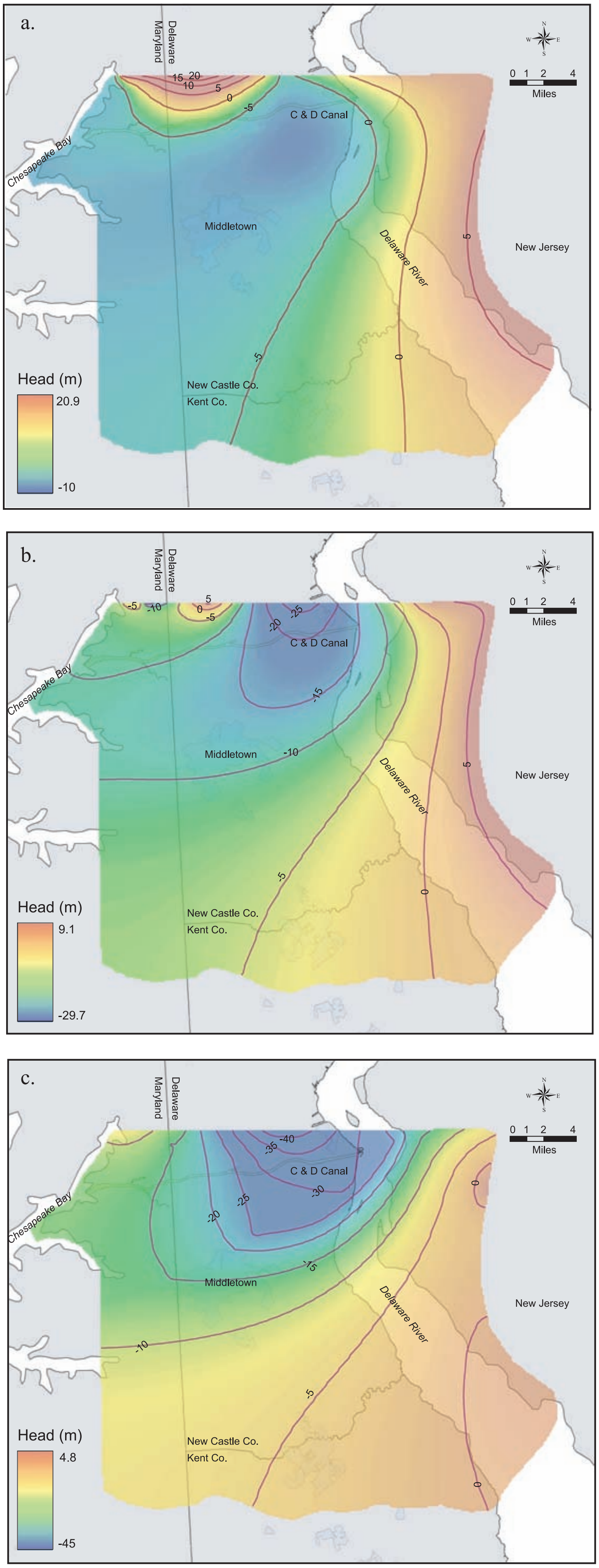

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