INFLUENCE OF THE CHESAPEAKE BAY IMPACT STRUCTURE ON GROUND-WATER FLOW AND SALINITY

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KEYWORDS: ground water, simulation, impact structure, salinity, variable-density flow

ABSTRACT

A preliminary three-dimensional variable-density ground-water flow model of the Virginia Coastal Plain aquifer system was constructed to investigate the occurrence of saltwater in the area of the Chesapeake Bay Impact Crater. Anomalously high salinities are observed in and around the crater, which is filled with low-permeability tsunami deposits. Simulations support the idea that preferential flushing occurred through hydraulically conductive parts of the aquifer system, while salt water was retained in low-permeability areas, including the crater fill. The persistence of saltwater within the crater throughout the Pleistocene places an upper bound on the effective hydraulic conductivity of the tsunami-breccia. Appreciable pumping stress is occurring in southeastern Virginia; consideration of miscible, density-dependent flow in this area improves the accuracy and potential usefulness of the ground-water model as a management tool.

INTRODUCTION

Multiple marine transgressions and regressions since the Cretaceous Period have deposited a sequence of unconsolidated marine sands and clays over Cretaceous fluvial-deltaic sediments in the Atlantic Coastal Plain of eastern Virginia. Approximately 35 million years ago, an asteroid or comet impact disrupted Lower Cretaceous through Middle Eocene sediments near the mouth of the present day Chesapeake Bay (Poag and others, 1994). Cederstrom (1943) mapped the distribution of dissolved solids in ground water in the Atlantic Coastal Plain of Virginia, and noted an “inland wedge” of anomalously high concentration near the southern Chesapeake Bay (fig. 1). The near coincidence of the Chesapeake Bay impact structure suggests geologic control of the observed salinity distribution (Powers and Bruce, 1999). Chemical analyses of ground water indicate a pre-Pleistocene seawater source of salt within the impact structure (McFarland, 2002). Brine within the crater may have formed by heating of the crater-fill slurry following impact (Sanford, 2003), and would therefore be of a similar age as the crater. The persistence of saltwater within the crater through the Pleistocene, and possibly since the Eocene, suggests that low permeability of crater-fill sediments and small hydraulic gradients prevented fresh-water flushing across the impact structure.

The sequence of lower Cretaceous to Holocene sands and clays, which dip and thicken to the east, comprise the Coastal Plain aquifer system in Virginia. Consolidated lower Mesozoic rift-basin and older crystalline bedrock west of the fall line (the western extent of the Coastal Plain aquifer system) extend eastward at depth and underlie the unconsolidated Coastal Plain

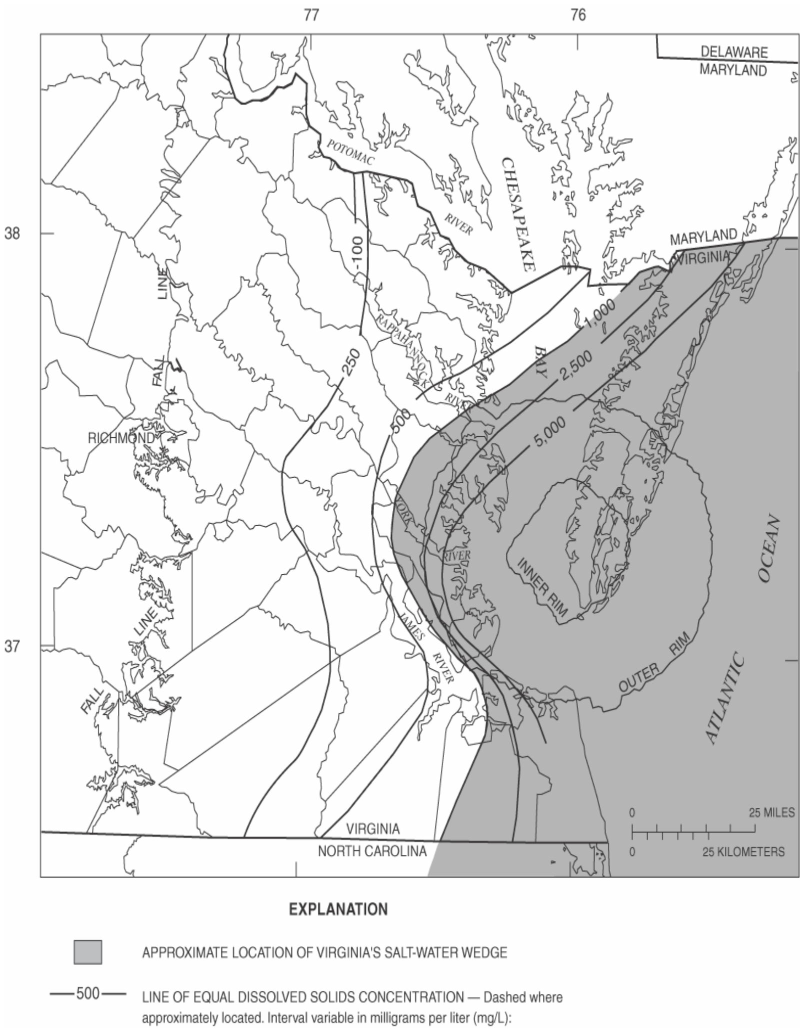

Figure 1. Dissolved-Solids Concentrations in the Potomac Aquifer and Location of the Chesapeake Bay Impact Crater. (North is up on all figures.)

sedimentary strata. The asteroid or comet impact excavated these strata to bedrock within the inner crater rim (fig. 1), which subsequently backfilled with tsunami deposits to produce a heterogeneous, fining upward formation termed the Exmore tsunami-breccia (Powars and Bruce, 1999). Surrounding strata within the outer rim were, less dramatically, disrupted. Continued Late-Eocene low-energy marine deposition buried these deposits with the Chickahominy Formation, which is a more extensive hydraulic-confining layer. Annual precipitation over the Virginia Coastal Plain averages 45 inches per year, and potential evapotranspiration is about 32 inches. Various large river systems, as well as the Chesapeake Bay and Atlantic Ocean, transect and are hydraulically connected to the aquifers composing the Virginia Coastal Plain aquifer system. The Cretaceous fluvial-deltaic Potomac formation is the deepest and largest producing aquifer in the system. Water that infiltrated Potomac sediments at shallow depths near the fall line (figure 1) may flow about 100 miles before discharging upward to the Atlantic Ocean near the fresh-saltwater interface. Mixing of fresh and saltwater near this interface has created a “transition zone” where salinity generally increases toward the ocean and with depth, though preferential flow and flushing through conductive strata have resulted in vertical salinity inversions. Aquifers overlying the Potomac formation are similarly recharged where they outcrop to the west, and also leak through intervening clay confining units.

The equilibrium location of the fresh-saltwater interface is affected by the magnitude and distribution of recharge and aquifer and confining-unit permeabilities, but is primarily controlled by the sea level. The Coastal Plain aquifers were entirely inundated and likely saturated with saltwater most recently during the Pliocene Epoch 1.6 million years ago, and numerous sea-level changes have occurred since that time. The magnitude of relative sea-level lowering during even the most recent glacial episode is uncertain, however. The ICE-4G model (Peltier, 1994), which incorporates mantle viscosity and lithospheric flexure, computes sea level during the last glacial maximum (21,000 years before present) 470 feet lower than present for the Virginia Coastal Plain. Age dating of basal peat below salt marshes and estuarine sediments in the Chesapeake Bay indicates sea level was 25 feet lower 6,000 years ago (Larsen and Clark, 2003), which is about one-third of the ICE-4G model value for that time. During glacial episodes when the sea receded to the continental-shelf-slope break, the average aquifer-system hydraulic gradient may have been two to four times greater than with the current sea level, causing enhanced flushing of saltwater from aquifers and a seaward migration of the fresh-saltwater transition zone. Repeated sea-level fluctuations during the late Tertiary and Quaternary have mixed fresh with seawater, widening the fresh-saltwater transition zone (Meisler and others, 1984). The general trend of sea-level rise over the past 18,000 years suggests that hydraulic forces affecting the location of the fresh-saltwater interface may be out of equilibrium, causing landward migration of the transition zone. The objective of this study was to quantitatively investigate the distribution and persistence of saltwater around the impact structure.

METHOD

Variable dissolved-solid concentrations can affect ground-water densities, and consequently ground-water flow. Ground-water systems without appreciable chemical reactions or temperature gradients are governed by equations for variable-density flow:

$$-\nabla \cdot (\rho \vec{q}) + \bar{\rho} q_S = \rho S_p \frac{\partial P}{\partial t} + \theta \frac{\partial \rho}{\partial C} \frac{\partial C}{\partial t}$$

and mass transport:

$$\frac{\partial C}{\partial t} = \nabla \cdot (D \nabla C) - \nabla \cdot \left(\frac{\vec{q}}{\theta} C \right) - \frac{q_S}{\theta} C_S$$

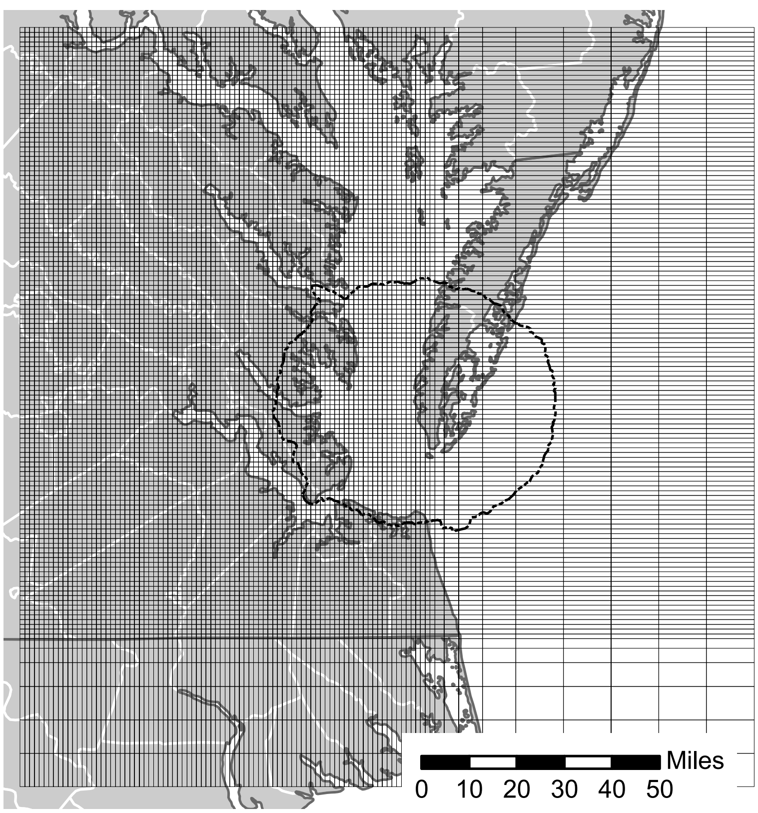

Figure 2. Location of Chesapeake Bay Impact Crater and Finite-Difference Model Grid in Virginia and Adjacent Parts of Maryland and North Carolina.

where: ∇ is the gradient operator, ρ is the fluid density [ML^{-3}], $\vec{q}$ is the specific discharge [LT^{-1}], P is the fluid pressure [$ML^{-1}T^{-2}$], S_p is the specific storage in pressure terms [$M^{-1}LT^2$], t is time [T], θ is the effective porosity, C is the solute concentration [ML^{-3}], D is the dispersion coefficient [L^2T^{-1}], q_S is the flow rate per unit volume representing sources or sinks [T^{-1}], $\bar{\rho}$ is the source or sink fluid density [ML^{-3}], C_S is the source or sink solute concentration [ML^{-3}]. These ground-water flow and transport equations are coupled by the specific discharge ($\vec{q}$) and concentration (C) terms. Guo and Langevin (2002) reformulated the flow equation using Darcy's law to express the specific discharge ($\vec{q}$) in terms of equivalent freshwater head. The dependence of fluid density on concentration can be approximated by a linear equation of state: $\rho = \rho_f + \frac{\partial \rho}{\partial C} C$, where ρ_f is the density of freshwater. The resulting flow and transport equations can be iteratively solved using the Variable-Density Flow and Integrated Mass Transport processes in SEAWAT-2000 (Langevin and others, 2003).

Geographic Information System coverages of aquifer and confining unit geometries define the hydrogeologic framework, which was incorporated in MODFLOW-2000 with the Hydrogeologic Unit Flow package (Anderman and Hill, 2000). A finite-difference model grid with 134 rows, 96 columns, and 56 layers encompasses the model domain of the aquifer system in Virginia and adjacent parts of Maryland and North Carolina (figure 2). Vertical discretization varies from 35 to 100 feet to adequately simulate stratigraphic effects on concentration gradients. Recharge flux was specified for the top model boundary, and head-dependent-flux boundary conditions simulate evapotranspiration and interaction with surface-water features, such as major rivers, lakes, the Chesapeake Bay, and the Atlantic Ocean. Initial estimates of aquifer and confining-unit permeabilities adapted from Harsh and Laczniak (1990) were used to simulate a constant-density, steady-state head distribution, which was used as the initial head distribution for subsequent transient simulations. A homogeneous distribution of seawater, such as might result from a marine transgression, was specified as the initial solute concentration condition for the variable-density transient simulations. Transient specified-head boundary conditions on the continental shelf and slope represented various lowered late-Pleistocene sea levels for these transient simulations. During the course of each simulation, recharged freshwater displaced and mixed with saltwater to form a fresh-saltwater transition zone that migrated toward a position of hydrodynamic equilibrium. To facilitate model calibration to different salinity indicators, simulated solute concentrations were normalized from zero to one for concentrations corresponding to fresh- and sea-water densities, respectively.

RESULTS AND DISCUSSION

The migration rate and equilibrium location of the fresh-saltwater transition zone were sensitive to the specified sea-level boundary head, which was varied in transient simulations of up to 110,000 years. Although transition zone equilibrium locations differ among alternative realizations of the magnitude and timing of sea-level change, similar fits of simulated and observed salinity distributions result at different simulation times. This results because sea level controls the hydraulic gradients, and consequently the ground-water flux and transport rates, through the aquifer system. Contours of present observed salinity and simulated relative salinity after 35,000 years of flushing with sea level 150 feet lower than present are shown in figure 3. Simulations representing lower glacial sea levels similarly fitted the observed salinity in shorter simulation times. Ground-water age dates will constrain estimates of Pleistocene ground-water recharge flux, and possibly the transition-zone equilibrium location. The general agreement between simulated and observed salinity distributions in both horizontal and vertical profile supports the hypothesis that a process of "differential flushing" around low-permeability crater-fill material caused the "inland wedge" of saltwater observed beneath the Virginia Coastal Plain. Hydraulically conductive parts of the aquifer system were flushed of saltwater, leaving remnant saltwater in low permeability areas, such as the crater fill. This process is more consistent with geochemical evidence and simpler than alternative salinity emplacement hypotheses, such as membrane filtration or halite dissolution.

The lithology of the Exmore tsunami-breccia is highly variable, and laboratory hydraulic-conductivity measurements of Exmore tsunami-breccia core samples conducted by the U.S. Army Corps of Engineers range from $6x10^{-5}$ to 3 ft/day. Samples of the Exmore tsunami-breccia matrix and Chickahominy Formation have hydraulic conductivities of 10^{-3} or less; the higher values are from relatively undisturbed Exmore tsunami-breccia sand clasts (Randy McFarland, U.S. Geological Survey, written communication, 2002). The interconnectedness of the higher permeability Exmore tsunami-breccia lithologies is speculative but determines the larger-scale effective hydraulic conductivity of the formation. The simulated persistence of saltwater in the Exmore tsunami-breccia sediments for more than 100,000 years bounds the effective hydraulic conductivity to less than 10^{-3} ft/day for those sediments shallower than about 1,800 feet below modern sea level, where vigorous Pleistocene glacial flushing occurred. Deeper sediments resided in more stagnant ground water where less flushing occurred, even if clast-supported Exmore tsunami-breccia facies had higher hydraulic conductivity. Fault movement around the crater margin may also have locally decreased conductivities, creating effective barriers to flow.

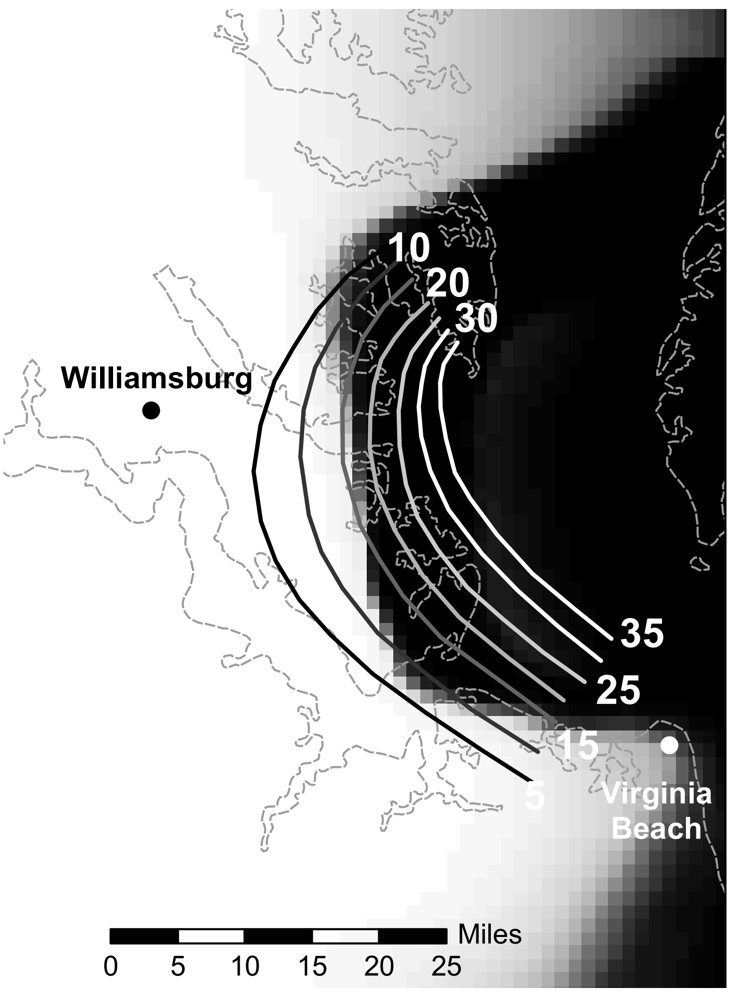

Figure 3. Observed Specific Conductance of Ground-water in Milliseimens near the Top of the Exmore Tsunami-breccia. Simulated Concentrations 1000 feet Below Sea Level Shown in Grayscale from Freshwater (white) to Seawater (black).

The low hydraulic conductivity of the crater structure should affect hydraulic responses to local and regional ground-water pumping stresses in an area of potential saltwater intrusion. The salinity distribution resulting from the Pleistocene sea-level change simulation will be used for the initial solute condition for a transient, variable-density-flow simulation encompassing the period of significant ground-water pumping from the late 1800's to present. Aquifer and confining-unit hydraulic conductivities and other ground-water model parameters will be estimated by non-linear regression of simulated to observed ground-water heads, ages, and salinity. Appreciable pumping stress is occurring in southeastern Virginia near the fresh-saltwater transition zone, which had been considered a no-flow boundary in previous system conceptualizations and ground-water models (i.e., Harsh and Laczniak, 1990). Consideration of miscible, density-dependent flow in this area should improve the accuracy of the ground-water-flow simulation, and its potential usefulness as a management tool.

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