Submarine Groundwater Discharge in the Southern Chesapeake Bay: Constraints From Numerical Models

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SUBMARINE GROUNDWATER DISCHARGE IN THE SOUTHERN CHESAPEAKE BAY:
CONSTRAINTS FROM NUMERICAL MODELS

by

Charles Louis Carlson
B.S. May 2014, Eckerd College

A Thesis Submitted to the Faculty of
Old Dominion University in Partial Fulfillment of the
Requirements for the Degree of

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OLD DOMINION UNIVERSITY
May 2019

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ABSTRACT

SUBMARINE GROUNDWATER DISCHARGE IN THE SOUTHERN CHESAPEAKE BAY: CONSTRAINTS FROM NUMERICAL MODELS

Charles Louis Carlson
Old Dominion University, 2019
Director: Dr. Jennifer E. Georgen

Terrestrial and oceanic forces drive fluid flow within the coastal zone to produce submarine groundwater discharge (SGD). Groundwater flowing from the seabed serves as a significant pathway for contaminants and nutrients, producing an active biogeochemical reaction zone. In order to quantify the importance of SGD in geochemical and hydrologic budgets for the lower Chesapeake Bay, three coastal Virginia transects (southern Eastern Shore, Lafayette River, and Ocean View beach) with different topographic gradients were modeled using similar boundary conditions and consistent treatment of hydrogeologic layers. A sensitivity study was performed on the variables of recharge rate, seawater density, and hydraulic permeability. Each two-dimensional transect is approximately 5 km in the shore-perpendicular direction with vertical elevations ranging from 10 m above sea level to 50 m below sea level. A pre-processing suite of code displays NOAA topography and bathymetry data, allows the user to identify a desired transect, and outputs a cross-sectional numerical domain for a series of steady-state calculations solved by a USGS program called SUTRA. SUTRA’s hybrid finite element and finite difference method computes buoyancy-driven flow of variable-density groundwater, solves the coupled solute transport equation, and predicts areas of discharge and recharge across the nearshore coastal zone. Model results suggested SGD in all transects, with common flow pattern characteristics including freshwater discharging below the elevation of sea level, seawater
recirculating in steep bathymetry, and intervening zones of relatively low flow. Although fluid velocity at the low tide mark was significantly dependent upon the slope of the transect, response to recharge rate was small over the range of modeled values. Permeability had the greatest effect on SGD; varying hydraulic conductivity by over an order of magnitude produced similar magnitude changes in discharge. Overall, this series of models provides a framework for identifying zones of high groundwater flow, reveals the variability of SGD rates between locations, and suggests which field measurements would be most valuable to better constrain the geochemical groundwater contribution to the coastal zone.
Copyright, 2019, by Charles Louis Carlson, All Rights Reserved.
This thesis is dedicated to future marine scientists. For, if there is magic contained on this planet, it is found within sea(water).

(Adapted quote from Loren Eiseley)
ACKNOWLEDGEMENTS

There are many people who have helped me along my educational journey. I extend many, many thanks to my committee members for their patience and hours of guidance on my research and editing for this manuscript. The untiring efforts of my major advisor deserve special recognition.
**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C^*$</td>
<td>Solute Concentration of Fluid Sources, M$_S$/M</td>
</tr>
<tr>
<td>$C_s$</td>
<td>Specific Concentration of Adsorbate on Solid Grains, M$_S$/M$_G$</td>
</tr>
<tr>
<td>$D_m$</td>
<td>Apparent Molecular Diffusivity of Solute in Solution in a Porous Medium, L$^2$/s</td>
</tr>
<tr>
<td>$g$</td>
<td>Gravitational Acceleration, L/s$^2$</td>
</tr>
<tr>
<td>$I$</td>
<td>Identity Tensor, (No Units)</td>
</tr>
<tr>
<td>$k$</td>
<td>Solid Matrix Permeability, L$^2$</td>
</tr>
<tr>
<td>$k_r$</td>
<td>Relative Permeability, (No Units)</td>
</tr>
<tr>
<td>$p$</td>
<td>Fluid Pressure, M/(L$\cdot$s$^2$)</td>
</tr>
<tr>
<td>$Q_p$</td>
<td>Fluid Mass Source, M/(L$^3$$\cdot$s)</td>
</tr>
<tr>
<td>$S_{op}$</td>
<td>Specific Pressure Storativity, M/(L$\cdot$s$^2$)$^{-1}$</td>
</tr>
<tr>
<td>$S_w$</td>
<td>Water Saturation, (No Units)</td>
</tr>
<tr>
<td>$U$</td>
<td>Fluid Temperature, °C, or Solute Mass Fraction, M$_S$/M</td>
</tr>
<tr>
<td>$v$</td>
<td>Average Fluid Velocity, L/s</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Porosity, (No Units)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Fluid Density, M/L$^3_r$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Fluid Viscosity, M/(L$\cdot$s)</td>
</tr>
<tr>
<td>$\rho_s$</td>
<td>Density of Solid Grains in Solid Matrix, M$_G$/L$^3_G$</td>
</tr>
<tr>
<td>$\Gamma_s$</td>
<td>Adsorbate Mass Source (per unit solid matrix mass), M$_S$/M$_G$$\cdot$s</td>
</tr>
</tbody>
</table>

where units of M represent mass, and units of L indicate length.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>List of Tables</td>
</tr>
<tr>
<td>List of Figures</td>
</tr>
<tr>
<td>List of Graphs</td>
</tr>
</tbody>
</table>

## Chapters

1. INTRODUCTION ........................................................................................................... 1  
   1.1. Submarine Groundwater Discharge: Definition, Historical Perspective, Previous Studies, and Importance .............................................. 1  
   1.2. The Physics of Coastal Groundwater Flow ............................................................ 5  
   1.3. The Importance of SGD: Global Fluxes and Biogeochemical Implications .................. 10  
   1.4. Study Motivation and Goals ................................................................................ 12  

2. STUDY AREA .............................................................................................................. 13  
   2.1. Chesapeake Bay Estuary ...................................................................................... 13  
   2.2. Lithology and Hydrogeology ................................................................................ 15  

3. METHODOLOGY ........................................................................................................ 18  
   3.1. Observational Data Compilation and Sources ...................................................... 18  
   3.2. Transect Locations .............................................................................................. 22  
   3.3. Numerical Model Domains and Boundary Conditions ........................................... 23  
   3.4. Governing Equations ......................................................................................... 26  
   3.5. Modeling Approach and Assumptions .................................................................. 27  
   3.6. Hypotheses ......................................................................................................... 28  

4. RESULTS .................................................................................................................... 29  
   4.1. Ocean View: Examples of Effects of Varying Seawater Salinity ......................... 29  
   4.2. Lafayette River: Examples of Effects of Varying Permeability .............................. 33  
   4.3. Eastern Shore: Examples of Effects of Varying Recharge Rate ............................. 36  
   4.4. Eastern Shore: Examples of Effects of Varying Seawater Salinity ....................... 39  
   4.5. Eastern Shore: Examples of Effects of Varying Permeability ................................ 41  
   4.6. Eastern Shore: Examples of Effects of Varying Domain Size and Boundary Conditions ................................................................. 43
5. DISCUSSION AND FUTURE WORK .................................................................47
   5.1. The Effect of Recharge Rate and Precipitation on SGD ..................................47
   5.2. The Effect of Saltwater Density and Concentration on SGD .......................47
   5.3. The Effect of Sediment Permeability on SGD .............................................50
   5.4. Transect Location Selection .......................................................................51
   5.5. Future Work ...............................................................................................51

6. CONCLUSIONS ..................................................................................................53

REFERENCES .........................................................................................................54

VITA.......................................................................................................................62
LIST OF TABLES

Table                                                                 Page
1. Table of hydraulic conductivities used in the analysis..........................20
LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Schematic drawing of submarine groundwater discharge (SGD) including fresh and saline components. From Knee &amp; Payton (2011)</td>
<td>2</td>
</tr>
<tr>
<td>2. Satellite imagery of Virginia’s coastal plain, highlighting the major rivers, cities, and coastal bodies. Retrieved from Google Earth</td>
<td>14</td>
</tr>
<tr>
<td>5. Topography and bathymetry data from Tayler et al. (2007, January 11), NOAA. Virginia Beach, VA 1/3 arc-second MHW DEM</td>
<td>19</td>
</tr>
<tr>
<td>6. Average surface salinities from the interpolated state monitoring data from NOAA</td>
<td>21</td>
</tr>
<tr>
<td>7. Maps of transect locations. (a) Ocean View Beach, (b) Lafayette River, and (c) Eastern Shore</td>
<td>24</td>
</tr>
<tr>
<td>8. Numerical domains calculated from DEM profiles</td>
<td>25</td>
</tr>
<tr>
<td>9. Ocean View salinity simulations</td>
<td>32</td>
</tr>
<tr>
<td>10. Lafayette River permeability simulations</td>
<td>35</td>
</tr>
<tr>
<td>11. Eastern Shore recharge simulations</td>
<td>38</td>
</tr>
<tr>
<td>12. Eastern Shore salinity simulations</td>
<td>40</td>
</tr>
<tr>
<td>13. Eastern Shore permeability simulations</td>
<td>42</td>
</tr>
<tr>
<td>14. Eastern Shore domain simulations</td>
<td>45</td>
</tr>
</tbody>
</table>
# LIST OF GRAPHS

<table>
<thead>
<tr>
<th>Graph</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Fluid velocity at the low tide mark (in/yr) for the three transect locations and three sensitivity parameters</td>
<td>48</td>
</tr>
<tr>
<td>2. Width of the freshwater-saltwater interface and migration of the 30% contour for the Eastern Shore Transect compared among three sensitivity parameters</td>
<td>48</td>
</tr>
<tr>
<td>3. Width of the freshwater-saltwater interface and migration of the 30% contour for the Ocean View Transect compared among three sensitivity parameters</td>
<td>49</td>
</tr>
<tr>
<td>4. Width of the freshwater-saltwater interface and migration of the 30% contour for the Lafayette River Transect compared among three sensitivity parameters</td>
<td>49</td>
</tr>
</tbody>
</table>
CHAPTER 1
INTRODUCTION

1.1. Submarine Groundwater Discharge: Definition, Historical Perspective, Previous Studies, and Importance

Water found beneath the Earth’s surface, in the pore spaces of sediment or rock, is defined as groundwater. Groundwater is an important resource in many areas of the country, providing water for drinking, irrigation, industry, and many other uses. Groundwater constitutes about 1% of the planet’s total water supply, making it a much more abundant freshwater source than that found in lakes and rivers (Freeze & Cherry, 1979). Groundwater is typically collected in subsurface geological features called aquifers, which are bodies of materials such as gravel, sand, and fractured rock that are sufficiently porous to hold economically-significant volumes of water (Freeze & Cherry, 1979). Aquifers occur in a range of settings, from interior regions of a continent to the coastal margins. When an aquifer is situated such that it is in contact with the seafloor, it can discharge water into the overlying ocean. This flow is called submarine groundwater discharge, or SGD (Figure 1). Surficial aquifer seepage can occur at and somewhat offshore of the low tide mark, leaking terrestrial nutrients, fertilizers, and heavy metals into the ocean. The coastal groundwater flow system also typically includes a subsurface, wedge-shaped freshwater-saltwater interface (FW/SWI) zone where the action of tides, or changes in sea level, can induce significant pore water exchange in permeable sediments by creating variations in hydraulic head (Gibbes et al., 2008).

Knowledge of subterranean springs has existed for many centuries. Over two thousand years ago, within the karst topography of the Mediterranean Sea, divers would gather water using a lead funnel and leather tube; the freshwater was transported to a nearby city for use (Kohout, 1966). Around the Red Sea and Black Sea, Bahrain and Etruscan citizens found submarine springs and used them as hot baths (Williams, 1946). The Greeks were aware of offshore discharge and built “fence” dams, which served as a freshwater irrigation reservoir (Zektser et al., 1996).
Quantitative study of inland groundwater systems began more than 150 years ago. In the 19th century, Henry Darcy, a water sanitation engineer, developed Darcy’s Law. Darcy’s Law relates groundwater flow velocity, the spatial gradient in head, and permeability. Toth (1963) conceptualized recharge and discharge cells based on local and regional topography. But while long-established studies of terrestrial-based groundwater systems have allowed water resource managers to drill wells, install dams, and engineer streamflow, coastal hydrology has been relatively unexplored until more recently.

Initially, coastal groundwater hydrologists focused their attention primarily toward identifying the location of the FW/SWI. Although the Ghyben-Herzberg relationship works well as an initial approximation for finding this interface, it only represents a stable hydrostatic situation. The calculation uses just the elevation of the water table and the gravitational balance between freshwater and saltwater to determine the geometry of the interface; the flux is unconstrained. Other analytical approaches, described in textbooks such as Freeze & Cherry (1979), similarly have shortcomings. For example, in the Dupuit approximation groundwater
flow is assumed to be mostly horizontal and saline water in the aquifer remains relatively stationary, leaving salty groundwater to grow unrealistically old. A hydrostatic coastal system is not conducive to a mass balance approach, either. Hubbert (1940) noted that the presence of hydraulic gradients in bathymetry would induce a cyclic flow of salty groundwater. It thus became recognized that the saline groundwater was not stationary. While these mathematical advancements were essential in developing the concept of SGD, scientists soon realized that field-calibrated models would provide a clearer picture of the groundwater flow system.

In more modern times, information about the coastal groundwater system has primarily been obtained through analytical methods, direct measurement, tracer/chemical studies, and numerical modeling. Analytical approaches, like pore water balance, rely heavily on the principles of Darcy's Law and knowledge of the water table elevation (Freeze & Cherry, 1979; Harvey et al., 1987; Harvey & Odum, 1990). Fortunately, the hydraulic head can be measured by drilling holes in the ground and installing monitoring wells; at least three are necessary for determining horizontal hydraulic gradient (Oberdorfer, 2003). In order to assess possible vertical water movements, piezometers (wells with very short screens) can record how hydraulic heads change through time. Thus, this information allows scientists to determine both the horizontal and vertical movement of groundwater flow. Permeability of the soil can be measured by performing certain tests on the well, such as pumping on the aquifer and monitoring aquifer water level response (Oberdorfer, 2003).

Many investigations (e.g., Bugna et al., 1996; Corbett et al., 1999; Burnett et al., 2002) have utilized a device invented by Lee (1977) called a seepage meter. This instrument is placed on the seafloor to capture direct seepage flowing from the bed. Cable et al. (1997) monitored a Florida marine shoreline with seepage meters for two years and found that SGD rates were similar to precipitation patterns and that seepage decreased with distance from the shore. As another example, groundwater discharge was also measured using seepage meters by Dulaiova et al. (2006) along nearshore waters of West Neck Bay, New York.

Coastal geochemistry studies (e.g., Corbett et al., 1999; Bugna et al., 1996; Cable et al., 1996) have used natural tracers such as methane or radon to demarcate freshwater and saltwater bodies. Methane is natural gas found below ground and under the seafloor, but in enriched levels relative to surface waters (Corbett et al., 2000). Radon (Rn), a conservative noble gas, is located in sediment’s pore water and is produced by the decay of radioactive isotopes when water is
flushed through the system. From a measured decay rate, a flux of either freshwater or saltwater can be determined. Radium (Ra) is a radioactive alkaline earth metal that is found in uranium and thorium ores. Particles are non-reactive in fresh groundwater systems but become mobile during saltwater intrusion (Oberdorfer, 2003). Monitoring the isotopes of radium ($^{222}\text{Ra}$, $^{223}\text{Ra}$, $^{224}\text{Ra}$, $^{226}\text{Ra}$, $^{228}\text{Ra}$) allows scientists to gain insight about water exchange rates within the saltwater-freshwater mixing zone (Oberdorfer, 2003; Burnett et al., 2003; Burnett et al., 2008; Povinec et al., 2008). Using a combination of both techniques, Rodellas et al. (2012) measured $^{222}\text{Rn}$ and Ra isotopes and identified different water body sources of groundwater discharge into a Mediterranean wetland. In another study, Tobias et al. (2001) injected a natural tracer, Br$^-$, and tracked its movement to the shoreline, but the spatial variability in detecting the tracer made it difficult to determine general flow trends.

The advancement of technology and computing power has allowed numerical models to solve the groundwater flow equation, which is Darcy's law combined with the conservation of fluid mass, using efficient finite difference or finite element techniques (Oberdorfer, 2003). Such models were first used by researchers such as Harvey et al. (1987). More recent water balance software includes MODFLOW, WETBUD, the ModelMuse package (USGS, 2019), and other modern numerical models. The USGS program SUTRA (an acronym for Saturated, UNSaturated TRAnsport) allows users to calculate fluid movement and the transport of either energy or dissolved substances in a subsurface environment (Voss & Provost, 2010). New numerical approaches, such as that used by Thompson et al. (2007) along the continental shelf of Louisiana, separate hydrogeologic layers into permeable zones with different hydraulic conductivities in order to capture subsurface geology. Nevertheless, there will always be calibration involved with numerical models, so collection of field data is suggested.

Many studies have taken a multidisciplinary approach to examining SGD in various hydrogeologic settings, from local nearshore environments to continental-shelf-wide flow regimes, and with methods ranging across the disciplines. SGD investigations address different scales, ranging from meters (e.g., tidal effects: Robinson et al., 2006; Wilson & Gardner, 2006; Gibbes et al., 2008) to regional (e.g., geothermal effects: Harris et al., 2000; Wilson, 2003). Other studies incorporate multiple methods: Weng et al. (2003) used piezometers and hydrological modeling to determine groundwater discharge along an agricultural wetland on the French Atlantic coast; Zapata-Ríos & Price (2012) used the methods of a water budget, hydraulic
gradient, environmental tracers, and temperature in the Everglades National Park to estimate groundwater discharge. Groundwater inflow within a Wisconsin wetland was investigated by Hunt et al. (1996) with a combination of Darcy’s law calculations and stable isotope mass balance, temperature profile modeling, and numerical water balance modeling techniques. It is important to note, though, that geographical coverage of global SGD studies is patchy, with some types of coastal settings (e.g., Atlantic Ocean passive margin, Pacific Ocean active margin, Gulf of Mexico passive margin) and some regions (e.g., North America, Europe) more represented than others (e.g., estuaries). Thus, in order to make conclusions about the relative groundwater contribution to the coastal body, it is best to incorporate multiple methods, settings, and scales.

1.2. The Physics of Coastal Groundwater Flow

In simple terms, groundwater flow near the shoreline involves the interaction between two fluids (freshwater and saltwater) with different densities, within a porous medium (Freeze & Cherry, 1979). Driven by a forcing such as a topographic gradient, freshwater that has percolated to the water table can flow toward the shoreline and discharge near the low tide mark (Figure 1). Saltwater, which is denser than freshwater, flows inland below the freshwater body to a position of gravitational balance between the two water masses, called the freshwater-saltwater transition zone (Freeze & Cherry, 1979). This zone is often dynamic, with seawater recirculation across the FW/SWI. This simple, generalized pattern of submarine groundwater flow can be modified by many factors. For example, subsurface hydrogeological structure has an effect on the coastal groundwater flow system (Burnett et al., 2006). Since aquitards, or confining units, restrict water flow, they can serve as a barrier to vertical freshwater convection. This promotes horizontal flow and discharge offshore (Figure 1). The roles of topography/bathymetry, ocean processes, density gradients, geothermal heat flux, and anthropogenic influence in controlling submarine groundwater flow patterns are discussed next. Although these forcings are described independently, it is important to note that changes in any one will have an effect on the overall system. For example, an annual increase of rain may recharge the aquifer and produce more freshwater discharge, but may cause the surrounding coastal body to decrease in salinity and thus restrict seawater recirculation.
Driving Forces of SGD

Topography and Bathymetry: As noted in the previous paragraph, there are numerous factors that influence the size of the subterranean estuary, the rate of freshwater discharge, and the amount of seawater diffusion. One of the most important is the topography of the land and bathymetry of the ocean, wherein changes in elevation and depth generate hydraulic gradients (Burnett et al., 2003). In a regional sense, topographic gradients in the water table drive freshwater from recharge zones in the mountains to discharge zones along the coast (Harvey & Odum, 1990; Taniguchi et al., 2002; Burnett et al., 2003; Wilson, 2005). Because the water table tends to follow the land topography, beach profiles with greater slope will generate faster groundwater flow. The bathymetry of the seafloor is also thought to have a great influence on the amount of seawater recirculated in the system. For example, if an area contains an offshore channel or trough, the seawater has a greater hydrodynamic potential to infiltrate landward (Shibuo et al., 2006). In general, the topography and bathymetry control the location of greatest SGD.

Ocean Processes: Additionally, SGD can be driven by any number of oceanic processes, such as sea level fluctuation, surface currents, tidal pumping, and wave activity (Burnett et al., 2003). Seepage meter records capture the temporal variations corresponding to the tidal period (Santos et al., 2009), known as tidal pumping. When water levels are high, more saltwater intrusion can occur; at lower water levels, more fresh and saline water drains (Gibbes et al., 2008). In addition to tidal patterns, SGD fluxes also reflect neap-spring lunar cycles (Kim & Hwang, 2002). Structures near the boundary layer, like sediment ripples in the seafloor, allow for vertical pore water exchange to depths approximately two times the wavelength (Burnett et al., 2003). Estimates suggest that the intertidal pump, driven by the swash and tidal water level changes, could filter the total ocean volume through permeable sediments within 14,000 years (Riedl et al., 1972; Moore, 2010). The dynamic nature of groundwater flow is additionally compounded by factors such as tidal range and period, and wind speed and direction.

Density Gradients: Temporal changes and spatial gradients in density can also be important in controlling SGD. In the Chesapeake Bay, estuarine water salinity changes seasonally; salinity is at a minimum when the major rivers are supplying the bay with freshwater during the winter and
spring, and at a maximum during the drier summer and fall months (Wells et al., 1928; NOAA, 2013). When salinity is at a maximum, density increases seawater recirculation flow, but when freshwater-saltwater salinity gradients are lower, convection tends to decrease. Additionally, density in the Chesapeake Bay is spatially variable, with the salinity at any particular location being a balance of inputs from terrestrial freshwater rivers and the Atlantic Ocean. Although salinity might fluctuate seasonally and spatially in estuarine water, the saltiness of the Atlantic Ocean remains relatively stable (NOAA, 2013). Adding to geographical density changes, there are also density differences vertically within the water column. Very salty groundwater masses known as connate waters, which have been trapped in sediments from past oceanic events, also prove to be barriers for groundwater movement.

Geothermal Convection: It is also important to consider the influence of geothermal heat flux on groundwater systems. Increased temperature within a system can affect the density, buoyancy, viscosity, and convective nature of the fluid. Since the amount of surface heat flow delivered from the Earth’s core and radioactive decay can change as a function of lithospheric age and crustal thickness, there are important and systematic differences between continental margin and fully oceanic settings. Geothermal convection may drive large-scale circulation of seawater through the warm interiors of continental shelves, which could allow significant volumes of seawater to react with subsurface rock bodies, in turn affecting major ion, trace element, and nutrient budgets for the ocean (Wilson, 2003). While this process must be included when investigating large regional-scale models, variations in basal heat flux at smaller scales can be considered negligible and may be neglected.

Recharge Rate: In many areas, the flux of water into a coastal aquifer is dependent upon a balance between precipitation and evapotranspiration (Freeze & Cherry, 1979). Patterns of wet or dry weather are responsible for changes in rain, snow, and any other types of precipitation. Evapotranspiration includes plant transpiration and processes that return water from the land to the atmosphere, including evaporation from soil surfaces, tree canopies, urban cover, and open water bodies (McFarland & Bruce, 2006). Recharge of a groundwater aquifer can occur when precipitation exceeds evapotranspiration and surface water runoff. In general, greater recharge within a system triggers more freshwater discharge at the low tide mark (Knee & Payton, 2011).


*Anthropogenic Influence:* Finally, since approximately 40% of the nation’s population lives along the coast, groundwater is considered a valuable resource. But when citizens, businesses, or commercial facilities overuse freshwater supply, excess pumping rates can cause seawater intrusion and well contamination (Hussain & Javadi, 2016).

**Hydrogeological Parameters and Material Properties**

The coastal groundwater system is heavily influenced by processes and properties that control how water flows through a geologic material. This section will provide details about how each of these properties have an effect on SGD, with an attempt to be specific about how changing the parameter increases or decreases the flow. As described later in the Methodology section, values for each of these parameters and properties were provided as inputs to the groundwater flow calculations in this modeling investigation.

*Porosity:* The total volume of a soil or rock can be divided into the volume of solid portions and the volume of the pores; these void spaces can be either filled with air or water (Freeze & Cherry, 1979). Porosity is a function of the type of rock and it may be classified as primary porosity (existing as a matrix of poorly- to well-sorted sedimentary grains) or secondary porosity (caused by dissolution in limestones, or regional fracturing in igneous material). Porosity values in sandy unconsolidated deposits, tight clays, and silty media have ranges of 25-50%, 40-70%, and 35-50%, respectively (Davis, 1969). Although one may think that materials with greater porosity would produce faster SGD patterns, the ease of flow is in fact determined by the connectivity of the void spaces, or permeability.

*Permeability:* Known as the ability of a porous material to allow fluids to pass through it, permeability has the greatest effect on groundwater movement of the major variables involved in porous flow (Hubbert, 1940; Freeze & Cherry, 1979). Permeability can also be expressed as hydraulic conductivity. Hydraulic conductivity describes the mechanical interaction between the fluid (which may have variable density and viscosity) and the geologic material through which the fluid travels. Permeability involves the forces of friction and drag, which may change throughout the geologic material. Because of this, permeability may be homogenous, or
independent of position within a geological material, or may it be heterogeneous, changing according to location (Freeze & Cherry, 1979). For example, grain size along a beach transect might get larger closer to the coast, causing permeability to increase and establishing a heterogeneous flow regime. In heterogeneous settings, permeability may range over several orders of magnitude for just one geologic material; clean sand permeability values extend from $10^{-2}$ m/s to $10^{-5}$ m/s (Davis, 1969).

Generally speaking, permeability controls the type of flow in the SGD system. In limestone regions like the ones found in the Mediterranean, Florida, and the Caribbean, caverns focus freshwater to discharge as subterranean springs. Offshore of California, remotely operated submarines following secondary porosity fractures in the basaltic bedrock have found thriving geothermal ecosystems (Solomon et al., 2017). Alternatively, Mid-Atlantic coastal plains that contain unconsolidated sediments like sands, silts, and clays have seep-like flows, where water slowly leaks through small holes in the substrate. Overall, constraining permeability in a study region is critical because it plays a large role in controlling the magnitude of the water discharge.

**Anisotropy**: Similar to the concept of homogenous and heterogeneous flows within a geologic material, anisotropy describes how groundwater flow is dependent on direction (Freeze & Cherry, 1979). In isotropic materials, groundwater flow is the same in the x, y, and z directions, while flow in anisotropic sediments is faster in one direction than the others. A barrier island setting, for example, can be described using a homogenous, isotropic scenario because transects are short, and material is uniform and well sorted. Anisotropic conditions are caused by preferred orientations of grain shape and permeability channels within clay, unconsolidated sediments, or rock, and must be considered when modeling layered formations (Freeze & Cherry, 1979). Proper assignment of anisotropy may be unique to a geographic area, but this principle helps capture the difference in flow direction magnitudes observed in the field. Although many numerical model studies treat geologic materials as isotropic (Harvey & Odum, 1990; Robinson et al., 2007; Gibbes et al., 2008; Hussain & Javadi, 2016), others incorporate permeability anisotropy (Tobias et al., 2001; Smith, 2003; McFarland & Bruce, 2006; Heywood & Pope, 2009; Li et al., 2009).
**Dispersivity:** The process of dispersion describes how dissolved solutes move within a geologic material. Often utilized when tracing contamination within aquifers, it is important to properly describe the movement of a tracer relative to the groundwater flow. In this study, for example, dispersivity is important in controlling how salt moves inland. Dispersion is heavily dependent upon the degree of anisotropy, and may be separated into longitudinal (x direction) and transverse (z direction) components (Freeze & Cherry, 1979). Typical longitudinal dispersivity values vary from 100 to 0.001, depending upon spatial extent. Transverse dispersivities are usually an order of magnitude lower in value, ranging from 10 to 0.0001 (Wilson, 2005; Wilson & Gardner, 2006; Robinson et al., 2007; Thompson et al., 2007; Li et al., 2009).

**1.3. The Importance of SGD: Global Fluxes and Biogeochemical Implications**

Although the major terrestrially-driven water fluxes from rivers into the ocean have been studied in depth, regional and global SGD inputs prove to be difficult to estimate. Because SGD occurs on a global scale along both active and passive margins, calculating a worldwide budget is a challenging task. Most estimates of terrestrially-derived fresh SGD range from 6 to 10% of surface water inputs and from 0.3 to 16% of global river flow, totaling anywhere from 100 – 6500 km³/yr (Burnett et al., 2003). Nevertheless, it should be noted that neither river flow nor groundwater seepage volumes total to the magnitude of seawater exchange caused by the subtidal pump.

Terrestrially-driven groundwater discharging from the seabed is recognized as an important mechanism for transferring chemical and biochemical material from land to ocean (Burnett et al., 2003). Given the known flux of nutrients, metals, and carbon contributed by rivers, several global mass balances recently have estimated nutrient input from SGD to be 20-40% greater than riverine inputs (e.g., Taniguchi et al., 2002). When nutrient-rich fluid travels through coastal sediments and reaches saltwater, chemical reactions cause the precipitation of many minerals and salts, which creates a chemically distinct water mass zone known as the “iron curtain” (Spiteri et al., 2006). The chemical reactions, often mediated by bacteria, occurring in coastal aquifers include: (1) desorption of ions from adsorbed sites due to increases in ionic strength, (2) dissolution and precipitation of carbonates, (3) remineralization of organic matter leading to carbon, nutrient, and metal release, and (4) oxidation-reduction reactions that produce
and consume metal oxides, which may release or sequester (Moore, 2010). Since nitrogen and phosphorus are considered limiting nutrients in the coastal system, additions of excess nutrients will not only cause eutrophication but are known to cause harmful algal blooms (HAB) and red tide events, which can deplete fin and shellfish populations and cause human respiratory problems (Knee and Payton, 2011).

Many anthropogenic fluids such as sewage, mining waste, and dissolved pesticides also pass through the coastal aquifer. These materials contain heavy metals such as arsenic, cadmium, copper, chromium, iron, lead, mercury, nickel, and zinc. Due to its prolonged contact with the metal-containing aquifer substrate, groundwater would be expected to have high dissolved metal concentrations relative to surface waters. Knee and Payton (2011) have found that metals do not always move conservatively through the subterranean estuary; rather, they may be either released into or removed from solution along the seaward flow path. If a metal is within a solid phase, it is considered immobile, attaching to part of the aquifer substrate. When a metal is within the dissolved or colloid phase, it tends to be more mobile. Although these metals are necessary for organism growth in trace amounts, excess levels are toxic to many plants and animals. Finally, submarine groundwater flow may transport many other constituents like dissolved organic carbon (DOC), or human-sourced fecal indicator bacteria (FIB), caffeine, pharmaceuticals, methane, and volatile organic compounds (VOCs) (Moore, 2010; Knee and Payton, 2011).

Submarine groundwater flow plays an important role for microorganisms within the coastal zone. As seawater moves to displace freshwater discharging along the transition zone, saline oceanic water is introduced to the subterranean estuary (Wilson, 2005). This recycling of ocean water has been referred to as “irrigation” or “ventilation” and may prove as a mechanism for filtering the ocean. With coastal sediments acting as a medium of filtration, the action of waves and tides can induce additional percolation and filtration (Wilson & Gardner, 2006; Gibbes et al., 2008). Areas of recharge and discharge of both freshwater and saltwater serve as active biogeochemical zones; when nutrients and gases travel through these zones, microorganisms like bacteria, flagellates, and benthic algae utilize this seep for energy by means of respiration, photosynthesis, and chemosynthesis. The supply of bioavailable iron to the coastal zone may be responsible for creating HAB events and may fuel the growth of the Chesapeake Bay dead zone during the summer (Moore, 2001; Charrette & Buesseler, 2004).
Understanding annual changes in SGD flow patterns may help scientists explain seasonal biological responses.

1.4. Study Motivation and Goals

The southern Chesapeake Bay offers a range of hydrogeological settings characteristic of estuarine environments, and so a main goal of this study is to examine how the contribution of SGD changes according to location and coastline type within this region of the estuary. In order to quantify the importance of SGD flow in geochemical and hydrologic budgets for the lower Chesapeake Bay, this investigation focuses on three coastal Virginia transects (southern Eastern Shore, Lafayette River, and Ocean View beach) with different topographic gradients. These transects are modeled using similar boundary conditions and consistent treatment of hydrogeologic layers. Additionally, a sensitivity study is performed on the variables of recharge rate, seawater density, and hydraulic permeability to assess how changing the values of these parameters over reasonable ranges affects predicted submarine groundwater recharge and discharge rates. In this way, this investigation provides a framework for researchers to use in studies of estuarine coastal groundwater processes worldwide.

Additionally, this study develops a package of numerical codes to run fast numerical simulations that yield rich information about coastal groundwater flow systems. This package includes a MATLAB program that allows the user to load their own topographic map and choose a desired transect, and a post-processing code that displays the simulation results in an intuitive, comprehensive way. These user-friendly scripts enable researchers to quickly set up a large suite of numerical models, which is useful for isolating variables that must be constrained or measurements that should be made in order to properly assess the contribution of SGD to coastal flow pathways for a given location.
CHAPTER 2
STUDY AREA

2.1. Chesapeake Bay Estuary

The Chesapeake Bay watershed spans the six Mid-Atlantic states of Delaware, Maryland, New York, Pennsylvania, Virginia and West Virginia, as well as the District of Columbia (Figure 2). The partially-enclosed basin where the rivers of the watershed meet oceanic water creates a transitional marine habitat and valuable nursery. Carved by a large paleo-river system and flooded by seawater, the Chesapeake Bay is the most productive estuary of North America and also the third largest by area in the world, 166,00 km² (Chesapeake Bay Program, 2019). Climate in this zone is temperate, heavily vegetated, and humid, with annual precipitation of approximately 100 cm/yr (McFarland & Bruce, 2006).

Topography in Virginia’s 34,000 km² coastal plain is characterized by rolling terrain and deeply-incised stream valleys carved by the major rivers: Potomac, Rappahannock, York, and James (Bailey et al., 2016) (Figure 2). Although depths range up to 30 m to 50 m in the deep part of the bay, the average is 3 m, allowing a person that is 2 m tall to wade around 25% of the bay’s area (Chesapeake Bay Program, 2019). In addition to a vast biodiversity of plants and animals including fish, shellfish, waterfowl, and seagrasses, the Virginia Chesapeake Bay watershed includes many large population centers. Associated with a heavy military presence in Norfolk, the people of Hampton Roads rely heavily on this waterway’s ecosystem services. Besides the several large metropolis areas, the rest of southeastern coastal Virginia is mainly cropland and forest, with a few small towns scattered (McFarland & Bruce, 2006).

The Chesapeake Bay offers an ideal location for this study because of the variety of topographic gradients and hydrogeologic structures. This investigation takes advantage of the range of available beach environments and landscape types to develop insight about how the estuary groundwater flow system functions as a whole. Several papers have been published about the hydrogeologic framework of this coastal region (e.g., Meng & Harsh, 1988; Trapp, 1992; McFarland & Bruce, 2006); these studies provide the permeability values and hydrostratigraphic patterns chosen for modeling. There have also been other studies completed
by the USGS (Hamilton & Larson, 1988; Richardson, 1994; Gallagher et al., 2001; Smith, 2003; Heywood & Pope, 2009; Sanford et al., 2009) which utilize numerical modeling and geographic information systems to determine regional flow trends in the Virginia coastal plain. Geochemistry data from both Charette & Buessler (2004), who completed a $^{228}\text{Ra}/^{226}\text{Ra}$ activity ratio investigation in the Elizabeth River, and Hussain et al. (1999), who studied similar isotopes with the addition of $^{222}\text{Rn}$ in six separate zones of the Chesapeake Bay, help with model results interpretation and calibration.

Figure 2. Satellite imagery of Virginia's coastal plain, highlighting the major rivers, cities, and coastal bodies. Retrieved from Google Earth.
2.2. Lithology and Hydrogeology

Virginia’s coastal plain is characterized by eastward-dipping, seaward-thickening, unconsolidated to partly consolidated sediments of Cretaceous, Tertiary, and Quaternary age that all overlie a basement of bedrock (McFarland & Bruce, 2006). These fluvial sediments are sequentially deposited with tight marine clays, created by several marine transgressions and regressions of the Atlantic (Bailey et al., 2016). Diverse alluvial, colluvial, estuarine, marsh, swamp, and dune deposits are present along channels, flood plains, and terraces of present-day rivers and streams, Chesapeake Bay, and the Atlantic coast. A Tertiary Period asteroid crater, greater than 90 km in diameter, not only formed a unique assemblage of impact-related material but also influenced long-term subsidence within the area (Heywood & Pope, 2009; Bailey et al., 2016). Nevertheless, the coastal plain aquifers yield large amounts of water due to the great thicknesses and large catchment basins. Groundwater is recharged regionally at a rate of 25-38 cm/yr, principally by precipitation which is allowed to percolate to the surficial aquifer (McFarland & Bruce, 2006; Sanford et al., 2009). Flow patterns within unconfined aquifers often discharge to streams, which can recharge deeper aquifers. A schematic diagram of groundwater flow of the Eastern Shore of Virginia is provided in Figure 3.

Columbia Aquifer: The unconfined surficial unit within the study area is known as the Columbia aquifer (Figure 4). This aquifer is composed of a series of primarily fluvial-deltaic and estuarine, variably-textured quartz sands and gravels with interbedded silts and clays that range in age from late Pliocene through Quaternary (McFarland & Bruce, 2006). The Columbia is characterized as an anisotropic, heterogeneous aquifer, and may be considered hydraulically continuous on a regional scale. The vertical hydraulic conductivity is approximately 0.15 m/day (Harsh & Lacznia, 1990; Smith, 2003; McFarland & Bruce, 2006), and horizontal hydraulic conductivity published values range from 3x10^{-4} m/day to 50 m/day (McFarland & Bruce, 2006), depending on whether the sample was extracted in silty, medium-grained sands or coarse-grained gravels and cobbles. The top of the unconfined aquifer is essentially equivalent to the land surface, with an altitude of greater than 60 m in the west decreasing to 0 m along the Atlantic Ocean. The saturated thickness of this aquifer fluctuates seasonally, but water tables are typically found within a meter depth near the lowlands (McFarland & Bruce, 2006). For low-density residential
developments, crop and livestock production, and landscape maintenance, the surficial aquifer yields an important water supply.

Figure 3. Schematic diagram of hydrostratigraphic units on the Eastern Shore of Virginia, with general direction of groundwater flow arrows included. Retrieved from Sanford et al. (2009).

Figure 4. Geologic age, geologic units, and hydrogeologic units of the shallow aquifer system at Virginia Beach, VA. Retrieved from Smith (2003). (right) Stratigraphic correlations of all major hydrogeologic units of Virginia’s Coastal Plain. Retrieved from Heywood & Pope (2009).
**Yorktown-Eastover Series**: Because the Columbia aquifer was deposited in a fluvial, estuarine, and marine environment and the Yorktown-Eastover series below it was formed during a full open marine setting (Figure 4), the two hydrologic groups are not considered to be continuous and hydraulically connected (Bailey et al., 2016). The top member of the Yorktown-Eastover series is known as the Yorktown confining unit. In this unit, vertical groundwater flow is locally impeded by silt and/or clay that is interbedded with glauconitic, phosphatic, and fossiliferous quartz sands of the estuarine to marine Yorktown Formation of Pliocene age (McFarland & Bruce, 2006). Discontinuous and patchy sediment deposits exhibit sharp contrasts in texture across short distances, suggesting a fluctuation of marine, estuarine, and fluvial-deltaic depositional environments (McFarland & Bruce, 2006). The Yorktown confining unit may also be divided into the upper, middle, and lower Yorktown-Eastover confining units with intervening aquifers (Richardson, 1994). Although the Yorktown confining unit is not one fine-grained interbed, it is acknowledged as a regional barrier for groundwater movement (Bailey et al., 2016). Since this unit is regarded an impediment to groundwater flow, horizontal permeability values are not considered, but reported values of vertical permeability range from $1.2 \times 10^{-3}$ m/day to $4.9 \times 10^{-6}$ m/day (Harsh & Laczniak, 1990; Smith, 2003; McFarland & Bruce, 2006).

Below the Yorktown confining zone is the Yorktown-Eastover aquifer. The second most heavily-used aquifer within the region, its upper extent consists of estuarine to marine, variably-textured, glauconitic, phosphatic, and fossiliferous quartz sands and interbedded silts and clays of the Yorktown Formation of Pliocene age (McFarland & Bruce, 2006). The bottom is composed of abundantly fossiliferous sands of the Eastover Formation of late Miocene age (McFarland & Bruce, 2006). A heterogeneous, anisotropic aquifer, its thickness is several tens of meters in the west, thinning towards the east. The Yorktown-Eastover aquifer contains sediments similar to the Columbia, but groundwater withdrawal has compressed the sediments, resulting in horizontal permeabilities which range from 0.2 m/day to 100 m/day and vertical permeabilities of approximately $6.1 \times 10^{-4}$ m/day (Smith, 2003; McFarland & Bruce, 2006). Below the Yorktown-Eastover aquifer is the St. Mary’s confining unit (Figure 4), which is the deepest extent that this study examines. The hydrostratigraphic morphology within this zone is heterogeneous and anisotropic, which forces groundwater to travel horizontally faster than vertically (Smith, 2003; McFarland & Bruce, 2006; Sanford et al., 2009).
CHAPTER 3

METHODOLOGY

The numerical codes used in this study are built around the USGS program SUTRA (Voss & Provost, 2010), which simulates groundwater flow through a fluid mass-balance approach. The program can be applied to saturated, partly saturated, or completely unsaturated material, with the options of constant fluid density, density as a function of solute concentration, or density as a function of fluid temperature. SUTRA will provide accurate answers only to well-posed, well-defined, and well-discretized simulation problems (Voss & Provost, 2010). A pre-SUTRA MATLAB script was developed to extract transects from a map of topography and bathymetry, and to generate a corresponding file of numerical domain grid locations and hydrostratigraphic properties which can be input into SUTRA. A post-SUTRA script was developed to display simulation data.

This study selected three different profiles and modeled them as 2D cross sections. While groundwater flow ideally should be investigated in 3D models because of spatial variability (e.g., paleochannels), such computations require considerable machine time per model run. Running SUTRA under the 2D mode is fast, allowing scientists to capture many snapshots of how the groundwater system behaves along given transects of interest. This section will discuss the processes of data acquisition and compilation, describe the three transects in detail, explain how the MATLAB script was developed, outline how to generate a numerical domain in SUTRA, and highlight which parameters were used in sensitivity tests.

3.1. Observational Data Compilation and Sources

Topography and Bathmetry: A map of Virginia’s coastal elevation and Chesapeake Bay’s bathymetry was obtained from NOAA’s NCEI website (https://www.ngdc.noaa.gov/metaview/page?xml=NOAA/NESDIS/NGDC/MGG/DEM/iso/xml/423.xml&view=getDataView&header=none). This high-resolution digital elevation model (DEM) is ideal for this study, as it provides a continuous transition from land to sea (Figure 5). Having been created to support tsunami forecast modeling, this 1/3 arc second file has a vertical datum adjusted to mean high water with grid resolution ranging from 10 m to 90 m in the
horizontal direction. Since this DEM consists of several previous surveys, metadata found on the website that contain important information such as survey type, accuracy, major units, and spatial extent must also be downloaded. The data and metadata files are the foundation for displaying maps, extracting cross sections, and generating numerical domains.

Figure 5. Topography and bathymetry data from Taylor et al. (2007, January 11), NOAA. Virginia Beach, VA 1/3 arc-second MHW DEM. Stars indicate approximate location of three transects.
Permeability: Values of permeability change according to the spatial extent under consideration, and the literature search of reasonable ranges reflects this principle. McFarland and Bruce (2006) produced a technical report describing all of the hydrogeological layers within Virginia’s coastal framework. Permeability values were also obtained from Sanford and Pope (2002) and Smith (2003). Both vertical and horizontal permeability values were extracted from these papers and reasonable ranges were determined. Table 1 provides the hydraulic conductivities used.

Table 1. Table of hydraulic conductivities used in the analysis. Data values in rightmost column were extracted from McFarland & Bruce, 2006.

<table>
<thead>
<tr>
<th>K_{ha}</th>
<th>Horizontal permeability, aquifers</th>
<th>ft/day</th>
<th>[10, 32, 100]</th>
</tr>
</thead>
<tbody>
<tr>
<td>K_{va}</td>
<td>Vertical permeability, aquifers</td>
<td>ft/day</td>
<td>[0.03, 0.11, 0.33]</td>
</tr>
<tr>
<td>K_{hc}</td>
<td>Horizontal permeability, confining units</td>
<td>ft/day</td>
<td>[0.01, 0.03, 0.05]</td>
</tr>
<tr>
<td>K_{hc}</td>
<td>Vertical permeability, confining units</td>
<td>ft/day</td>
<td>[0.0003, 0.001, 0.017]</td>
</tr>
</tbody>
</table>

Recharge Rate: Values for recharge rate were determined by searching the literature and using similar values for published studies around the Chesapeake Bay. While precipitation usually averages around 100 cm/yr in this region, roughly only 30% of this water (30 cm/yr) will percolate to the water table and become groundwater (Brown & Silvey, 1977; Heywood & Pope, 2009). Sanford and Pope (2002) used a recharge rate that varied from 12-60 cm/year, and McFarland and Bruce (2006) found that the area has a recharge rate of roughly 25 cm/year. Considering annual differences in recharge and the variety of landscape types that this study encompasses, a range of 12 cm/yr to 65 cm/yr was chosen for this investigation.
Seawater Density: Because the Chesapeake Bay has annual differences in salinity, seasonal averages between summer and fall were used. These data were obtained from maps of salinity produced by the Chesapeake Bay Program, in addition to the report produced by Wells et al. (1929). A map of annual changes in bay salinity is shown in Figure 6. Given the previous data collected, salinity values of 15 ppt, 25 ppt, and 32 ppt were chosen to reflect yearly and spatial differences within the coastal waters of the bay. The relationship between density and salinity varies as a function of temperature, and thus these salinity values produce densities of 1011 kg/m³, 1018 kg/m³, and 1025 kg/m³, respectively.

Sensitivity tests were performed on the variables of recharge, seawater density, and permeability for each of the three transect locations. As described above, reasonable ranges for these variables were determined by a literature review search. By inputting different values of each of these parameters into the numerical models, the corresponding changes in groundwater flow velocity were determined.

Figure 6. Average surface salinities from interpolated state monitoring data from NOAA.
3.2. Transect Locations

The three transects compared in the analysis (Figure 7; Ocean View beach, Lafayette River, and Eastern Shore) were selected because of previous hydrostratigraphic work available for two of the three locations. The shore-perpendicular topographic and bathymetric profiles extracted from the DEM data were averaged using a running mean, with the intent of de-emphasizing location-specific irregularities and providing more generalized results that can be applied to many settings within Tidewater, VA and similar estuarine settings globally. The three locations have similar oceanic influence (wave energy, tidal range, salinity), hydrostratigraphy (layered aquifers and confining units), and hydrologic patterns (recharge). Given these factors, the three environments were specifically chosen to highlight how differences in topography and bathymetry can generate different SGD patterns.

**Ocean View Beach:** The Ocean View beach transect, trending approximately north-south (Figure 7a), starts near Norfolk International Airport (ORF), runs through Chic’s Beach housing and a large dune system parallel to the Chesapeake Bay Bridge Tunnel, intersects an offshore channel, and terminates before reaching the first tunnel island. Elevation ranges from 5 m above sea level to 10 m below sea level. Consisting of surficial unconsolidated sediments and a shallow confining layer, this setting represents an idealized beach environment typical for many areas around the bay. This transect has a topographic slope that falls between the others, and so it will be used as a standard for comparative analysis.

**Lafayette River:** The east-west trending Lafayette River profile begins on the east side of Larchmont, intersects the neighborhood just north of Old Dominion University, and terminates before the dredged section in the Elizabeth River. The Lafayette transect presents an urban riverine environment with fresher saltwater and decreased recharge due to the impervious surfaces. Hydrogeologic properties are similar to the Ocean View beach location, but the hydraulic gradient is lesser, as elevation ranges from 3 m above sea level to 10 m below sea level. Field-measured radium and radon isotope-derived SGD patterns from Charette and Buesseler (2004) within the area allow for calibration.
Eastern Shore: The northeast-southwest trending Eastern Shore transect begins on the spine of the Delmarva Peninsula (Figure 7c), crosses north of Kiptopeke State Park near Butler’s Bluff, and concludes in the southern Cape Charles shipping channel. Although all of the profiles are intended to be generalized and simple, this profile was chosen for its large hydraulic gradient. In addition, elevations range from 10 m above sea level to 25 m below sea level. Because the offshore channel intersects the confining unit and aquifer, the profile must include deeper hydrostratigraphic units.

3.3. Numerical Model Domains and Boundary Conditions

Numerical domains lengths ranged from 3500 m to 7000 m in the x-direction, with depths ranging to a maximum of 35 m to 40 m (Figure 8). All of the scenarios used in this study implemented the mesh type of gmsh (Geuzaine & Remacle, 2009, Kourakos, & Harter, 2014). The Ocean View domain is discretized using 46,536 quadrilateral elements and 47,133 nodes, while the Lafayette River contains 22,866 elements and 23,231 nodes, and the Eastern Shore uses 106,504 elements and 107,425 nodes.

Highlighting processes occurring at the shoreline, the top surfaces of the domains are prescribed boundary conditions of freshwater recharge along the land surface and seawater pressure along the water-sediment interface; no flow occurs on the left, right, and bottom sides of the domain. While the no flow boundaries do not represent conditions natural to recharge and discharge cells, the intent was to have the left and right sides of the numerical domain far enough from the shoreline to not have an effect at the coastline. Fluid densities of 1000 kg/m$^3$ and 1018 kg/m$^3$, and fluid concentrations of 0 ppt and 25 ppt, were assigned for the freshwater and saltwater water bodies, respectively.
Figure 7. Maps of transect locations. (a) Ocean View Beach, (b) Eastern Shore, and (c) Lafayette River.
Figure 8. Numerical domains calculated from DEM profiles. (a) Ocean View Beach, (b) Lafayette River, and (c) Eastern Shore. Boundary conditions are indicated along the margins of the models, and yellow or brown dots show the locations of the numerical grid.
3.4. Governing Equations

Fluid movement in porous media, specifically where fluid density varies spatially, may be driven by differences in fluid pressure or by fluctuations in fluid density. Pressure-driven flows are directed from regions of higher hydrostatic head toward areas of lower head. Density-driven flows occur when gravitational forces act on denser regions of fluid, causing them to flow downward relative to regions that are less dense (Voss & Provost, 2010). The mechanisms of pressure and density and their effect on groundwater flow can be described by SUTRA’s representation of Darcy’s Law (Equation 1):

\[ v = -\frac{kk_r}{\varepsilon S_w \mu} \cdot (\nabla p - \rho g) \]  

Equation 1

where \( v(x,y,[z],t) \) is the average fluid velocity \([L/s]\), \( k(x,y,[z],t) \) is the solid matrix permeability \([L^2]\), \( k_r(x,y,[z],t) \) is the relative permeability to fluid flow \([L]\), \( \varepsilon(x,y,[z],t) \) is the porosity \([l]\), \( S_w(x,y,[z],t) \) is the water saturation \([l]\), \( \mu \) is the fluid viscosity \([M/(L \cdot s)]\), \( p(x,y,[z],t) \) is the fluid pressure \([M/(L \cdot s^2)]\), \( \rho(x,y,[z],t) \) is the fluid density \([M/L^3]\), and \( g \) is the gravitational acceleration \([L/s^2]\) (Voss & Provost, 2010).

Because the total fluid mass in a system may change with time due to ambient groundwater inflows and outflows, injection or withdrawal from wells, changes in fluid density caused by changing temperature or concentration, or changes in saturation, it is necessary to also calculate fluid mass balance. Equation 2 accounts for the amount of fluid within the void spaces and tracks the changes in time:

\[ Q_p = \left( S_w \rho S_{op} + \varepsilon \frac{\partial S_w}{\partial p} \right) \frac{\partial p}{\partial t} + \left( \varepsilon S_w \frac{\partial \rho}{\partial U} \right) \frac{\partial U}{\partial t} - \nabla \cdot \left[ \left( \frac{kk_r}{\mu} \right) \cdot (\nabla p - \rho g) \right] \]  

Equation 2

where \( Q_p(x,y,[z],t) \) is the fluid mass source \([M/(L^3 \cdot s)]\), \( S_{op}(x,y) \) is the specific pressure storativity \([M/(L \cdot s^2)^{-1}]\), and \( U(x,y,[z],t) \) is either fluid temperature \([\degree C]\) or solute mass fraction \([M_s/M]\). Adapting Equation 2 to solve for solute transport yields (Equation 3):

...
\[
\frac{\partial (\varepsilon S_w \rho C)}{\partial t} + \frac{\partial [(1 - \varepsilon) \rho_s C_s]}{\partial t} = - \nabla \cdot (\varepsilon S_w \rho v C) + \nabla \cdot [\varepsilon S_w \rho (D_m I + D) \cdot \nabla C] + \varepsilon S_w \rho \Gamma_s + Q_p C^* \tag{Equation 3}
\]

where \( \rho_s \) is the density of solid grains in solid matrix \([M_G/L^3_G]\), \( C_s(x,y,[z],t) \) is the specific concentration of adsorbate on solid grains \([M_S/M_G]\), \( D_m \) is the apparent molecular diffusivity of solute in solution in a porous medium including tortuosity effects \([L^2/s]\), \( I \) is an identity tensor \([I]\), \( D(x,y,[z],t) \) is the dispersion tensor \([L^2/s]\), \( \Gamma_s(x,y,[z],t) \) is the adsorbate mass source (per unit solid matrix mass) due to production reactions within adsorbed material itself \([M_S/M_G\cdot s]\), and \( C^*(x,y,[z],t) \) is the solute concentration of fluid sources \([M_S/M]\) (Voss & Provost, 2010).

### 3.5. Modeling Approach and Assumptions

The series of 2D steady-state models provide general information about how the system operates in equilibrium. This study makes several simplifying assumptions in order to explore first-order SGD processes, including neglecting any residual sediment compaction related to the Chesapeake Bay impact crater (Heywood & Pope, 2009; Bailey et al., 2016), relative sea level rise (Boon et al., 2010; Ezer & Corlett, 2012), and anthropogenic groundwater withdrawal from aquifers. Additionally, factors like tidal influence, which have short spatial scales compared to the size of the model domains, are neglected. This study focuses on providing a framework for further investigations, while exposing how different SGD patterns can be among different transects.
3.6. Hypotheses

Two main hypotheses are tested in this investigation:

(1) The parameters of recharge rate, permeability, and salinity will all significantly affect the groundwater flow system. While changes in recharge and salinity will produce velocity variations on the order of percentages, permeability will generate larger differences, on the scale of an order of magnitude.

(2) Including deeper hydrostratigraphy or favoring a boundary condition area (i.e., including more of the terrestrial land surface instead of the marine environment or vice versa) will change the fluid flow and solute transport pathways.
CHAPTER 4
RESULTS

A total of 45 models were run for this investigation. This section presents results for selected, representative runs in order to illustrate the array of flow and solute patterns calculated for each of the three study transects as well as for different hydrogeologic parameters and boundary conditions. Three variables have important effects on SGD – salinity, permeability, and recharge – and their effects vary by transect location. This section is organized as follows. First, the Ocean View transect results are used to show how varying seawater salinity affects groundwater flow. Next, results from the Lafayette River transect illustrate how changing permeability alters SGD velocity and the location of the FW/SWI. Finally, the remainder of this section concentrates on results from the Eastern Shore transect, which is arguably the most complex in terms of topographic variability and subsurface hydrogeologic structure. First discussed is the effects of varying recharge. Then, additional results are provided to demonstrate how varying seawater salinity and permeability change groundwater flow patterns and solute transport. Concluding the results section is a demonstration of how different numerical domain sizes alter SGD predictions for the Eastern Shore transect. Although it is not possible to include results from all 45 model runs, the figures presented herein are provided as a framework to illustrate the behavior of the three groundwater flow systems under different physical forcings.

4.1. Ocean View: Examples of Effects of Varying Seawater Salinity

Figure 9 shows a subset of models for the Ocean View transect, focusing on the sensitivity of the fluid flow and solute concentrations to varying salinity. Both seawater density and seawater solute concentration were altered in these trials. The base simulation, where salinity is 25 ppt (1018 kg/m$^3$), is displayed in the vertical column of panels in the middle of Figure 9. Results for decreased salinity within the Chesapeake Bay (15 ppt; 1011 kg/m$^3$) appear in the leftmost vertical column of panels in Figure 9; results for increased salinity (32 ppt; 1025 kg/m$^3$) are in the rightmost column.
In all of the subpanels of this figure, the horizontal axis is the distance along the profile, with the terrestrial portion on the left and the seaward side on the right. For the Ocean View transect, the southernmost extent of the profile occurs at \( x = 0 \) m, and the northernmost at \( x = 5700 \) m. Topographic elevation or seafloor depth is annotated on the vertical axis, with the numerical domain extending from \( z = 40 \) m below sea level to \( z = 6 \) m above sea level. Note that the vertical exaggeration for this series of figures is approximately 40. On all panels, mean sea level is indicated by a black horizontal line at an elevation equal to \( z = 0 \) m.

The first horizontal row of Figure 9 plots groundwater flow velocity magnitude (in/yr). Areas of high flow are indicated by yellow colors, while low flow zones are displayed in blue. The velocity magnitude plots provide information about local discharge and recharge zones, highlighting the locations where the greatest groundwater flow might be measured by field instrumentation. The second horizontal row of panels in Figure 9 presents percent seawater results, with freshwater designated as yellow and saltwater displayed as blue. The transition zone between terrestrial water and salty ocean water is illustrated by contours at 30%, 50%, and 90% seawater. These seawater concentration plots provide information about the spatial extent of the seawater recirculation system, which is important for identifying saltwater contamination in wells or saltwater intrusion from sea level rise. Finally, the bottommost horizontal row of panels display flow vectors (arrows) corresponding to the direction of groundwater movement. Plotted on top of the arrows are the paths traced by passive, non-reactive, neutrally-buoyant particles placed 0.5 m below the numerical domain’s top surface.

The width, angle, and location of the freshwater-saltwater transition zone changes with each simulation, and the curvature of each contour provides information about flow in confining units versus aquifers. For this investigation, the horizontal distance along the top of the model between the 30% and 90% contour is defined as the FW/SWI surface width (\( \text{FSI}_{\text{surface\_width}} \)) (Figure 9e). The horizontal distance between the 90% contour at the top of the domain versus the bottom of the domain is described as the FW/SWI 90% contour distance (\( \text{FSI}_{90\text{dx}} \)). Similarly, the horizontal distance between the 30% contour at the top surface versus the bottom is the FW/SWI 30% contour distance (\( \text{FSI}_{30\text{dx}} \)). These latter two measures provide a means of quantifying the lateral shift in the FW/SWI zone with depth.
Groundwater Velocity Results and Fluid Flow Patterns: Two groundwater flow systems exist within the Ocean View transect. The first system is comprised of strictly freshwater, and it extends along the top surface of the model domain from x = 0 m to x = 2900 m. Freshwater infiltrates the unconfined aquifer and moves horizontally seaward, traveling a vertical distance from z = 6 m to z = -20 m, before it migrates up to discharge at the low tide mark. A second flow system is characterized by seawater recharging in a convection cell; it extends along the top surface of the domain from x = 2900 m to x = 5700 m (Figures 9b, h). Within the saltwater cell, changes in seafloor depth (of approximately 2-3 m) create several localized recharge and discharge zones, where increases in the bathymetric gradient and changes in hydrostatic pressure cause more seawater percolation. One localized saltwater cell is located around x = 3100 m, and a second cell is found at x = 4200 m (Figure 9c, h). The freshwater and saltwater convection cells meet and mix around x = 2500 m. Groundwater velocity within the confining unit is very slow compared to the velocities in the unconfined aquifer (Figure 9b).

A comparison of the three simulations displayed in Figure 9 indicates that the fluid velocity in the freshwater convective cell does not show a significant change with either an increase or a decrease of salinity. This is illustrated by consistent colors in the velocity magnitude plots (Figure 9a-c) and similar arrow lengths and particle paths in Figure 9g-i. In contrast, the groundwater velocity within the saltwater circulation cells is more sensitive to salinity changes, increasing with a salinity increase (Figures 9c, i) and decreasing with a salinity decrease (Figure 9a, g). Results suggest that the fastest groundwater flow along the transect occurs offshore of the beach (x = 4150 m) where bathymetric slope increases slightly. Seawater velocity at this location varies from 250 in/yr (1.7 cm/day) for the model run with a salinity decrease, to 370 in/yr (2.5 cm/day) for the base salinity, to 510 in/yr (3.5 cm/day) for increased salinity. At the low tide mark, where both freshwater and seawater discharge, velocity is 210 in/yr (1.5 cm/day), 325 in/yr (2.3 cm/day), and 475 in/yr (3.3 cm/day) for the decreased, base, and increased salinity cases, respectively. Within the low-tide zone, increasing salinity from 15 ppt to 32 ppt produces a 2.3-fold increase in velocity. Although velocity magnitudes within the saltwater convection cell are sensitive to salinity, the streamline paths do not change considerably between the three simulations.
Figure 9. Ocean View salinity simulations with the base trial in the middle column, decreased salinity on the left column, and increased salinity on the right column. Velocity magnitude (in/yr) is displayed in the top three panes, percent seawater in the middle three panes, and particle paths and velocity vectors in the bottom three panes. Quantification of the freshwater-saltwater interface (FW/SWI) slope using the 30% and 90% contour lines is explained in the percent seawater plot for the base simulation.
**Solute Concentration Results and Fluid Density Patterns:** Results for the percent seawater plots capture how the large ranges of density and solute concentrations assigned to the coastal water affect saltwater intrusion. In the base scenario, the FSI\textsubscript{surface width} is approximately 300 m wide, and the FSI\textsubscript{90dx} and FSI\textsubscript{30dx} are 200 m and 100 m, respectively (Figure 9e). In the decrease salinity simulation, the sea-groundwater is displayed as a green color to highlight the brackish nature of the simulation (Figure 9d). The angle and slopes of the 90% and 30% contours are similar. When salinity increases, the FSI\textsubscript{surface width} compresses to 200 m and the FSI\textsubscript{90dx} decreases to 175 m, but the FSI\textsubscript{30dx} remains the same at 100 m (Figure 9f). Thus, increasing salinity reduces the size of the FW/SWI, decreases the angle of the 90% contour, and shifts the zone of terrestrial and oceanic mixing landward.

**4.2. Lafayette River: Examples of Effects of Varying Permeability**

Figure 10 displays a series of models for the Lafayette River transect, concentrating on the sensitivity of groundwater flow and solute transport to permeability. Similar to Ocean View, this transect consists of an unconfined aquifer and a lower confining unit. In these sensitivity tests, the ratio of the hydraulic conductivity of the aquifer to that of the confining unit was kept constant. In the base simulation (middle vertical column of Figure 10), the permeability of the unconfined aquifer is assigned a value of 33 ft/day. The leftmost vertical column of panels displays the results when aquifer permeability is decreased to 10 ft/day. The permeability increase, where the aquifer permeability is set to 100 ft/day, is shown on the right side.

For the Lafayette River model runs, the horizontal distance covered is less than Ocean View, with the landward portion of the numerical domain extending westward from x = 0 m to x = 1700 m and the seaward part covering from x = 1700 m to x = 3400 m. Elevation and seabed depth ranges from z = 35 m below sea level to z = 3 m above sea level. Note that the vertical exaggeration of this transect, roughly 20, is less than that in Figure 8.

**Groundwater Velocity Results and Fluid Flow Patterns:** Although the Lafayette River transect has a lower topographic slope compared to Ocean View, there are many similarities in the fluid flow patterns. In the base case, freshwater recharges along the top of the numerical domain, from x = 0 m to x = 1700 m, percolates down into the aquifer across a vertical distance from
approximately $z = 3\text{ m to } z = -13\text{ m}$, and flows toward the coastline (Figures 10b, h). Compared to Ocean View, freshwater infiltrates to a greater depth, and travels along different pathways between simulations (Figures 10g, i). Saltwater also flows horizontally landward, along the top side of the numerical domain from $x = 3400\text{ m to } x = 1700\text{ m}$. These two flow systems meet halfway along the transect near the low-tide mark at $x = 1700\text{ m}$. Small changes in the bathymetry along the transect produce two separate local saltwater recharge and discharge cells located at approximately $x = 1900\text{ m and } x = 3000\text{ m}$ (Figures 10b, c); as discussed next, the increase of permeability highlights the importance of this microbathymetry. Unlike Ocean View, the local saltwater cell located closest to the shoreline contains the fastest groundwater flow (Figure 10c). Groundwater flow within the confining unit is low compared to that within the aquifer.

Charrette and Buesseler (2004), who determined an SGD velocity based on radon/radium particle tracking, showed that field-derived measurements within the Lafayette River can vary between 1.7-3.2 cm/day (244 - 460 in/yr). Model results yielded velocities of 1.5 in/yr for the minimum permeability, to 210 in/yr for the base permeability, to 650 in/yr for the maximum permeability, which are well within the range of the field-determined velocities. Increasing the aquifer permeability by one order of magnitude from 10 ft/day to 100 ft/day produces a 7.2-fold increase in discharge velocity. Generally speaking, there is very little flow across the transect in the reduced permeability simulation (Figure 10a). The particle tracking plots show a small difference in freshwater streamline patterns between the three simulations, and the flow vectors show the significant differences in velocity in the saltwater convection cells (Figures 10g-i).

**Fluid Density Results and Fluid Density Patterns:** Changing the permeability of the coastal sediments alters the width of the FW/SWI and also moves the shoreline position of the 90% contour. In the base scenario, $FSI_{\text{surface width}}$ is 225 m, $FSI_{90dx}$ is 175 m, and $FSI_{30dx}$ is 100 m (Figure 10e). Compared to the Ocean View transect, the slope of the 90% contour is similar. When permeability decreases, $FSI_{\text{surface width}}$ and $FSI_{90dx}$ decrease to 150 m and 100 m, respectively, while $FSI_{30dx}$ maintains a 100 m width (Figure 10d). At the maximum permeability value implemented, $FSI_{\text{surface width}}$ increases to 275 m, $FSI_{90dx}$ rises to 200 m, and $FSI_{30dx}$ increases to 125 m (Figure 10f). With the increase of permeability, the overall slope of the 90% contour decreases, while its curvature becomes more exaggerated because of the confined
Figure 10. As in Figure 9, but for the Lafayette River transect and permeability sensitivity test.
aquifer below. In the sensitivity increase plot (Figure 10f), the seawater volume occupies approximately 63% of the numerical domain, while it only covers 54% for the permeability decrease (Figure 10d). The increase of permeability across the whole transect has the greatest effect on dilating or compressing the FW/SWI zone compared to the two other sensitivity variables.

4.3. Eastern Shore: Examples of Effects of Varying Recharge Rate

Figure 11 provides model runs for the Eastern Shore transect, directing attention toward the importance of the recharge value that is assigned. Fluid flow entering the terrestrial boundary condition was altered to simulate differences in the net effects of factors such as precipitation and evapotranspiration. The middle panel of the figure represents current precipitation patterns of 45 in/yr; a value of one third of this precipitation rate, 15 in/yr, was assigned to be recharge (Pope and Sanford, 2009). The left side of the figure simulates a lower recharge rate of 10 in/yr. This value is representative of city areas more prone to surface runoff instead of groundwater recharge. On the rightmost column of subpanels in Figure 11, recharge rate is 20 in/yr.

The distance along the transect is similar to the two previous model domains, with the landward side occupying the numerical domain from x = 0 m to x = 3800 m and the seaward component extending westward from x = 3800 m to the end of the profile at x = 4700 m. This setup creates a numerical domain which does not have proportional boundary conditions (i.e., the extent of the landward portion is greater than the extent of the marine portion). The elevation and seabed depth ranges from z = 40 m below sea level to z = 11 m above sea level. The vertical exaggeration of this transect is approximately 31, which is between the values for the two previous transects.

Groundwater Velocity Results and Fluid Flow Patterns: While the Eastern Shore numerical domain contains a higher topographic slope compared to the previous two, the fluid flow patterns are similar. Freshwater recharges across the top of the numerical domain along a distance from x = 0 to x = 3800 m and flows horizontally toward the shoreline, mimicking the topography of the land (Figures 11h). Increasing recharge rate expands distance between the streamlines and
allows the freshwater convection cell to reach a depth equal to mean sea level (Figures 11g, i). In the decreased recharge scenario, freshwater only travels to a depth of z = 4 m. Saltwater recharged from x = 3800 m to x = 4700 m flows down through the confining unit into the confined aquifer before it is forced back up through the confining unit and eventually toward the shoreline. The difference in landward migration of the saltwater can be seen in the “fish-hook-like” particle pathway, as the position of the “hook” changes from x = 2400 m in the sensitivity decrease to x = 2550 m in the sensitivity increase (Figures 11g-i). Although the numerical domain is freshwater-dominated, the saline groundwater travels farther horizontally and vertically than that of the freshwater. These two flow systems meet at the low-tide mark at x = 3800 m. Flow in the two aquifers is mainly horizontal while flow in the confining units is entirely vertical.

Much of the transect is characterized by low flow (blue) areas, with an area of high flow occurring offshore (x = 3900) just below mean sea level (Figure 11b). Results indicate that discharge velocity at the low-tide mark changes from 540 in/yr (3.8 cm/day) for the decreased recharge, to 545 (3.8 cm/day) for the base value of recharge, to 555 in/yr (3.9 cm/day) with increased recharge. Thus, increasing the recharge rate from 10 in/yr to 20 in/yr produces a 15 in/yr increase in groundwater flow. Comparing the three sensitivities, recharge rate has minimal effects on groundwater velocity.

Fluid Density Results and Fluid Density Patterns: Altering recharge rates within the coastal zone has an effect on both the size of the FW/SWI and the location of this transition zone. In the base scenario, the FSI_{surface \_width} is 700 m wide, the FSI_{90dx} is 225 m, while the FSI_{30dx} is 400 m (Figure 11e). For this transect, the 30% contour has a greater slope, and contains a larger overall FW/SWI because water can travel inland through the confined aquifer (Figure 11h). When freshwater fluid flow is relaxed, the FSI_{surface \_width} increases to 1025 m wide, the FSI_{90dx} increases to 250 m, while the FSI_{30dx} decreases to 325 m (Figure 11d). When recharge is at a maximum value, the FSI_{surface \_width} compresses to 475 m wide, the FSI_{90dx} decreases to 200 m, while the FSI_{30dx} increases to 475 m (Figure 11f). In the sensitivity increase percent seawater plot, the seawater influence only occupies around 38% of the numerical domain, while it covers 47% during the sensitivity decrease. Recharge rate influences the size of the FW/SWI significantly, showing a greater response compared to velocity magnitude.
Figure 11. As in Figure 9, but for the Eastern Shore transect and recharge sensitivity test.
4.4. Eastern Shore: Examples of Effects of Varying Seawater Salinity

In Figure 12, the model runs illustrate how groundwater velocity and solute transport vary response to seawater salinity changes for the Eastern Shore transect. Both saltwater density and saltwater concentration were adjusted proportionally with the same values used in the Ocean View transect. Axis properties, numerical domain characteristics, and figure pane displays are the same as the Eastern Shore recharge simulations (Figure 11).

**Groundwater Velocity Results and Fluid Flow Patterns:** Because the transect domain models a freshwater-dominated scenario with a greater extent of land surface than sea surface, salinity simulations from the Eastern Shore transect yield more information about what an increase or decrease in salinity does to the terrestrial part of the coastal groundwater system. Freshwater recharged along the top of the numerical domain along a distance from \( x = 0 \) m to \( x = 3800 \) m is forced upward in the aquifer with the increase of salinity. At the minimum salinity, the pathlines flow at the elevation of sea level (Figure 12g). When salinity is increased, the pathlines are compressed and forced upwards (Figure 12i). Saltwater, which recharges from \( x = 3800 \) m to \( x = 4700 \) m, flows down through the confining unit into the confined aquifer; it is then forced back up through the confining unit and toward the shoreline (Figure 12h). The difference in landward migration of the saltwater can be seen in the particle pathways (Figure 12g-i).

The fastest groundwater velocity occurs where the two flow systems meet at the low tide mark. Color values on the velocity magnitude plot indicate discharge velocity changes from 335 in/yr (2.3 cm/day) for decreased salinity, to 545 in/yr (3.8 cm/day) for the base salinity, to 755 in/yr (5.3 cm/day) with increased salinity. Increasing the density and solute concentration from 15 ppt to 32 ppt produces a 2.3-fold increase in velocity. This increase is much greater than the velocity magnitudes found in the recharge simulations.

**Fluid Density Results and Fluid Density Patterns:** As previously stated, increasing the solute density near the coastal zone has its greatest effect on migrating the FW/SWI system landward. The width of the zone shows a greater response for this transect because flow occurs underneath the confining unit (Figure 12h). In the base scenario, the FW/SWI contains the same
Figure 12. As in Figure 9, but for the Eastern Shore transect and salinity sensitivity test.
characteristics as the base scenario in the recharge simulation. When salinity of the coastal body decreases to 15 ppt, the FSI_{surface_width} decreases to 100 m wide, the FSI_{90dx} increases to 250 m, and the FSI_{30dx} decreases to 350 m (Figure 12d). When salinity is at a maximum value, the FSI_{surface_width} increases to 1175 m wide, and the FSI_{90dx} increases significantly to 575 m (Figure 12f). The 30% contour maintains the same slope and angle characteristics of the base simulation. The curvature of the 90% contour responds greatly within the unconfined aquifer as salinity increases. In the sensitivity increase percent seawater plot, the seawater influence only occupies around 55% of the numerical domain, while it covers 28% during the sensitivity decrease. The decrease in recharge may produce a wider FW/SWI but the increase of salinity shifts the system farther landward.

4.5. Eastern Shore: Examples of Effects of Varying Permeability

Figure 13 displays the results from the Eastern Shore transect permeability simulations, which highlights the importance of the deep hydrostratigraphic pattern. Like the other permeability sensitivity runs described previously, values were altered similarly in both aquifers and the confining unit. That is, the ratio of aquifer to confining unit permeability was kept constant as the aquifer permeability was changed. Axis properties, numerical domain characteristics, and figure pane displays are the same as the Eastern Shore recharge and salinity simulations.

Groundwater Velocity Results and Fluid Flow Patterns: The simulations displayed within this section show the greatest changes in groundwater flow patterns among all the previous transects and sensitivities. Similar to the salinity sensitivity, pathlines are forced upward in the aquifer as permeability increases (Figure 13i). Water channelizes and flows faster within this zone during the permeability increase. Compared to the salinity simulations, the freshwater is allowed to flow vertically to a greater depth when permeability is at a minimum (Figure 13g). The seawater system also shows a greater response to permeability. In the simulation decrease, particles travel through the confining unit and into the confined aquifer before migrating vertically upward toward the low tide mark (Figure 13g). With the increase in permeability, saltwater travels farther horizontally in the confined aquifer before it migrates upward (Figure 13i); the pathline
Figure 13. As in Figure 9, but for the Eastern Shore transect and permeability sensitivity test.
plots do not connect to the low tide mark in this scenario. The distance inland that these saltwater particles travel changes from \( x = 3000 \) m when permeability is lowered to \( x = 1900 \) when permeability is greatest.

Results suggest that the greatest groundwater flow along the transect occurs at the low tide mark, where both freshwater and seawater discharge. Color values on the velocity magnitude plot indicate discharge velocity changes from 310 in/yr (2.2 cm/day) for the minimum permeability, to 545 in/yr (3.8 cm/day) for the base permeability, to 1645 in/yr (11.4 cm/day) with the maximum permeability. Increasing the aquifer permeability from 10 ft/day to 100 ft/day produces a 5.3-fold increase in discharge velocity. As a fundamental parameter in determining fluid velocity, increasing permeability an order of magnitude shows the greatest changes in fluid flow patterns among all parameters.

**Fluid Density Results and Fluid Density Patterns:** Fluid density patterns and solute transport are very dependent upon the permeability of the soil and thus these results show the greatest changes. When permeability decreases, the \( \text{FSI}_{\text{surface width}} \) decreases to 125 m wide, the \( \text{FSI}_{90dx} \) is 100 m, while the \( \text{FSI}_{30dx} \) is 200 m (Figure 13d). When permeability is at a maximum value, the \( \text{FSI}_{\text{surface width}} \) increases to 2100 m wide, the \( \text{FSI}_{90dx} \) doubles in width to 500 m, while the \( \text{FSI}_{30dx} \) maintains the same 400 m width (Figure 13f). As permeability increases, the base of the 90% contour curves landward as more seawater is migrates through the confined aquifer. In the sensitivity increase percent seawater plot, the seawater influence occupies almost 75% of the numerical domain.

**4.6. Eastern Shore: Examples of Effects of Varying Domain Size and Boundary Conditions**

Figure 14 displays the final set of results, showing model runs using three different domain geometries: a simulation with equal land and marine portions in the middle column, a domain that is saltwater dominated in the left column, and a model that favors terrestrial conditions in the right column. For the middle simulation, the distance along the transect has been reduced to 2075 m, with the freshwater boundary condition from \( x = 0 \) m to \( x = 1150 \) m and saltwater from \( x = 1150 \) m to \( x = 2075 \) m. For the saltwater-dominated model run, the freshwater boundary condition is imposed from \( x = 0 \) to \( x = 1150 \) m and the saltwater from \( x = \)}
1150 to \( x = 4700 \) m. The freshwater-dominated simulation was used in the sensitivity analysis for the Eastern Shore and contains the same boundary conditions as previously discussed. Axis properties and figure pane displays are the same as the Eastern Shore recharge, salinity, and permeability simulations.

**Groundwater Velocity Results and Fluid Flow Patterns:** Comparing simulations from the same geographic area with different treatments of the transect emphasized how sensitive the model was to small changes in topography and bathymetry. In all three sets of boundary conditions, the general groundwater velocity characteristics are similar with freshwater and saltwater cells meeting to discharge at the low tide mark. While freshwater flows towards the shoreline in all scenarios, mimicking the topography of the land, the saltwater system shows the greatest changes in fluid flow. In the domain with equal boundary conditions, saltwater flows down through the confining layer and landward through the confined aquifer before it is recirculated upwards towards the low tide mark; it does not flow as far inland as the freshwater dominated case. The pathlines show differences in the vertical extent that the saltwater particles travel below the low tide mark (Figure 14h, i). Flow characteristics within the saltwater-dominated scenario are very different (Figure 14a, g). The channel offshore serves as a local recharge area as well as a flow divide for the saltwater entering the coastal sediments. This phenomenon is caused by the local increase in depth and hydrostatic pressure. Groundwater to the west of the channel flows seaward while flow to the east of the channel flows toward the land. In addition, salty groundwater flows deeper within the offshore confined aquifer.

The maximum flow velocities did not differ significantly for the three model domains. The domain with equal boundary conditions produced the fastest velocity of 547 in/yr, the saltwater model yielded a reduced velocity of 542 in/yr, and the freshwater-dominated scenario generated a velocity of 545 in/yr. The velocity in the x-direction is greatest during the equal boundary condition scenario and at a minimum during the saltwater model run. The vertical velocity is greatest for the saltwater dominated domain.

**Fluid Density Results and Fluid Density Patterns:** Although there are small differences in the velocity magnitude compared to previous sensitivities, the changes in fluid density patterns are much more pronounced. Domain size and boundary conditions have an effect on the freshwater
Figure 14. Eastern Shore domain simulations with equal boundary conditions in the middle column, saltwater-dominated system in the left column, and freshwater-dominated system in the right column. Other details of the plots are as in Figure 9.
and saltwater systems within the Eastern Shore transect. In the freshwater-dominated scenario, the results are the same as discussed above where the $\text{FSI}_{\text{surface\_width}}$ is 700 m wide, the $\text{FSI}_{90dx}$ is 225 m, and the $\text{FSI}_{30dx}$ is 400 m (Figure 14f). For the transect with equal boundary conditions, the $\text{FSI}_{\text{surface\_width}}$ decreases to 500 m wide, the $\text{FSI}_{90dx}$ decreases to 200 m, and the $\text{FSI}_{30dx}$ decreases to 325 m (Figure 14e). For the saltwater-dominated runs, the metrics used to calculate $\text{FSI}_{\text{surface\_width}}$ span throughout the whole domain, the $\text{FSI}_{90dx}$ increases to 700 m, and the $\text{FSI}_{30dx}$ cannot be determined because it is not included within the domain (Figure 14d). Interestingly, the saltwater recirculation system is at a minimum when boundary conditions are proportional and the domain is smaller. Saltwater shows the greatest migration, extent, and contour slopes within the saltwater-dominated scenario.

The numerical simulations presented in the last results section illustrate how sensitive SUTRA is to changes associated with favoring a certain boundary condition. The velocity magnitudes may have been similar, but the freshwater-saltwater system responded greatly. In order to overcome these differences, and in order to fully replicate the values found in the field, the model must simulate natural recharge and discharge cells where no-flow boundaries are placed on groundwater divides.
CHAPTER 5
DISCUSSION AND FUTURE WORK

5.1. The Effect of Recharge Rate and Precipitation on SGD

Among the three sensitivity parameters tested at each transect, recharge rate had the smallest effect on groundwater velocity at the low tide mark. This can be determined from the slope of the line for recharge rate on Figure 15. However, while increasing the rate of precipitation did not cause an appreciable increase in discharge velocity for any of the three transects, the location and width of the FW/SWI did respond to recharge changes (Figures 16a-c). For example, in the case where recharge is decreased for the Eastern Shore transect, the width of the saltwater recirculation cell increases by 46% (Figure 16a), with the unconfined aquifer showing the greatest migration of saltwater landward (Figure 11). Conversely, increasing recharge compresses the overall FW/SWI width by 32%, and shifts the system seaward. The particle pathways illustrate how a decrease of recharge allows saltwater to travel farther inland (Figure 11). If future climatological patterns in a particular region cause an increase of severe rains and storms, and thus of precipitation and recharge, this set of model results would generally imply a seaward shift of the FW/SWI and a decrease in its width. However, it is important to remember that the salinity of an adjacent coastal body could concomitantly decrease as well. The effects of decreasing salinity are described next.

5.2. The Effect of Saltwater Density and Concentration on SGD

Increasing the assigned salinity of the coastal body changed the SGD rate nearly linearly in all transects; for example, there was a 2.3-fold increase in velocity at both Ocean View as density changed from 1018 kg/m$^3$ to 1025 kg/m$^3$ (Figure 15). Not only did the magnitude of velocity change with each salinity simulation, but the FW/SWI showed a response by uniformly migrating landward for all transects (Figure 16a-16c). For the Eastern Shore transect, the width of the saltwater recirculation cell increased by 68% with an increase of 7 ppt salinity. Decreasing salinity by 10 ppt reduced the overall FW/SWI width by 86% percent. Changing saltwater density from one extreme case to the other within the Eastern Shore model generated a
Figure 15. Sensitivity of SGD velocity at the low tide mark to seawater density, recharge rate, and aquifer horizontal permeability. Results are shown for all three transects (Eastern Shore, Ocean View, and Lafayette River). Note that because of the estuarine setting, salinity values vary as a function of distance from the mouth of the Chesapeake Bay.

Figure 16a. Sensitivity of freshwater/saltwater interface (FW/SWI) width and location to recharge rate, seawater density, and permeability for the Eastern Shore transect. Note that the fill color for each data point corresponds to either the left or right axis, and that negative migration indicates the contour moves landward. 

D = decrease of variable value, B = base case, I = increase of variable value.
Figure 16b. As for Figure 16a, but for Ocean View model runs.

Figure 16c. As for Figure 16a, but for Lafayette River model runs.
126% difference in velocity and an 11-fold increase in FW/SWI width (Figures 15 and 16a) as the fluid driving forces associated with spatial density contrasts changed.

Simulations of salinity changes suggest that the coastal aquifer may have a dynamic component related to variations in density forcing that has not, to our knowledge, been heretofore quantified. Previous studies that have assigned a constant value of oceanic salinity and density may have been over-estimating the saltwater contribution occurring at the low tide mark, or not fully understanding the full effect of this forcing. While daily changes in salinity within the bay caused by tidal flushing can create different seawater pressures placed on the coastal plain strata, which may alter the velocity slightly, seasonal differences in water density within the bay could be capable of generating significantly different subterranean flow environments. The nature of these seasonal fluctuations can be inferred from the difference in FW/SWI width and 30% contour migration from Figures 16a-16c. The results of these models suggest that groundwater velocities and the width of the FW/SWI are greatest during the fall when density is at a maximum, and least during the spring when salinity is at a minimum within the Bay (Figures 15 and 16). Simulating a climate with wetter conditions would require both increased recharge and decreased salinity, which would have a compound effect on SGD velocity and FW/SWI width. The combination of these two forcings would create a fresher subterranean environment with less saltwater recirculation and an overall decrease in SGD velocity. These effects may allow for more freshwater pumping, but biogeochemical cycles within the marine environment could feel an effect of a decreased circulation. Changes in salinity and recharge within the Chesapeake Bay watershed will continue to force biological communities to adapt and change, and hence it is important to understand how these combined effects will affect hydrodynamics near the coast.

5.3. The Effect of Sediment Permeability on SGD

Hydraulic conductivity is a fundamental variable in SUTRA’s calculations of groundwater velocity and, accordingly, varying this parameter causes the most pronounced changes in SGD patterns. Increasing permeability over the values listed in Table 1 caused the velocity at the low tide mark to increase by 7.2-fold and 5.3-fold for the Ocean View and Eastern Shore transects, respectively (Figure 15). For all three transects, the location of the FW/SWI, as
indicated by the 30% concentration contour, had the greatest spread as permeability was changed (Figures 16a-c). Aquifer permeability was altered proportionally throughout the whole domain, and thus the marine setting showed greater changes in velocity, due to the differences in fluid density forcing between freshwater and saltwater (Equation 1). Since the amount of vegetation or biological activity present within an area can increase the surficial aquifer permeability, a climate that favors tree, or submerged aquatic vegetation growth, may produce faster SGD velocities. Seagrass meadows host a community of organisms that could alter the permeability of marine sediment as well (Fanjul et al., 2008). A cold, dry climate with salty and productive seas would increase seawater ventilation while warm, wet weather patterns may slow SGD rates. This would suggest that a combined increase of both permeability and saltwater density could have a greater effect on the marine environment compared to the terrestrial.

5.4. Transect Location Selection

Assigning the location of confining units is an essential part of the numerical process. Groundwater flow within these units is at a minimum, and they thus can act as barriers for vertical freshwater infiltration or saltwater recirculation flow. In contrast, when permeability increases within the confined aquifer, it can act as a pathway for the migration of saltwater. This extends the width of the FW/SWI and increases the residence time of saltwater within the subterranean aquifer. As shown in the Eastern Shore transect, one order of magnitude permeability decrease reduces the width of the FW/SWI by approximately 2 km, which is a significant distance when considering siting wells for potable water. Because defining the magnitude and spatial variation of permeability along a transect is both challenging and extremely valuable in the calculation of groundwater flow, constraint of this variable using field data is critical.

5.5. Future Work

While this study advances our understanding of the mechanisms involved within coastal groundwater flow, there are many other opportunities for future work. Of greatest importance is gathering detailed field data of groundwater velocity, hydraulic permeability, and water column
chemistry along each of the transect profiles. Data collected during these future operations will support and calibrate the model, and can facilitate running chemical transport simulations. Additionally, running models in 3D will allow thorough exploration of the spatial controls on groundwater flow along a beach profile, possibly identifying areas which are prone to faster groundwater flow and greater freshwater discharge.

Time-dependent models with boundary conditions that change temporally can provide information about how fast the seawater recirculation system recycles water. For example, simulations of rain events could reveal interesting relationships between the timing and abundance of precipitation, groundwater recharge, and submarine groundwater discharge. An important process that was not considered in this study, but that plays a significant role within the Hampton Roads area, is sea level rise. A time-dependent model would be able to simulate different rates of sea level rise and may reveal new information about the behavior of the FW/SWI. Although the Eastern Shore transect included deeper hydrostratigraphy, all of the other transects spanned relatively short profile and depth extents. Future studies could model longer transects in an effort to understand regional patterns like the connectivity between surficial and confined aquifers, or the residence time of groundwater within the coastal plain strata. Including reservoirs of water such as lakes or ponds could also provide information on how these bodies will change with sea level rise and saltwater contamination. It is clear that while these models have provided valuable information toward advancing SGD science, there are many other questions to answer.
CHAPTER 6

CONCLUSIONS

Groundwater flow near the coastal plain is a complex process that researchers are just beginning to understand. There are many methods for studying SGD, including direct flow measurements and pore water chemistry. The numerical simulations presented here yield new information about how different coastal settings behave during changes of seawater salinity, recharge rate, and permeability.

While groundwater flow paths were generally similar among all three transects, the topographic slope and bathymetric gradient significantly influenced the velocity of both freshwater and saltwater. Numerical domains with the greatest slope generated the fastest groundwater velocities, and domains with a gentle slope produced slower SGD rates. For example, The Eastern Shore domain, which had a slope of 0.0069, yielded a maximum velocity of 545 in/yr. The Ocean View domain modeled a slope of 0.0028 and generated a maximum velocity of 325 in/yr. Changes in bathymetry offshore increased the rate of seawater recirculation, which suggests that these areas are active biogeochemical zones.

For the sensitivity tests, varying permeability resulted in magnitude-scale differences in discharge rate. Although recharge rate was hypothesized to have a large effect on SGD velocity, this in fact was not observed. However, there were significant changes associated with solute transport patterns when recharge was varied. Model results from the salinity sensitivity tests yielded greater changes than expected, which indicates that flow patterns might be in continual dynamic response to saltwater density forcing and suggests that there might be seasonal changes in contributions to regional geochemical and hydrologic budgets. Including a confined aquifer in the numerical domain for the Eastern Shore allowed saltwater to migrate farther inland. Overall, this study establishes a framework of numerical results for assessment of factors that affect saltwater intrusion in riverine, estuarine, and coastal settings.
REFERENCES


Burnett, W.C., Peterson, R., Moore, W.S., & Oliveira, J.D. (2008). Radon and radium isotopes as tracers of submarine groundwater discharge – Results from the Ubatuba, Brazil SGD


Chesapeake Bay Program. (2019). Retrieved from https://www.chesapeakebay.net/


Hussain, N., Church, T., & Kim, G. (1999). Use of $^{222}$Rn and $^{226}$Ra to trace groundwater discharge into the Chesapeake Bay. Marine Chemistry, 65(1-2), 127-134. doi:10.1016/s0304-4203(99)00015


Tobias, C.R., Harvey, J.W., & Anderson, I.C. (2001). Quantifying groundwater discharge through fringing wetlands to estuaries: Seasonal variability, methods comparison, and


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Career Overview
Masters graduate with a specialty in ocean and earth sciences. Thesis work involved developing a numerical model used to simulate submarine groundwater discharge.

Education
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