Modeling the Transport of Radium Isotopes Offshore Tampa Bay Through Submarine Groundwater Discharge

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Modeling the Transport of Radium Isotopes Offshore Tampa Bay Through Submarine Groundwater Discharge

By

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Abstract

Radium isotopes have been used in years past to observe and understand coastal mixing processes and submarine groundwater discharge. There are four radium isotopes used as natural tracers: Ra-224, Ra-223, Ra-226, and Ra-228, with half lives ranging in length from a few days to over a thousand years, which makes them applicable tracers of process of a variety of lengths of time. In this project, I simulated the flow of these isotopes through submarine groundwater discharge into coastal and offshore waters. I constructed a model of the study area, using a computer program called Visual MODFLOW, which uses finite difference methods to model groundwater flow. I then ran the model, and determined the results of the model support the excess radium activity seen offshore, as attributed to submarine groundwater discharge.

Introduction

1.1 The Hydrology of Tampa Bay

Tampa Bay is located on the west-central coast of Florida and has a moderate temperate climate, as can be seen in Figure 1. The Bay is a sinkhole conglomerate (Suthard 2009), and can be divided into four subsections: old Tampa Bay, Hillsborough Bay, Middle Tampa Bay, and lower Tampa Bay, as can be seen in Figure 2. With an average depth of 3m and a surface area of 1030 km²,
the Bay has an approximate volume of $4 \times 10^9 \text{m}^3$ (Clark and MacAuley, 1989).

Tampa Bay is an estuary of fresh and saline water inputs. Saline water enters the bay at the opening to the Gulf of Mexico at the south western portion of the Bay.

Freshwater inputs are primarily from four rivers: the Hillsborough, Manatee, Little Manatee, and Alafia, and from groundwater, as Florida’s karst topography allows for multiple springs throughout the 4600 km$^2$ Tampa Bay watershed. The watershed consists of portions of Pinellas, Hillsborough, and Manatee counties (Clark and Maculey, 1989). Fresh submarine groundwater discharge into the Bay has been estimated to range between 2.2 and 14.5, according to estimations using Darcy’s law and water budget methods (Swarzenski et al. 2007). The four main rivers flowing into Tampa Bay account for 70% of the inflow of freshwater in Tampa Bay. The other 30% consists of precipitation, groundwater flow, and minor springs and rivers. The cumulative average flow rate of all surface water sources into Tampa Bay is $63 \text{m}^3/\text{s}$.

Of this the Hillsborough River contributes a flow rate of $15 \text{m}^3/\text{s}$, the Alafia River contributes a flow rate of $13 \text{m}^3/\text{s}$, the Little Manatee River contributes an average flow rate of $6 \text{m}^3/\text{s}$, and the Manatee River contributes and average flow rate of $10 \text{m}^3/\text{s}$ (Lewis and Estevez, 1988). Each of the rivers mix with the saline water of Tampa Bay as
a salt wedge formation, where the saline ocean water forces its way up river during a flood tide under the fresh water. Upstream, this transitions to a partially mixed estuary, where the salt wedge becomes less evident, and then to a mixed system, where salinity is constant with depth (Davis and FitzGerald 2004). Special note should be made here of the Hillsborough River, which contains a dam to supply water to the urban sprawl of Tampa, as can be seen in Figure 3. Because of the presence of the dam, salinity in the downstream area of the dam is higher than would be expected, due to disruption of the natural mixing with upstream water. The river downstream of the dam experienced extreme stress in the recent past, due to excessively high salinity. A minimum flow rate was introduced to ensure health of the downstream portion of the river (XinJian et al, 2000).

Surface flow information is important in this study, because it determines how much radium in the water column comes from surface water flow into Tampa Bay, since fresh water is enriched in radium. Only a portion of the radium in the bay is a direct result of submarine groundwater discharge. In order to determine the amount of radium which is a result of groundwater, the amount of total radium and the amount of radium from surface water sources must be known. Salinity at the mouths of rivers is also of note, because the amount of radium released into the water column in an estuary is directly related to salinity. In areas of freshwater,
radium adheres strongly to particles in the water column and river bed. As salinity increases, radium is out-competed for binding sites on particles and its concentration increases in the water column. The concentration of radium then decreases as advection and diffusion distributes radium in offshore waters, resulting in a bell curve, where the concentration of radium is inversely in the seaward section of the estuary (Webster et al. 1994). In waters with high amounts suspended sediment, suspended sediment may need to be measured to account for how much activity is a result of the suspended sediment (Moore 2008). This does not apply to the rivers of this study, due to their low rate of suspended sediment.

1.2 Tides on the West Central Coast of Florida

This area of the Gulf Coast experiences semidiurnal and diurnal tidal components. The semidiurnal tidal component is 24% of the whole of tidal components, and the diurnal tidal component is 42% of the whole of tidal components. The remaining components are mainly weather driven (Weisberg 2006). Tides are one major component in controlling how quickly radium is flushed out of the bay, because the ebb tide carries radium out to sea.

1.3 The Nutrients of Tampa Bay

The waters of west central Florida are naturally nitrogen limited, meaning primary production is limited by the amount of nitrogen present in the environment (Kroeger et al. 2006). However, Tampa Bay is surrounded by urban sprawl, with Hillsborough, Manatee, and Pinellas Counties containing a total population of 2,406,804 in 2008 (US Census Bureau 2009). Excess nutrients in water have been shown to increase with increasing populations in watersheds (Valiela et al. 2000; Nolan and Stoner
Accordingly, large amounts of nitrogen and phosphate enter the bay in the form of waste water and fertilizer runoff (Valiela et al. 1997). Also, the land south of Tampa Bay is naturally rich in phosphate, causing the phosphate concentrations in groundwater to be higher than the US average (Nolan and Stoner 2000). Groundwater also contributes nutrients to the bay in the form of phosphate, nitrates, ammonium, and silicate (Swarzenski et al. 2007).

However, waters offshore from Tampa Bay are nutrient poor. Yet, it is within these nutrient poor waters that algal blooms originate, eventually moving onshore (Tester and Steidinger 1997). Algal blooms are known to occur in areas of high nutrient loading, and can cause hypoxic conditions. Why the blooms originate in supposedly nutrient poor waters remains an anomaly. Since groundwater, fresh and saline, is historically rich in nutrients, it is possible that submarine groundwater discharge provides the nutrients needed for these algal blooms to grow (Swarzenski et al. 2007). By using the radium quartet and groundwater modeling to study submarine groundwater discharge, the answer as to why the algal blooms originate offshore may be at hand.

1.4 Radium in Tampa Bay

Radium concentrations in Tampa Bay are inversely related to salinity. In general, concentrations of the radium quartet, Ra-223, Ra-224, Ra-226, and Ra-228, are highest in Old Tampa Bay, with concentrations ranging from 300 to 180 dpm/100L. Concentrations are lower in Hillsborough Bay and lower Tampa Bay, with concentrations in Hillsborough Bay ranging from 240 to 80 dpm/100L, and concentrations in lower Tampa Bay ranging from 140 to 60 dpm/100L. Middle Tampa Bay represents a mixing zone of waters from lower Tampa Bay, Hillsborough Bay, and Old Tampa Bay, with
concentrations ranging from 200 to 100 dpm/100L (Swarzenski et al. 2007). This gradient shows how radium concentrations drop off as water from the bay mixes with saline water in the Gulf.

1.5 The Study Area

The west central coast of Florida has the characteristics of a marginal seas coast, which means it has a long, gently sloping continental shelf, as can be seen from Figure 4. Despite the length of the continental shelf, this portion of the Florida coast is wave dominated, as indicated by the long, thin, barrier islands along the coast from just north of Tampa Bay to the Ten Thousand Islands, south of Naples (Davis et al. 2003).

The model area is composed of the neck of Tampa Bay through the ebb tidal delta and onto the continental shelf, as can be seen in Figure 5. It extends normal from the coastline approximately 37 km into the Gulf. The shallow sediment layers of the study area meet the description of

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Figure 4, Stratigraphy of the west continental shelf of Florida, reproduced from Duncan et al. (2003)

Figure 5, the study site of the model, extending from the neck of Tampa Bay south west onto the continental shelf
an unconfined aquifer, as indicated by sediment cores taken in 2003 (Duncan et al. 2003). The cores indicate a sand layer ten to fifteen meters deep, through which waters can easily flow. The sand layer is underlain by a confining blue/green clay layer which is only one to two meters thick. The clay layer has very low hydraulic conductivity of $3.53 \times 10^{-10} \text{ m/day}$, which limits flow from the permeable sands underneath it to the sands above (Broska and Barnette 1999). Another sand layer lies below the unconsolidated clay layer with a width of four to five meters and hydraulic conductivity of $6.53 \times 10^{-5} \text{ m/day}$; it is more inclined to transport groundwater than the clay layer. Finally, bedrock of limestone/dolostone completes the relevant sediment layers (Duncan et al. 2003, Broska and Barnette 1999, Crandall 2007).

1.6 Visual Modflow

Modflow is a computer software program through which groundwater flow can be modeled in a three dimensional format. For this project, I used a student version of Modflow which accompanied Hydrogeology (Fetter 2001).

Modflow is based on the finite difference equation (Equation 2), which calculates the flow into and out of cells which compose an aquifer system. The $z$ (vertical) components of the cell boundaries are defined by the structure of sediment layers, and the $x$ and $y$ (horizontal) component of cell boundaries are typically a function of latitude and longitude, as can be seen in Figure...
6. The following advection-diffusion equation (Equation 1) calculates the specific storage for each cell:

\[
\frac{\partial}{\partial x} \left( K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_{zz} \frac{\partial h}{\partial z} \right) + W = S_s \frac{\partial h}{\partial t}
\]

(1)

Where:

- \( K_{xx}, K_{yy}, \text{and } K_{zz} \) are values of hydraulic conductivity along the x, y, and z coordinate axes
- \( h \) is the potentiometric head
- \( W \) is a volumetric flux per unit volume representing sources and or sinks of water
- \( S_s \) is the specific storage of porous material
- \( t \) is time

The flow of water in and out of each cell is then calculated by the following finite difference equation:

\[
\sum Q_1 = SS \frac{\Delta h}{\Delta t} \Delta V
\]

(2)

Where:

- \( Q_1 \) is the flow rate into the cell
- \( SS \) has been introduced as the notation for specific storage (the volume of water that can be injected per unit volume of aquifer material per unit change in head)
- \( \Delta V \) is the volume of the cell
- \( \Delta h \) is the change in head over a time interval of length \( \Delta t \).

Modflow calculates flow for all the cells in the model individually, and then combines the flow of each cell to generate the flow of all the combined cells. Because particles are
typically transported at a different rate than the flow of the water, a separate transport engine, MT3DMS, is used to calculate transport of a substance and the resulting concentrations. Another feature, Modpath, can allow the user to view specific pathlines of imaginary particles strategically placed within various areas of the model. Finally, Zonebudget may be used to specify specific zones within the model. Net flow and submarine groundwater discharge can then be examined as a whole within these zones (US Geological Survey, 2005).

Methods

2.1 Modflow Construction

The following sections detail the construction of the model study area, and the data for the model parameters.

2.1.1 Cell Construction

To start the model a base map of the study area in bitmap format was imported. A screen shot of the Key West to Mississippi River chart from NOAA, as viewed in Sea

![Figure 7](image.png)

Figure 7, the cells of the model superimposed on the basemap of the study site.
Clear, was used as the basemap. The transect stations from an unpublished study (Deszo, USFSP Senior Project 2007) were imported as waypoints on the chart. These points on the map were used to geo-reference the map coordinates with real world coordinates. MODFLOW uses the Universal Transverse Mercator coordinate system and a model coordinate system. This allows the model to be rotated within the 3D explorer while maintaining the UTM coordinate system. The study site was built with the parameters of twenty columns by twenty rows by three layers. Additional grid lines were added to the rows in the model which most closely corresponded with the sampling transect, to allow for more precise modeling of this area, as can be seen in Figure 7.

Parameters for the three model layers were then derived from the work of Duncan et al. (2003) in which two cores were taken through the relevant sediment layers. For purposes of this model, two cores from the Duncan study were analyzed to establish sediment layers: a core near Egmont Key and a core near Anna Maria Island. The Egmont core, EGM, is directly north of the Anna Maria core, AMI. The cores show the same layering sequence of sand followed by mud/clay followed by more sand then limestone/dolostone. However, the southern core is slightly higher in the elevation of its layers than the northern core. The depths of these layers were used to estimate the thicknesses of the layers of the model.

2.1.2. Boundary Conditions

To build the body of water for the model, the boundary conditions rivers function of Modflow was used. The shoreline of the body of water for the model was built by tracing the contours of the shoreline on the basemap. Due to the raster characteristics of the model, cells containing land and water could only be designated as one or the other.
Judgment and apportionment of land/water in the cell was used to determine as whether the cell should be designated as land or water. Depth of the body of water was specified to replicate the depths measured on the sampling trips of the Dezo study. Riverbed conductance was calculated for the various regions of the body of water from Equation 3:

\[ C = \frac{KLW}{M} \]  

Where:

- \( L \) is the length of reach through a cell,
- \( W \) is the width of the river in a cell,
- \( M \) is the thickness of the riverbed, and
- \( K \) is the hydraulic conductivity of the riverbed material.

The land areas of the model were designated as recharge zones. Precipitation quantities were researched to be 1400 mm/yr (Schmidt & Luther 2002). Several recharge situations were designed, which tested SGD in drought and rainy conditions.

2.1.3 Properties

Hydraulic conductivity and storage were estimated from Broska and Barnette (1999) and Crandall (2007). These studies have utilized the same sediment series as the Duncan (2003) study. The USGS studies (Broska and Barnette 1999, Crandall 2007) break up the sediments and series into permeable layers. Effective porosity, storativity, and hydraulic conductivity were taken for each layer from the USGS papers. Specific storage was estimated from Equation 4 (Fetter 2001):

\[ S = bSs \]
Where:

- \( S \) is storativity,
- \( S_s \) is specific storage, and
- \( b \) is thickness of the aquifer.

The final values for the properties by layer can be seen in Table 1. Layer 1 is the topmost sand layer, layer 2 is the blue-green clay layer, and layer 3 is the underlying sand layer. Due to limitations of the model, storage variables were held constant throughout the sediment layers.

2.2 **MT3DMS Construction**

The transport model MT3DMS was then used to simulate the flow of the four radium isotopes, Ra-223, Ra-224, Ra-226, and Ra-228, through the aquifer system. The transport engine used, because it can account for first order irreversible decay. Table 2 shows the species name, decay constants, and initial concentration, for the transport engine. Concentrations were determined from Swarzenski et al. (2007), who collected various pore water samples from around Tampa Bay. The decay constants were derived from the **Equation 5:**
\[ K = \frac{\ln 2}{t_{1/2}} \]  

Where:

- \( K \) is the decay constant and
- \( t_{1/2} \) is the half life of the isotope.

Within MT3DMS, an adsorption/desorption needed to be designated. Linear isotherm was selected for this purpose, as the simplest reaction available. Desorption is controlled in the model by the distribution coefficient (Kd), which is the ratio of activity of the sediment per microgram per the activity per liter of water (Faure, 1986).

The dominant factor in desorption of radium in cation exchange on the particles (Li and Chan 1977). However, desorption is also affected by sediment concentrations and resuspended bottom sediment, with most sediment with low suspended sediment yielding a Kd of less than 300 (Astwood, Masters Thesis 1991). To match the characteristics of the study area, a Kd of \( 8 \times 10^{-8} \text{ug l}^{-1} \) was used.

2.3 Modpath Construction

Modpath is a component within the MODFLOW package which allows the modeler to designate particles within specific cells. When the model is run, the modeler can then see the paths the particles travel through the study site. Because submarine groundwater discharge is the focus of this study, particles representing radium isotopes were placed in the semi-confining unconsolidated clay layer and the sand layer underlying the clay layer, to see if the particles paths discharged from the lower layers to the body of water in the first layer.

2.4 Zone Budget Construction
Zone Budget is a component within MODFLOW which allows the modeler to group cells together into Zones. This allows for the modeler to calculate net groundwater flow from one zone to another as well as river leakage (or in this case submarine groundwater discharge) within different zones. It should be noted that the river leakage number includes a re-circulated groundwater component as well as un-re-circulated groundwater component. It should also be noted that river leakage represents discharge averaged over the entire zone, this may include dry land where no discharge is present. In this model, three zones were designated to represent the onshore (zone 1), near shore (zone 2), and offshore (zone 3) areas.

Results

3.1 ModFlow

When the Model was allowed to run the simulation without hydraulic head held constant, the net flow of groundwater showed a tendency toward offshore waters. The velocity diagram also showed a tendency toward the center of the model, as can be seen in Figure 8. This tendency may be the result of the flow barriers the model experiences at the edges. However, despite the definite groundwater flow offshore, no definite vertical flow across the layers was observed visually.
3.2 Zone Budget

3.2.1 Variations in Hydraulic Head

The model-determined hydraulic head varied from 1 to 2.7 meters above sea level on land, depending on location. However, Crandall (2007) indicates that coastal hydraulic heads in Pinellas and Manatee County can vary from -2 to 3 meters above sea level. In order to see how these different hydraulic heads affected discharge in the different zones, the model was rerun, while holding hydraulic head constant, with values determined by Crandall (2007). Table 3 shows the discharge in each of the zones and flow from the on

<table>
<thead>
<tr>
<th>Hydraulic Head meters above sea level</th>
<th>Zone 1 Discharge $m^3m^{-2}d^{-1}$</th>
<th>Zone 1 to Zone 2 Discharge $m^3d^{-1}$</th>
<th>Zone 2 Discharge $m^3m^{-2}d^{-1}$</th>
<th>Zone 2 to Zone 3 Discharge $m^3d^{-1}$</th>
<th>Zone 3 Discharge $m^3m^{-2}d^{-1}$</th>
<th>Average Overall Discharge $m^3m^{-2}d^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model-determined head</td>
<td>0.00312</td>
<td>1145800</td>
<td>0.00478</td>
<td>666000</td>
<td>0.00489</td>
<td>0.00407</td>
</tr>
<tr>
<td>0.0</td>
<td>0.000161</td>
<td>000000</td>
<td>0.00101</td>
<td>000000</td>
<td>0.00172</td>
<td>0.000843</td>
</tr>
<tr>
<td>0.1</td>
<td>0.000161</td>
<td>000000</td>
<td>0.00101</td>
<td>000000</td>
<td>0.00172</td>
<td>0.000843</td>
</tr>
<tr>
<td>0.25</td>
<td>0.000161</td>
<td>000000</td>
<td>0.00101</td>
<td>000000</td>
<td>0.00172</td>
<td>0.000843</td>
</tr>
<tr>
<td>0.75</td>
<td>0.000161</td>
<td>000000</td>
<td>0.00101</td>
<td>000000</td>
<td>0.00172</td>
<td>0.000843</td>
</tr>
<tr>
<td>1.00</td>
<td>0.000161</td>
<td>000000</td>
<td>0.00101</td>
<td>000000</td>
<td>0.00172</td>
<td>0.000843</td>
</tr>
<tr>
<td>1.5</td>
<td>0.000161</td>
<td>000000</td>
<td>0.00101</td>
<td>000000</td>
<td>0.00172</td>
<td>0.000843</td>
</tr>
</tbody>
</table>

Table 3, SGD in each zone according to hydraulic head, and quantities of groundwater flow from onshore zone 1 toward offshore zone 3.

shore zone toward the offshore zone to three significant digits. As can be seen, the model-determined hydraulic heads resulted in more SGD than the designated constant heads. Additionally, any
variation in designated constant head had little to no affect on the quantity of SGD. The low patterns of SGD also differed in the model-determined heads and designated constant heads. Unlike the model-determined heads, the designated constant heads did not exhibit a seaward flow of groundwater. In all scenarios where the hydraulic head was held constant, backflow of groundwater was actually exhibited.

### 3.2.2 Variations in Recharge

<table>
<thead>
<tr>
<th>Number of Days</th>
<th>Zone 1 Discharge $m^3m^{-2}d^{-1}$</th>
<th>Zone 1 to Zone 2 Discharge $m^3m^{-2}d^{-1}$</th>
<th>Zone 2 Discharge $m^3m^{-2}d^{-1}$</th>
<th>Zone 2 to Zone 3 Discharge $m^3m^{-2}d^{-1}$</th>
<th>Zone 3 Discharge $m^3m^{-2}d^{-1}$</th>
<th>Average Discharge $m^3m^{-2}d^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.00312</td>
<td>1145800</td>
<td>0.00478</td>
<td>666000</td>
<td>0.00489</td>
<td>0.00407</td>
</tr>
<tr>
<td>15</td>
<td>0.00312</td>
<td>1145800</td>
<td>0.00478</td>
<td>666000</td>
<td>0.00489</td>
<td>0.00407</td>
</tr>
<tr>
<td>20</td>
<td>0.00312</td>
<td>1145800</td>
<td>0.00478</td>
<td>666000</td>
<td>0.00489</td>
<td>0.00407</td>
</tr>
<tr>
<td>35</td>
<td>0.00312</td>
<td>1145800</td>
<td>0.00478</td>
<td>666000</td>
<td>0.00489</td>
<td>0.00407</td>
</tr>
</tbody>
</table>

Table 4. SGD in each zone according to recharge, and quantities of groundwater flow from onshore zone 1 toward offshore zone 3.

The results of the variations of recharge showed little affect on the quantity of SGD and flow from onshore to offshore zones as well, as can be seen from Table 4.
3.3 ModPath

The pathlines of imaginary particles in modflow followed a general direction of ascending through the sediment layers, then flowing along the bottom of the body of water, as can be seen in Figure 9. Particles from both the intermediate clay and lower sand layer moved into the uppermost layer. The particles also showed a tendency to travel toward the center of the model, once reaching the topmost layer, as can be seen in Figure 10. This tendency may again be the result of the flow barriers the model experiences at the edges of the model.
3.4 MT3DMS

The concentrations of Radium predicted by the MT3DMS showed little variance from near shore to offshore in the sediment. However, MT3DMS showed a lot of variability in concentrations within the sediment for each isotope, as can be seen in Figures 11, 12, 13, 14, where moving from right along the x-axis to left symbolizes the onshore to offshore transition, and the y-axis represents elevation through the sediment layers in meters.

Figure 11, Variance of Radium 223 through the layers, from on shore to offshore, units are in ug/L

Figure 12, Variance of Radium 224 through the layers, from on shore to offshore, units are in ug/L.

Figure 13, Variance of Radium 226 through the layers, from onshore to offshore, units are in ug/L.
Within the water column, MT3DMS showed little variance in regard to radium concentration, as can be seen in Figure 15, which represents Ra-223. The other isotopes show a similar pattern.

Discussion

4.1. Modflow

The model’s most accurate estimation of submarine groundwater discharge was observed in the offshore area known as zone three. In this zone, SGD was observed in the model to be approximately $0.00489 \text{ m}^3\text{m}^{-2}\text{d}^{-1}$. Alterations to boundary conditions of the model had little to no affect on the quantity of SGD observed. This implies that
the properties of the model played the dominant role in the SGD observed. While storage was uniform throughout the layers, hydraulic conductivity varied between layers. Layers one and three were characterized by high hydraulic conductivity of $6.35 \times 10^{-5} \text{m/d}$ while layer two, the blue-green clay layer, was characterized by low hydraulic conductivity of $3.35 \times 10^{-10} \text{m/d}$. This clay layer may be the limiting factor to how much of the SGD observed was from groundwater which originated below the clay layer. Due to the confining characteristic of the clay layer, much of the SGD observed in the model may be re-circulated groundwater. The same may be said of the near shore zone. In the near shore area SGD was calculated to be $0.00478 \text{m}^3 \text{m}^{-2} \text{d}^{-1}$. The near shore zone, like the offshore lacks any land cells. Also, the amounts of SGD observed in this area varied little, with the alterations of the properties of the model.

However, the measurements for the onshore area of SGD should be viewed cautiously. The measurement of SGD in the near shore zone is averaged across all cells, including cells which are entirely land-locked, which experience no SGD. Therefore the SGD observed here as $0.00312 \text{m}^3 \text{m}^{-2} \text{d}^{-1}$ is an average of the coastlines and submerged areas which experience a high rate of SGD, and the landlocked areas which experience no SGD. Also, since the model is built using raster parameters, each cell must be designated as either land or sea. Thus much of the subtleties of the coastlines are lost in this model. SGD would be expected to be higher along the coastlines, but this model is unable to account for that.

Table 5 show values for submarine groundwater discharge measured at various study sites around Florida. The other sites most like the offshore and near shore zone of
this model are northeaster Gulf of Mexico site and Offshore of Florida Keys site. Many of the sites which have higher SGD rates are closer to the coast.

Table 5, Submarine Groundwater Discharge around Florida

<table>
<thead>
<tr>
<th>Region</th>
<th>Discharge</th>
<th>Method</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apalachee Bay, Florida</td>
<td>20 – 29 m$^3$m$^{-1}$d$^{-1}$</td>
<td>Rn</td>
<td>Burnett &amp; Dulaiova 2003</td>
</tr>
<tr>
<td>Apalachee Bay, Florida</td>
<td>43 m$^3$m$^{-1}$d$^{-1}$</td>
<td>Radium Quartet</td>
<td>Burnett &amp; Dulaiova 2003</td>
</tr>
<tr>
<td>Pinellas Peninsula</td>
<td>5.6 m$^3$m$^{-1}$d$^{-1}$</td>
<td>Rn</td>
<td>Kroeger et al. 2007</td>
</tr>
<tr>
<td>Pinellas Peninsula</td>
<td>1.2 m$^3$m$^{-1}$d$^{-1}$ (fresh only)</td>
<td>Darcy’s Law</td>
<td>Kroeger et al. 2007</td>
</tr>
<tr>
<td>Pinellas Peninsula</td>
<td>2.9 m$^3$m$^{-1}$d$^{-1}$ (fresh only)</td>
<td>Water Budget</td>
<td>Kroeger et al. 2007</td>
</tr>
<tr>
<td>Crescent, Florida</td>
<td>0.01 – 0.1 m min$^{-1}$</td>
<td>Salinity, Rn-222</td>
<td>Swarzinski et al. 2001</td>
</tr>
<tr>
<td>Northeast Gulf of Mexico, Florida</td>
<td>10 – 80 ml m$^{-2}$min$^{-1}$</td>
<td>Seepage Meter</td>
<td>Bugna et al. 1996</td>
</tr>
<tr>
<td>Northeast Gulf of Mexico, Florida</td>
<td>180 – 710 m$^3$s$^{-1}$</td>
<td>Rn, Ra</td>
<td>Cable et al. 1996</td>
</tr>
<tr>
<td>Northeast Gulf of Mexico, Florida</td>
<td>0.23 – 4.4 m$^3$s$^{-1}$</td>
<td>Seepage Meter</td>
<td>Cable et al. 1997a</td>
</tr>
<tr>
<td>Northeast Gulf of Mexico, Florida</td>
<td>17.7 ml m$^{-2}$min$^{-1}$</td>
<td>Seepage Meter</td>
<td>Cable et al. 1997b</td>
</tr>
<tr>
<td>Keys and Florida Bay</td>
<td>7.2</td>
<td>Seepage Meter</td>
<td>Corbett et al. 1999</td>
</tr>
<tr>
<td>West Florida</td>
<td>25 l s$^{-1}$</td>
<td>Flowmeter</td>
<td>Fanning et al. 1981</td>
</tr>
<tr>
<td>Northeast Gulf of Mexico, Florida</td>
<td>1 – 10 l m$^2$day$^{-1}$</td>
<td>Seepage Meter</td>
<td>Rasmussen 1998</td>
</tr>
<tr>
<td>Northeast Gulf of Mexico, Florida</td>
<td>4.5 – 7.3 l m$^{-2}$day$^{-1}$</td>
<td>Numerical Modeling</td>
<td>Rasmussen 1998</td>
</tr>
<tr>
<td>Offshore of Florida Keys</td>
<td>5.4 – 8.9 l m$^{-2}$day$^{-1}$</td>
<td>Seepage Meter</td>
<td>Simmons 1992</td>
</tr>
<tr>
<td>Offshore Zone of Tampa Bay</td>
<td>0.00489 m$^3$m$^{-2}$d$^{-1}$</td>
<td>Visual MODFLOW</td>
<td>Lecher 2010</td>
</tr>
<tr>
<td>Nearshore Zone of Tampa Bay</td>
<td>0.00478 m$^3$m$^{-2}$d$^{-1}$</td>
<td>Visual MODFLOW</td>
<td>Lecher 2010</td>
</tr>
<tr>
<td>Onshore Zone of Tampa Bay</td>
<td>0.00312 m$^3$m$^{-2}$d$^{-1}$</td>
<td>Visual MODFLOW</td>
<td>Lecher 2010</td>
</tr>
</tbody>
</table>

4.2 ModPath

Modpath also demonstrated that the particles will move up through the sediment layers into the water column, in addition to moving offshore. Both particles that were
placed within the clay layer and below the clay layer were able to ascend through the layers and into the water column. Once in the water column, the particles skirted along the bottom of the water body in an offshore direction.

4.3 MT3DMS

MT3DMS showed a stark difference between the concentrations of radium in the water column and radium in the sediment. With all isotopes, radium concentrations varied dramatically in the sediment, but not in the water column. The model suggests that radium concentrations are uniform with depth in the water column. However, this version of MT3DMS cannot account for complexities that fresh and saline water mixtures impose on radium concentrations in the water column or the complexities that a pycnocline in saline water would impose on radium concentrations. Therefore, MT3DMS is most helpful in the way it illustrates the variance of radium in the sediment. Also, MT3DMS indicates that radium is ascending into the water column, as radium concentrations were only inputted into the bottommost sand layer.

Conclusion

In this study, it was found that the nearshore and offshore zones of the West Central Coast of Florida experience submarine groundwater discharge in amounts ranging from $0.00478 \text{ m}^3 \text{ m}^{-2} \text{ d}^{-1}$ to $0.00489 \text{ m}^3 \text{ m}^{-2} \text{ d}^{-1}$. While this may seem like a small amount of submarine groundwater discharge compared to the coast, it is enough to serious implications in nutrient poor waters, such as the introduction of nutrients into the water column. By additional tests with the model, it was determined that the most influential component of the model in determining SGD is the hydraulic conductivity of the sediment, not hydraulic head or recharge. Also, Modpath and MT3DMS displayed,
in both path and concentration models how radium accompanies the SGD through the various sediment layers of the continental shelf into the water column.
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