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A hydrogeologic model of submarine groundwater discharge: Florida intercomparison experiment

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Abstract. A hydrogeologic model of submarine groundwater discharge (SGD) to the near-shore environment at a site on the northeast Gulf of Mexico has been developed to provide a basis for comparison with measurements of SGD made using seepage meters, and with estimates derived from chemical tracers. The hydrogeologic model incorporates the seaward movement of fresh water and the re-circulation of sea water at the fresh water–salt water interface. The hydrostratigraphy at the site includes the Surficial Aquifer, a thin confining unit known as the Intracoastal Formation, and the underlying Upper Floridan Aquifer. It is not possible to explain either the magnitude or spatial distribution of SGD recorded by the seepage meters, or the magnitude of SGD estimated using radium and radon tracers, if only steady state flow in the Surficial Aquifer is considered. Nor does it appear likely that the difference between the model-based prediction of SGD and the field-based estimates can be fully resolved by leakage across the Intracoastal Formation from a source in the Floridan Aquifer. These results suggest that processes driven by variations in fluid pressure in the marine water column, which occur on a variety of time scales, be examined to quantify their contribution to fluid circulation within and discharge from that segment of the Surficial Aquifer located beyond the low tide line.

Introduction

Submarine groundwater discharge (SGD) in the near-shore environment is typically a composite of waters reflecting different fluid histories. The components of SGD include fresh water discharging from an unconfined aquifer that extends offshore, and a mixed water created at the interface of this fresh water with an intruding salt water wedge. Sea water circulating within the wedge will also discharge across the sea bed. Depending upon the local geology, there may be a component of fresh water originating as leakage from a deeper confined aquifer that extends beyond the coastline. There are also mixing processes and components of flow that occur at the sea bed due to shorter-cycle processes such as wave action, tidal forcing, and salt-water fingering (e.g., Li et al. 1999; Rasmussen et al. in press). In addition to submarine discharge in the region beyond the low tide line, water will also drain from the seepage face that forms along the shoreline during the tidal cycle. This water includes both fresh water and sea water components.

Three principal approaches are in use to estimate the magnitude of SGD: (1) direct measurement using manual or automated seepage meters, (2) a suite of isotopic techniques that use chemical tracers to compute the component of SGD present in the water column above the sea bed, and (3) hydrogeologic modeling. Approaches based

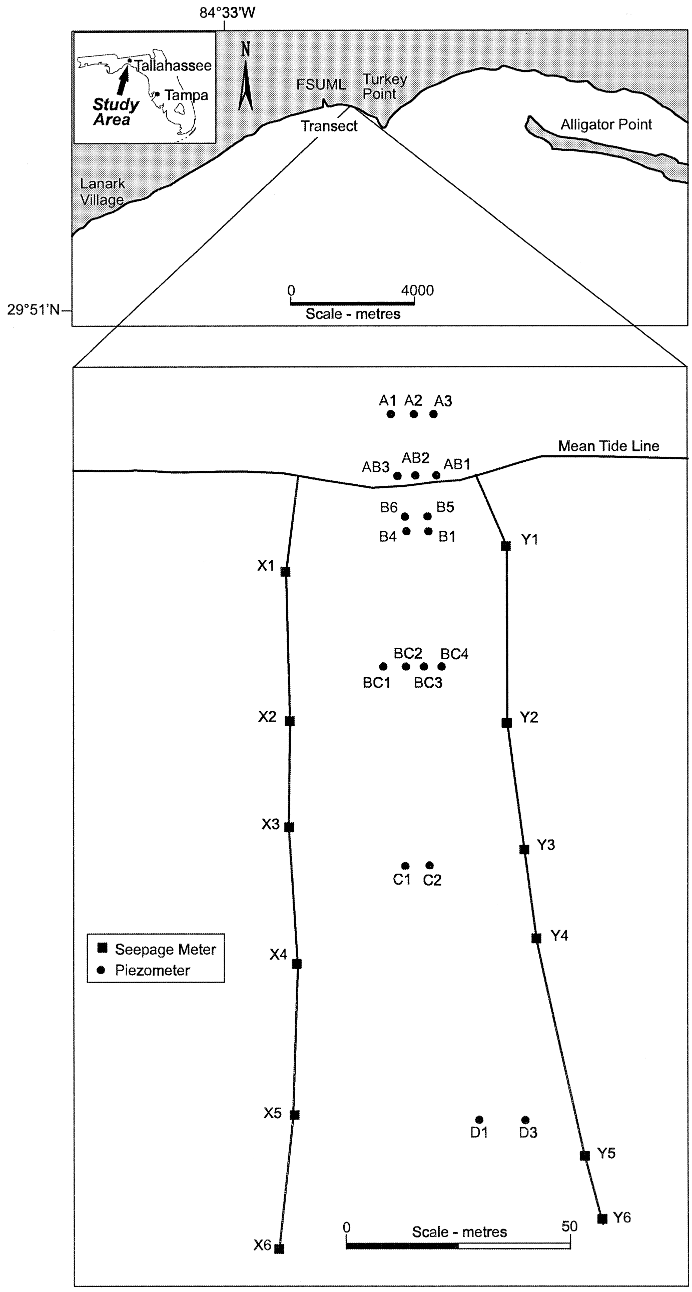

Figure 1. Plan view of the near-shore seepage zone, showing the location of the experimental site, the locations of piezometer nests (circles) and seepage meter transects (squares).

on hydrogeologic models vary widely in their complexity, from simple water balance calculations to density-dependent groundwater flow and solute transport models (Oberdorfer this issue). From 2000 August 13–18 an SGD intercomparison experiment was carried out by members of the Scientific Committee on Oceanic Research Working Group 112 (Burnett et al. 2002). The purpose of this experiment was to compare estimates of SGD obtained from various types of seepage meters, geochemical tracers, and hydrologic modeling. The experiment was conducted in an area adjacent to the Florida State University Marine Laboratory (FSUML), within Apalachee Bay in the northeastern Gulf of Mexico, about 60 km south of Tallahassee, FL (Figure 1). The objective of this paper is to develop predictions of SGD for this site by constructing a hydrogeologic model of offshore groundwater flow, and to compare this estimate with direct measurements of SGD from seepage meters (Taniguchi et al. this issue), estimates derived from radium isotopes (Moore this issue) and continuous radon monitoring (Lambert and Burnett, this issue).

Geologic setting

The regional hydrostratigraphy of the Florida Panhandle is divided into the Surficial Aquifer system, a lower-permeability confining unit, and the Floridan Aquifer System (Miller 1986). The FSUML is located in a transition zone where to the west the carbonate units of the Floridan Aquifer form a confined aquifer, and to the east the units outcrop to form an unconfined aquifer system with common occurrences of karst. The Intracoastal Formation forms the upper confining unit for the Floridan Aquifer in the area of Apalachee Bay.

There are no borehole data at the FSUML that define the local hydrostratigraphy of these geologic units. Interpolation from regional geologic maps by Schmidt (1984) suggests that the Surficial Aquifer at the FSUML is about 4 m thick. This thickness approximately coincides with the depth to which piezometers can be jetted into the aquifer. Figure 2 illustrates in cross-section the hydrogeologic model that is adopted for our simulation of groundwater flow in the near-shore environment. The Surficial Aquifer is composed predominantly of sand with minor silt. The representation of the Surficial Aquifer as three distinct layers is discussed in a later section of this paper. The underlying confining unit, the Intracoastal Formation, is described as a sandy, poorly consolidated, argillaceous, calcarenitic limestone. In the area of the FSUML, the Intracoastal Formation is quite thin, likely no more than 5 m. The underlying Bruce Creek Limestone forms the upper unit of the Floridan Aquifer system in this part of the Florida Panhandle. There are no substantive groundwater withdrawals from the Floridan Aquifer in the vicinity of the FSUML that could promote salt water intrusion.

Previous hydrogeologic assessment of SGD at FSUML

Rasmussen (1998) presented the results of a field investigation of groundwater discharge at the FSUML, and developed a numerical model of offshore flow in the

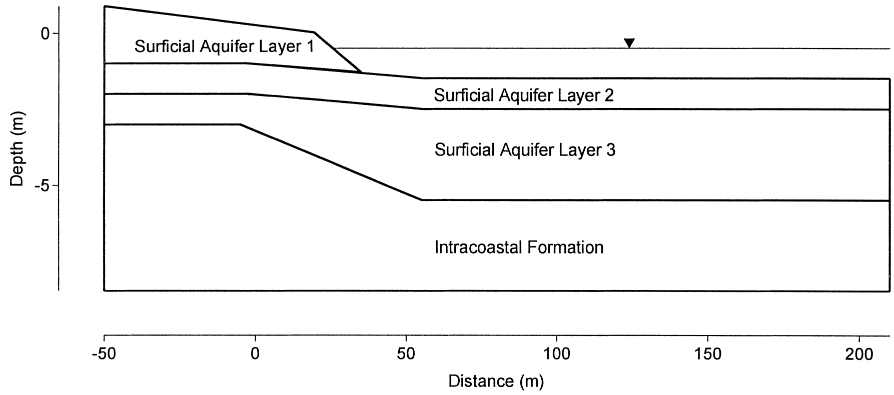

Figure 2. Generalized cross-section illustrating the hydrogeologic units in the near-shore environment at FSUML, and the model domain used in simulating groundwater flow. Distance is specified relative to an origin at piezometer nest A (see Figure 1).

Surficial Aquifer. A set of five piezometer nests (with 18 piezometers) were installed in the Surficial Aquifer, with one nest on the beach above the high tide line, two piezometer nests in the intertidal zone, and two nests 30 and 75 m beyond the low tide line. Subsequently, one additional piezometer nest has been added 130 m beyond the low tide line. Figure 1 shows the piezometer network. Also shown are the locations of seepage meters used during the 2000 intercalibration experiment.

Rasmussen (1998) collected cores near the low tide line and 30 m offshore, for measurement of pore water salinity and vertical hydraulic conductivity. Data from the core 30 m offshore indicated a range in the vertical hydraulic conductivity from 4×10^{-5} to 6×10^{-9} m/s over the depth from 0.1 to 2.8 m (seven measurements). The geometric mean value for the vertical hydraulic conductivity was 1×10^{-7} m/s. These values were viewed as lower-bound estimates, because of possible compaction of the core during sampling, and disruption of the macropore structure in the subcores taken for permeameter testing. Using the uniform fluid density code MODFLOW, Rasmussen (1998) modeled the discharge of fresh water from the Surficial Aquifer into a zone that extended 80 m offshore. Hydraulic head values assigned to the lateral inflow boundary beneath the beach, and along the base of the model domain, were interpolated from water level measurements in the piezometer network. Model predictions of SGD, which effectively included fluid input from both the Surficial Aquifer and the Intracoastal Formation, agreed well with measurements of flux using seepage meters (1–10 cm/day).

Salinity

Figure 3 illustrates the salinity of the pore waters sampled in the piezometers on 15–16 August 2000, with all the piezometers projected onto a common section.

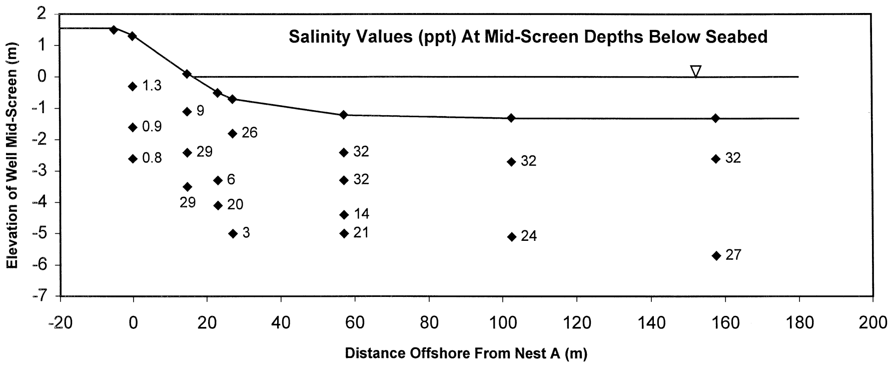

Figure 3. Salinity profile (ppt), 15–16 August 2000. Salinity values are plotted at the depth corresponding to the midpoint elevation of the open screen for each piezometer.

Salinity in the water column above the sea bed was 32 ppt. The salinity pattern suggests: (1) beyond the low tide line, to depths beneath the sea bed of 1–2 m, pore water has a salinity nearly equal to that of seawater, and (2) at greater depths, a relatively small component of fresher water can be recognized. An electrical resistivity profile parallel to transect y (see Figure 1) that extended approximately 180 m offshore, with a probe spacing of 10 m and a probe depth of 0.6 m, indicated that the pore water was dominantly saline along the entire section (C. Smith personal communication). The salinity measured inside one of the automated seepage meters, and that measured outside the chamber in the marine water column, differed by less than 1 ppt (S. Krupa personal communication). Water retrieved from manual seepage meters also had a salinity very close to that of sea water. Within the intertidal zone, a complex salinity pattern is apparent in Figure 3, which in part likely reflects lateral variations in salinity parallel to the shoreline.

Data presented by Rasmussen (1998) shows that this same general pattern was replicated in earlier years, although there was a greater component of fresh water at depth in the offshore region. For example, the salinity in piezometer C1, 75 m beyond the low tide line, was 8 ppt when sampled on 16 October 1996, and 4 ppt when sampled on 7 May 1997. The higher salinity at piezometer C1 observed during the 2000 intercalibration experiment (24 ppt) probably reflects a lower rate of fresh water input to the offshore region as a result of drought conditions in Florida from 1998 to 2000. While the salinities were considerably lower at the sampling depth of piezometer C1 (3.75 m below the sediment interface), the salinity (30 ppt) was close to that of the sea water in piezometer C3, open 1.38 m below the sediment interface. This behavior must reflect the influence of mixing processes that operate close to the sediment–marine water interface.

No data are available to characterize the salinity of pore waters in the Intracoastal Formation or the Bruce Creek Limestone in the offshore area. The water supply well for the FSUML withdraws potable water from the Upper Floridan Aquifer.

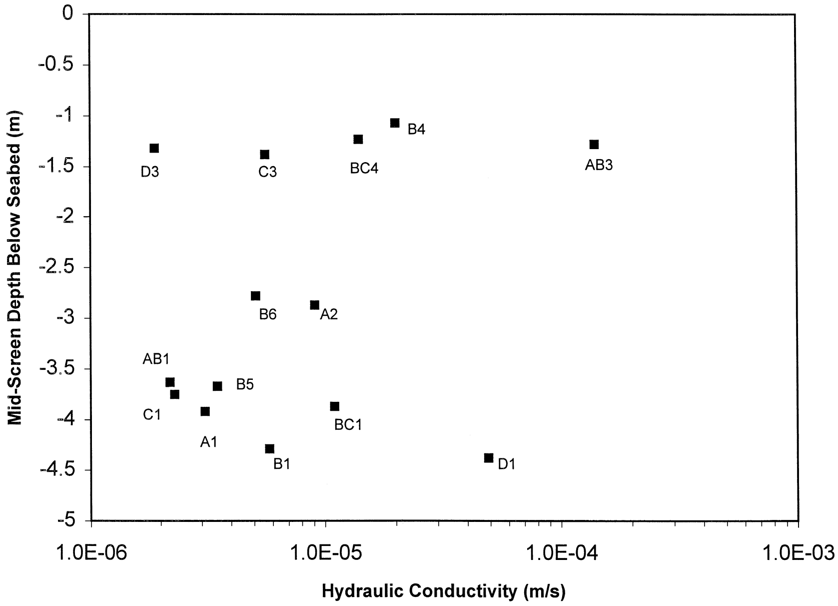

Figure 4. Hydraulic conductivity data set for the Surficial Aquifer, derived from slug testing in the piezometers. The letter labels indicate the estimate of hydraulic conductivity for a particular piezometer, see Figure 1 for piezometer locations.

Hydraulic conductivity data set

Estimates for the horizontal hydraulic conductivity of the Surficial Aquifer are derived from slug tests carried out in 14 of the piezometers (Figure 4). Values range from 2×10^{-6} to 2×10^{-4} m/s, with a geometric mean of 8×10^{-6} m/s. A slug test in piezometer A3 with a mid-screen depth of 1.7 m equilibrated too rapidly to permit manual water level measurements, suggesting the hydraulic conductivity of the sands on the upper beach in the region of the water table is greater than 2×10^{-4} m/s. At five of the six piezometer nests, the hydraulic conductivity measured in the shallow piezometer is greater than that measured at the adjacent deeper piezometer, with the exception of nest D.

Seepage data sets

Manual seepage meters were placed along two transects, with six measurement stations in each transect (Figure 1). The first station in each transect was located approximately 20 m beyond the mean tide line, the last station approximately 178 m (x transect) or 165 m (y transect) beyond the mean tide line. Figure 5 illustrates the average seepage rate at each station, integrated over a 24 h period, for 14–16

August 2000. For logistical reasons, manual seepage meters were not located within the intertidal zone. Data was not collected that would permit a comparison of the diffuse discharge from the intertidal zone, with that measured by the seepage meters located beyond the low tide line. Rasmussen (1998) observed that seepage rates large enough to form rivulets on the beach face only occurred after heavy rainfall events.

From the perspective of developing a hydrogeologic model with which to compare the offshore flux measurements, several general characteristics should be noted:

1. There is considerable variability in the average seepage flux when comparing transects x and y at similar distances beyond the mean tide line.
2. Along transect y, the highest seepage rates are recorded at the station closest to the shoreline. A secondary peak is evident approximately 120 m beyond the mean tide line (station near 140 m).
3. Along transect x, elevated seepage rates were recorded in the region 80–130 m beyond the mean tide line, on 14 and 16 August. This pattern is not as apparent on 15 August.

Seepage estimates reported by Rasmussen (1998), over a time period when water with a substantially lower salinity was observed in the deeper offshore piezometers, are generally at the lower end of the range seen in Figure 5.

If the measured seepage is summed for each 24 h period, and linearly extrapolated to an area 100 m (along shore) and to 200 m beyond the mean tide line, estimated values of SGD for 14–17 August are 1.9, 1.6, 2.3, and 2.5 m^3/min, respectively (Taniguchi et al this issue). Moore (this issue) using radium isotope methods, estimates an SGD value of 1.1 m^3/min for this same offshore area. For the period of 14–17 August, the range of SGD values derived from continuous radon monitoring is 1.7–2.5 m^3/min (Lambert and Burnett this issue). These three methods for estimating SGD are considered to be in good agreement, and suggest a range from 1.1 to 2.5 m^3/min as a benchmark for comparison to predictions derived from the hydrogeologic model of the site.

By applying a three-component mixing model to the concentrations of radium isotopes measured in the near-shore ($\sim$200 m) seepage zone, Moore (this issue) has estimated the fraction of marine water that originates as groundwater discharge from the Surficial Aquifer, and from a second isotopically distinct source, likely the Floridan Aquifer. For a set of four measurements, two samples yielded similar fractions of these two subsurface sources, and two samples yielded values in which seepage from the Surficial Aquifer was the more dominant subsurface component.

Hydrogeologic model

Data available to develop a hydrogeologic model of SGD at the FSUML consists principally of the topographic profile from the upper beach to a point 200 m

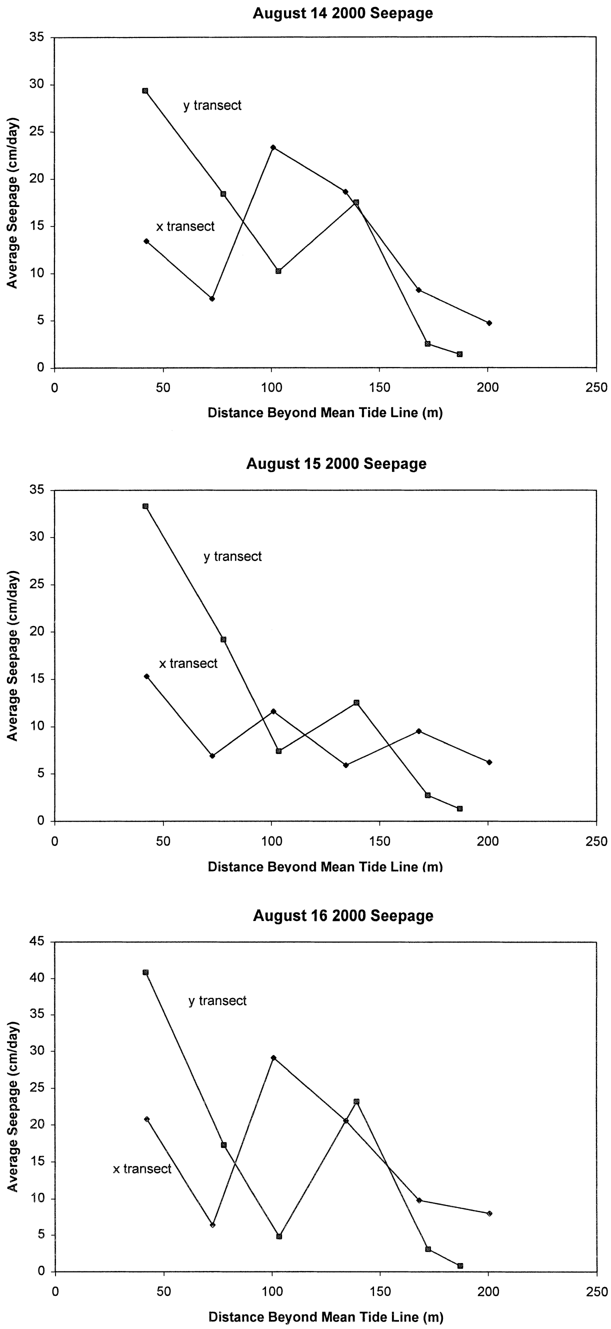

Figure 5. Average seepage rates along *x* and *y* transects on 14–16 August 2000. Distance is measured from piezometer nest A. Modified from Taniguchi et al (this issue).

offshore, a simplified description of the geologic setting, hydraulic conductivity estimates from slug tests, and the salinity of water samples withdrawn from the piezometers. The objective of the intercomparison experiment precludes the use of the seepage estimates as a calibration constraint in the construction of the model. The salinity distribution provides useful guidance in the development of a hydrogeologic model of SGD. In particular, a model that could be considered viable should preserve both the general position of the fresh water–salt water interface at the shoreline, and a freshening of the water below depths of 1–2 m in the offshore zone. Several rounds of manual water level measurements in the offshore piezometers, made during the intercalibration experiment, did not yield a data set of sufficient reliability to use fluid pressures or hydraulic gradients as a calibration constraint in model construction. This behavior likely reflects very small hydraulic gradients in the region seaward of the seepage face that are difficult to resolve using conventional piezometers.

A model-based prediction of SGD has been developed using the density-dependent model FEFLOW (Diersch 1996). FEFLOW simulates both the seaward movement of fresh water and the recirculation of sea water in the salt water wedge. Both of these components of flow are included in the model-based calculation of SGD. The use of a density-dependent flow model requires that it be coupled to a solute transport model that simulates the distribution of salt within the model domain. When a uniform density flow model such as MODFLOW is used to simulate discharge to the near-shore environment, only the fresh water component of SGD is included in the calculation, and the influence of the salt water interface on the location of fresh water discharge is neglected.

The hydrogeologic model we examine is shown in schematic form in Figure 2. This two-dimensional section is perpendicular to the shoreline and extends 50 m inland from piezometer nest A ($x = 0$ m). The mean tide line is at an elevation of -0.5 m relative to the model datum. The model domain extends 184 m beyond the mean tide line. Boundary heads are expressed in terms of an equivalent freshwater head, which is the formulation used in FEFLOW to solve the groundwater flow equation. Only steady state boundary conditions are applied, fluctuations in sea level due to diurnal tides are neglected. Thus, a strong periodicity observed in the seepage meter measurements (Taniguchi et al. this issue) is not reproduced in the simulation model. Boundary conditions for solute transport are expressed in terms of the total dissolved solids (TDSs) in the pore water. FEFLOW converts these values to a fluid density when solving for concentration. We assume a sea water TDS of 35000 mg/l, and a corresponding fluid density of $1022.5\,\mathrm{kg/m^3}$.

Two models have been constructed to provide a basis for comparison with the field-based estimates of SGD. In Model 1, it is assumed that all the SGD originates as groundwater flow in the Surficial Aquifer. The three layers within the Surficial Aquifer that are shown in Figure 2 are discussed below. In Model 2, a set of boundary conditions is applied that also permits leakage to develop across the Intracoastal Formation from a fresh water source in the Bruce Creek Limestone.

The boundary conditions assigned to Model 1 are:

Left-hand side – Fresh water from an inland recharge area enters the model domain. A uniform hydraulic head value is assigned to the boundary. The height of the water table in the region behind the beach has not been measured. It is assumed that the height of the water table is 1.5 m above mean sea level. A TDS concentration of 0 mg/l is assigned to this inflow.
Base – The base of the unconfined aquifer is the top of the Intracoastal Formation, which is assumed to form an impermeable boundary for both fluid and solutes. For computational efficiency, the finite element grid used by FEFLOW does not incorporate the Intracoastal Formation in Model 1.
Top – In the region behind the beach, to the high tide line, a groundwater recharge rate equal to 30% of the mean annual precipitation is applied (8.2×10^{-4} m/day). The TDS concentration along this portion of the boundary is set to 0 mg/l. Between the high tide line and mean sea level, a seepage face can develop. This segment of the boundary is assigning a fresh water head equal to the local elevation of the beach slope, with an additional constraint imposed that permits only discharge across the seepage face. Along the sea bed, a hydrostatic fluid pressure is applied, calculated for a TDS concentration of 35000 mg/l.
Right-hand side – A hydrostatic pressure is applied, calculated for a TDS concentration of 35000 mg/l.

Along the sea bed, an exit-type boundary condition is applied when solving the solute transport equation. If the groundwater velocity vector indicates flow into the sea bed (recharge), the concentration assigned to the boundary is applied at that point (i.e., a TDS of 35000 mg/l). If the groundwater velocity vector indicates discharge across the sea bed, the TDS concentration at the node immediately beneath the boundary is assigned to the sea bed. In this way, the model can simulate sea-bed discharge with a concentration less than that of the overlying marine water column.

The distribution of salinity in the Surficial Aquifer was obtained using a transient simulation by stepping though time from a specified initial condition and letting the stable position of the salt water interface develop. Table 1 lists the values of the model parameters held constant in the numerical simulations.

Results

Model 1 – Surficial Aquifer

Figure 6(A) illustrates the TDS concentration in the Surficial Aquifer, for the case where it is assumed this unit is homogeneous and isotropic, with a hydraulic conductivity equal to the geometric mean value of the slug test data (8×10^{-6} m/s). The section is plotted with a vertical exaggeration of 2:1. The TDS contours that are plotted range from 5000 to 30000 mg/l, with an contour interval of 5000 mg/l. A

Table 1. Model parameters.

Porosity	0.30
Longitudinal dispersivity (m)	2
Transverse dispersivity (m)	0.2
Diffusion coefficient (m^2/s)	1×10^{-9}

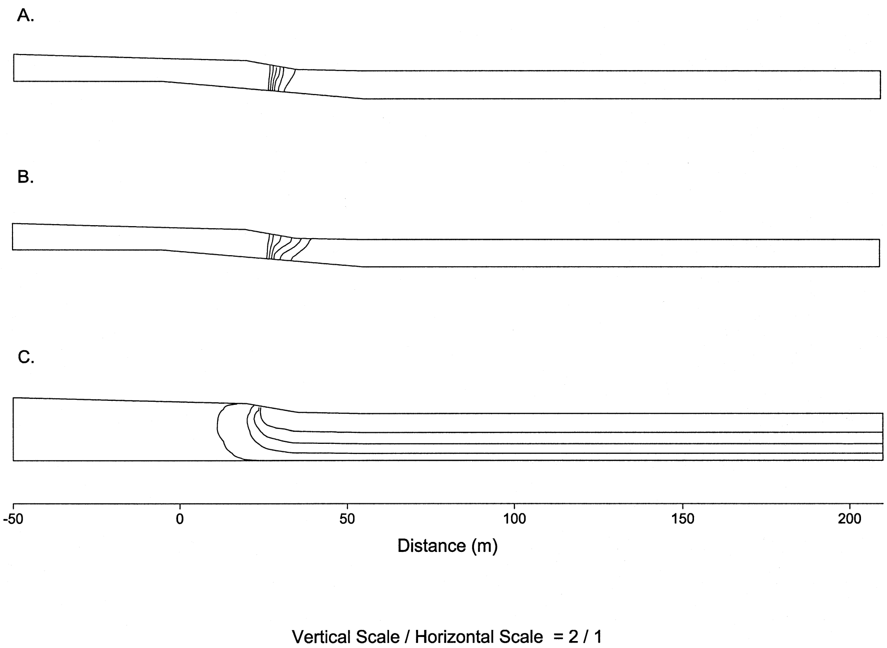

Figure 6. Concentrations of total dissolved solids in pore water. (A) Model 1 with a homogeneous hydraulic conductivity in the Surficial Aquifer. (B) Model 1 with a three-layer hydraulic conductivity distribution in the Surficial Aquifer. (C) Model 2 with leakage across the Intracoastal Formation. For plots A and B, the contour interval is 5000 mg/l. For C, the contours are 10, 100, 3500, and 10,000 mg/l. Plotted at 2:1 vertical exaggeration.

few meters to the left of the 5000 mg/l contour the TDS values are all 0 mg/l; a few meters to the right of the 30000 mg/l contour the pore water has full sea water salinity. The flux of fresh water is sufficient to displace the mixing zone to a zone a few meters seaward of the mean tide line. The width of the mixing zone, measured along the beach face, is 8 m. There is no component of fresh water in the aquifer beyond the beach slope. If this discharge profile is assumed to be representative of a region 100 m wide (to permit a comparison with the field-based seepage estimates), the predicted SGD into the region is 0.0052 m^3/min. Using a TDS concentration equal to 10% of the sea water concentration as an arbitrary reference point, then 53% of the groundwater discharge occurs landward of this point, with 47% constituting recirculated sea water offshore. It is important to note that the great majority of the total discharge occurs on the beach slope, with only a minor component occurring farther offshore.

A comparison of both the magnitude and location of SGD for this simulation, with that obtained by direct measurement and by chemical tracers indicates a poor correspondence. The SGD is two to three orders of magnitude smaller than the estimates derived from field measurements. The predicted discharge 50–200 m offshore, in the region where most of the seepage meters were located, is negligible in comparison to the seepage that was measured along the x and y transects.

A second simulation was completed in which the Surficial Aquifer was assigned a higher hydraulic conductivity at shallower depths. This assumption was implemented using the three-layer structure illustrated in Figure 2. Estimates of hydraulic conductivity assigned to each of three layers were derived from Figure 4, with emphasis on the highest values in the data set, at a given depth. The hydraulic conductivity values assigned were 1×10^{-3}, 2.4×10^{-5}, and 5.6×10^{-6} m/s, for Layers 1, 2, and 3, respectively. The higher hydraulic conductivity, when coupled with the specified head boundary on the landward side of the model domain, must lead to higher values of SGD. This model predicts a discharge into the study area of $0.15\,m^3/min$, or about one order of magnitude smaller than the estimates based on the seepage meters or tracers. Much of this enhanced discharge occurs high on the slope of the beach (Figure 6(B)). Again using a 10% sea water concentration as a reference point, 99% of the seepage occurs as fresh water, with only 1% of the total seepage occurring as recirculated sea water within and seaward of the mixing zone. This fresh water outflow would not be incorporated in the SGD estimates based on the seepage meters, but as it mixes into the near-shore marine water column, this component of SGD would presumably be reflected in the tracer-based estimates. The fresh water–salt water interface is broader when compared to the homogeneous case, extending 14 m beyond the mean tide line.

These simulations suggest that within the constraints imposed by the hydraulic conductivity data set, it does not appear to be possible to explain the magnitude or spatial distribution of SGD recorded by the seepage meters, or estimated by tracers, if only steady state flow in the Surficial Aquifer is considered. It is emphasized that these components of flow include both the offshore flux of fresh water, and recirculation within the salt water wedge.

Model 2 – Incorporation of Leakage Across the Intracoastal Formation

A second model was developed that permits fresh water to enter the Surficial Aquifer as leakage across the Intracoastal Formation from the Upper Floridan Aquifer. This leakage provides a mechanism for discharge to occur farther offshore, and with a higher flux. The following simulations are presented in the context of sensitivity calculations to see if conditions can be identified where model-based predictions of SGD fall within the range provided by field-based estimates. The Surficial Aquifer is modeled as a homogeneous unit with a hydraulic conductivity equal to the geometric mean value from the slug test data.

The model domain is expanded to include the Intracoastal Formation as a 4 m thick unit beneath the Surficial Aquifer (Figure 2). Leakage across this confining layer is introduced by specifying fresh water hydraulic heads along the bottom of the Intracoastal Formation. No piezometers penetrate to this depth; so data are not available to characterize the salinity of water at the top of the Bruce Creek Limestone, or the magnitude and lateral dissipation of artesian fluid pressures offshore. To proceed, we assume: (1) the salinity of pore water in the Bruce Creek Limestone is zero, (2) in the region onshore from the beach the vertical hydraulic gradient across the Intracoastal Formation is 0.075, and (3) the lateral hydraulic gradient at the top of the Bruce Creek Limestone is 0.001. In both of the latter two assumptions, the hydraulic gradient is linear. For our purposes the main variable to focus on is the magnitude of the leakage that develops across the Intracoastal Formation, rather than the precise value assigned to the vertical hydraulic conductivity of the unit or the hydraulic gradient across the unit.

To maintain consistency with Model 1, the boundary condition on the left-hand side of the model domain is modified. Along the boundary segment corresponding to the Surficial Aquifer, the volumetric flux of fresh water calculated to cross this boundary in Model 1 was determined and applied in Model 2 (0.018 m^2/day per m width). With an assumption of upward vertical leakage across the Intracoastal Formation, the segment along the boundary corresponding to the Intracoastal Formation is impermeable.

The simulation of upward leakage into the Surficial Aquifer introduces a difficulty in preserving the appropriate boundary condition on the sea bed. Preliminary simulations indicated that even small amounts of leakage would act to displace salt water from the Surficial Aquifer, creating a situation where the salinity value assigned to the base of the Intracoastal Formation was simply propagated across the Surficial Aquifer. As a consequence, in the solution for the fluid pressure distribution in the aquifer, a fluid density corresponding to sea water was not preserved as the upper boundary condition on the sea bed. To address this issue, a zone 0.5 m in vertical extent was defined immediately below the sea bed with a high diffusion coefficient (1 m^2/s), which has the effect of homogenizing sea water salinity across this zone. In effect, a condition is imposed that mimics the influence of the unmodeled mixing processes at the sea bed, such as salt water fingering and tidal forcing, which introduce salt water to this region. From a numerical perspective, this approach permits fluid with a component of fresh water to move toward the sea bed, without controlling the hydrodynamic boundary condition along the sea bed.

Figure 6C illustrates the TDS distribution for the case where the hydraulic conductivity of the Intracoastal Formation is 1×10^{-7} m/s, or 80 times smaller than the value assigned to the Surficial Aquifer. A value of this magnitude is consistent with the Intracoastal Formation responding as a distinct confining unit separating the Surficial Aquifer from the Floridan Aquifer. To illustrate the distribution of salinity in the model, TDS concentration contours of 10, 100, 3500, and 10,000 mg/l have been plotted. The SGD increases to 0.06 m^3/min, with the great majority of this discharge (>90%) originating as leakage across the Intracoastal Formation. Except for a region of enhanced discharge on the beach slope, the discharge is relatively uniform with distance offshore. However, the calculated SGD is still much smaller than the estimates derived from field-based techniques (1.1–2.5 m^3/min). Furthermore, such a high proportion of water originating from the Floridan Aquifer is not consistent with the proportional estimate derived by Moore (this issue) using radium isotopes.

It should be noted that the hydrodynamic conditions, and the main determinant of the salinity distribution in the Surficial Aquifer for models one and two, are quite dissimilar. Model 1 reflects a conventional pattern for an unconfined aquifer in which fresh water and salt water meet and a salt water wedge forms in the coastal zone. In Model 2, the salinity distribution in the offshore portion of the aquifer reflects the interplay of an upward advective/dispersive flux of low-salinity water entering a region of high salinity near the sea bed. The large-scale recirculation pattern associated with the development of a salt water wedge does not develop within the Surficial Aquifer, as it does in Model 1.

The salinity distribution in the offshore zone that is illustrated in Figure 6C is sensitive to the magnitude of the longitudinal dispersivity that controls fluid mixing as fresh water moves upward across the Surficial Aquifer. With a hydraulic conductivity of 1×10^{-7} m/s assigned to the Intracoastal Formation, the salinity distribution in the Surficial Aquifer is dominated by the affects of advection. The strong concentration gradient that drives a downward diffusive flux of salt from the sea bed is overridden by magnitude of the upward fluid flux. If the longitudinal dispersivity of the medium is reduced, then a thinner transition zone between fresh and saline water than seen in Figure 6C will develop in the Surficial Aquifer. For example, with a longitudinal dispersivity of 0.25 m, much of the Surficial Aquifer is predicted to have a near-uniform salinity that corresponds to the value assumed at the top of the Bruce Creek Limestone.

To obtain higher values of SGD in Model 2, leakage across the Intracoastal Formation can be increased. Although this approach is counter to the evidence that groundwater discharge from the Surficial Aquifer into the near-shore (200 m) seepage zone is an equal if not predominant fluid source when compared to the Floridan Aquifer, such simulations can provide useful insight to bounding conditions. If the hydraulic conductivity of the Intracoastal Formation is 5×10^{-7} m/s, (a factor of 16 smaller than the value assigned to the Surficial Aquifer), the predicted SGD increases to 0.27 m^3/min, or about one order of magnitude less than the values derived from field-based estimates. It is also conceivable that there may be zones where the Intracoastal Formation locally has a higher hydraulic conductivity. This latter possibility is suggested by the seepage meter profiles, which indicate a region of enhanced SGD from 80 to 120 m offshore (Figure 5). A simulation was completed for the case where the hydraulic conductivity of the Intracoastal Formation was 1×10^{-7} m/s, but a zone from 80 to 120 m offshore was assigned a value of hydraulic conductivity equal to geometric mean value for the Surficial Aquifer (8×10^{-6} m/s). In effect, there is a window through the Intracoastal Formation that directly connects the Surficial and Floridan Aquifers. The seepage flux is enhanced in the region above this window, with the total SGD increasing to 0.48 m^3/min. Although the magnitude of this flux approaches that derived from the field-based measurements, there are currently insufficient data at the FSUML to independently evaluate this geologic model. Note also that the increased flux originates entirely from the Floridan Aquifer, and it will carry the isotope signature of that unit.

Conclusions and discussion

Predictions of SGD at the Florida State University Marine Lab have been derived using a density-dependent groundwater flow model that accounts for both fresh water discharge from the Surficial and Floridan Aquifers, and the recirculation of sea water within the mixing zone that develops at the fresh water–salt water interface. Within the constraints that can be imposed by the available hydraulic conductivity data, it does not appear to be possible to explain either the magnitude or spatial distribution of SGD recorded by the seepage meters, or the magnitude of SGD estimated using radium and radon tracers, if only steady state flow in the Surficial Aquifer is considered. This model also suggests that the seepage meters used in the intercalibration experiment may record a slightly different component of the SGD budget than do the tracer-based techniques. Although the estimates are in reasonable numeric agreement, the simulations suggest that the seepage meter closest to the shore may be located seaward of the main discharge zone for the Surficial Aquifer. This water discharging from the Surficial Aquifer will, however, mix in the marine water column and contribute to the SGD estimate derived from radium and radon tracers.

Model calculations that include the Intracoastal Formation also suggest that the underestimation of the field-based estimates of SGD is unlikely to be fully resolved by invoking leakage across the Intracoastal Formation from a source in the Upper Floridan Aquifer. Unless the hydraulic conductivity of the Intracoastal Formation is much higher than we have considered, the fluid flux across that unit is insufficient to lead to SGD predictions that are consistent with the field-based estimates. However, even for the case we have presented in Figure 6C, the relative contributions of water in the near-shore seepage zone that originate from the Surficial and Floridan Aquifers would be inconsistent with an estimate derived from radium isotopes (Moore, this issue). The simulations incorporating leakage indicate that the salinity – depth profile in the offshore region of the Surficial Aquifer may be a sensitive function of the longitudinal dispersivity, which we can presently quantify for this site using only representative values from the literature. While loosely constrained, it is our impression that the salinity data collected during the intercalibration experiment in August 2000 (Figure 3) also argue for a lower rate of upward seepage than has been simulated in Model 2.

Future field work is planned to investigate the potential of transient processes such as tidal pumping to drive fluid circulation in the Surficial Aquifer below the low-tide line. Such processes may introduce a means of resolving the apparent discrepancy between model-based predictions of SGD at the FSUML, and that estimated by seepage meters or chemical tracers. To advance the framework for modeling the terrestrially driven component of SGD, several data sets are needed: (1) higher resolution salinity-depth profiles in the offshore seepage zone that would ideally extend through the Intracoastal Formation into the top of the Bruce Creek Limestone, (2) measurements of fluid pressure at the top of the Bruce Creek Limestone, both onshore and in the vicinity of piezometer nests C or D, (3) *in situ* estimates of the hydraulic conductivity of the Intracoastal Formation, and (4) measurements of the seaward hydraulic gradient in the Surficial Aquifer, inland from the beach area.

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