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Numerical modelling to determine freshwater/ saltwater interface configuration in a low-gradient coastal wetland aquifer

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Abstract A coupled hydrodynamic surface-water/groundwater model with salinity transport is used to examine the aquifer salinity interface in the coastal wetlands of Everglades National Park in Florida, USA. The hydrology differs from many other coastal areas in that inland water levels are often higher than land surface, the flow gradients are small, and, along parts of the coastline, the wetland is separated from the offshore waters by a natural embankment. Examining the model-simulated aquifer salinities along a transect that cuts the coastal embankment, a small zone of fresh groundwater is seen beneath the embankment, which varies seasonally in size and salinity. The simulated surface-water and groundwater levels suggest that this zone exists because of ponding of surface water at the coastal embankment, creating freshwater underflow to the offshore waters. The seasonal variability in the freshwater zone indicates that it is sensitive to the wetland flows and water levels. The small size of the zone in the simulation indicates that a model with a higher spatial resolution could probably depict the zone more accurately. The coastal ecology is strongly affected by the salinity of the shallow groundwater and the coastal freshwater zone is sensitive to wetland flows and levels. In this environment, predicting the aquifer salinity interface in coastal wetlands is important in examining the effects of changing water deliveries associated with ecosystem restoration efforts.

Key words numerical model; freshwater–saltwater interface; wetlands

INTRODUCTION

Coastal groundwater, under the influence of saltwater intruding from the sea, tends to have a definable interface dividing the fresh and saline zones. The classical conceptual model of the salinity interface in a coastal aquifer is shown in Fig. 1, which shows an intruding saltwater wedge at the base of the aquifer with the upper edge of the interface located a short distance offshore and a freshwater discharge face located between the upper edge and the shore. This situation can be represented by the Ghyben-Herzberg approximation, which assumes a hydrostatic pressure distribution and implicitly assumes flow is only horizontal (Chin, 2000). Horizontal-only flow is not possible, however, because the freshwater that moves downgradient towards the coast must discharge to surface. The Ghyben-Herzberg representation can be modified to include the offshore freshwater discharge face (actual saltwater interface in Fig. 1).

The modified Ghyben-Herzberg representation assumes that the only significant vertical flow occurs at the offshore freshwater discharge face and the inland water table lies below land surface. The conditions of a coastal wetland, however, may be different. For example, inland water levels are higher than land surface with a surface-water flow

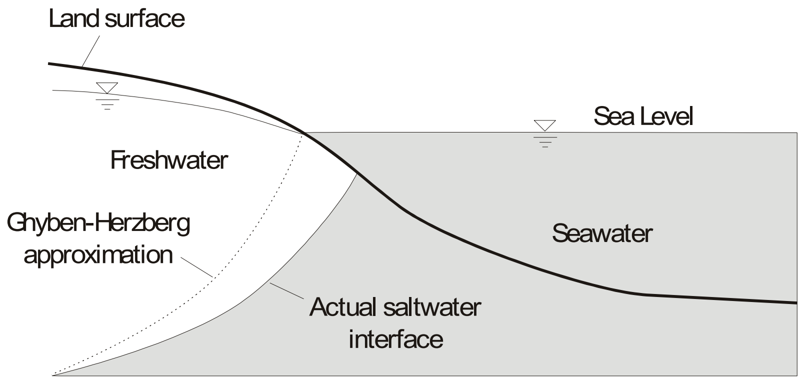

Fig. 1 Saltwater interface in a coastal aquifer where the Ghyzen-Herzberg approximation nearly applies.

connection between the wetlands and the offshore waters. Coastal wetlands often form in "protected areas", meaning that a partial obstruction to surface-water flow, such as a mudbank, shoal, or coastal embankment is present between the coastal wetlands and the offshore area. The surface-water level difference across this coastal embankment can be large relative to the mean gradient, and significant vertical flow is induced in the groundwater. In this case, salinity can still intrude inland from the coastal embankment, but freshwater flows would impound inland, creating fresh groundwater flow through and beneath the embankment. This atypical groundwater salinity-interface configuration affects the quantity and distribution of fresh groundwater discharge offshore.

The coastal wetland in the southern Everglades of Florida, USA, has been the subject of many studies to determine existing and historical conditions, trends, and the effects of restoration efforts. The numerical modelling effort described in this paper involves coupling the two-dimensional hydrodynamic surface-water model SWIFT2D (Schaffranek, 2004) with a three-dimensional groundwater flow model SEAWAT (Guo & Langevin, 2002). Both models simulate variable-density salinity transport. The coupling represents the leakage and salt flux between the surface and groundwater. SWIFT2D computes vertically-integrated two-dimensional forms of the equations of surface-water mass and momentum conservation, and solute transport equations for salt, heat, and other constituents. The code was modified for application to coastal wetlands, such as the Everglades, to allow the input of spatially variable rainfall, computation of evapotranspiration, variation of frictional resistance with depth, and other necessary features (Swain, 2005). SEAWAT combines the three-dimensional groundwater flow model MODFLOW (McDonald & Harbaugh, 1988) with the solute-transport code MT3DMS (Zheng & Wang, 1998) to incorporate the effect of salinity transport. Linking SWIFT2D and SEAWAT to account for leakage and salt flux between the surface water and groundwater is accomplished by constructing a code that calls both models and passes the necessary information between them (Langevin *et al.*, 2005). This coupled code is referred to as Flow and Transport in a Linked Overland/Aquifer Density Dependent System (FTLOADDS).

The purpose of this paper is to describe the results of using the FTLOADDS model to examine the groundwater salinity configuration in an aquifer underlying a coastal wetland. The application of a numerical model supports and helps quantify the proposed salinity distribution. The model also provides a guide to future field measurement locations that can better define the salinity interface. Ecosystem restoration efforts in south Florida concentrate on the timing and volumes of freshwater to the Everglades and other areas. Making effective and meaningful changes to Everglades water deliveries must rely on accurate conceptualizations of the coastal aquifer salinity interface and its relation to the wetlands.

BACKGROUND

The application of FTLOADDS to Everglades National Park is referred to as Tides and Inflows in the Mangroves of the Everglades (TIME). The application simulates the wetland and offshore tidal stage along with the groundwater heads and salinity in both regimes. A robust field data set has been compiled for many hydrological parameters and used for model development and comparison. As a result, the data set supports a complete calibration, and the model has been shown to reproduce field-measured flows, water levels and salinities (Swain *et al.*, 2004; Langevin *et al.*, 2005; Wang *et al.*, 2007). One of the field data-collection projects includes airborne electromagnetic surveying to determine the location of the subsurface saltwater interface (Fitterman & Deszcz-Pan, 2001). The top of this saltwater interface tends to be farther inland than the classical conceptual model.

The TIME application domain consists of about 5250 km^2 of pine uplands, cypress swamps, hardwood hammocks, wetland marsh, wet prairies, lakes, sloughs and rivers composing the Everglades National Park area. The domain of the TIME application is bounded to the north by the Tamiami Trail (US Highway 41), to the west by US Highway 29 and the Gulf of Mexico, to the south by Florida Bay, and to the east by Levee 31N, Levee 31W, and US Highway 1 (Fig. 2).

Several major drainage features, including sloughs and topographic depressions, intersect the approximately 85 × 75 km domain. The largest feature is Shark River Slough, which extends southwest from the northeastern corner of the domain to the west coast shoreline. Taylor Slough is a smaller drainage feature in the southeastern corner of the domain and, together with several coastal creeks, is the main source of runoff to northeastern Florida Bay. The northwestern part of the domain has several additional sloughs and rivers that are connected by the Wilderness Waterway and discharge to the coast. A higher elevation feature along the southeastern coast, the Buttonwood Embankment (Fig. 2), is estimated to be about 15 cm higher than the surrounding marsh (Holmes *et al.*, 2000). An equivalent feature does not exist along the west coast, where the coastal area has less topographic relief.

The climate of southern Florida is characterized by a wet season from May to September and a dry season from October to April. Sixty percent of the total rainfall occurs during this wet season. Daily rainfall patterns during the wet season and dry season are characterized by local, small-scale afternoon showers and frontal patterns, respectively. The area of surface-water inundation in the domain fluctuates greatly between the wet and dry seasons, as does the quantity of coastal freshwater flow.

The highly permeable surficial aquifer system extends over most of the Everglades National Park/Big Cypress National Preserve area and underlies a thin peat layer in

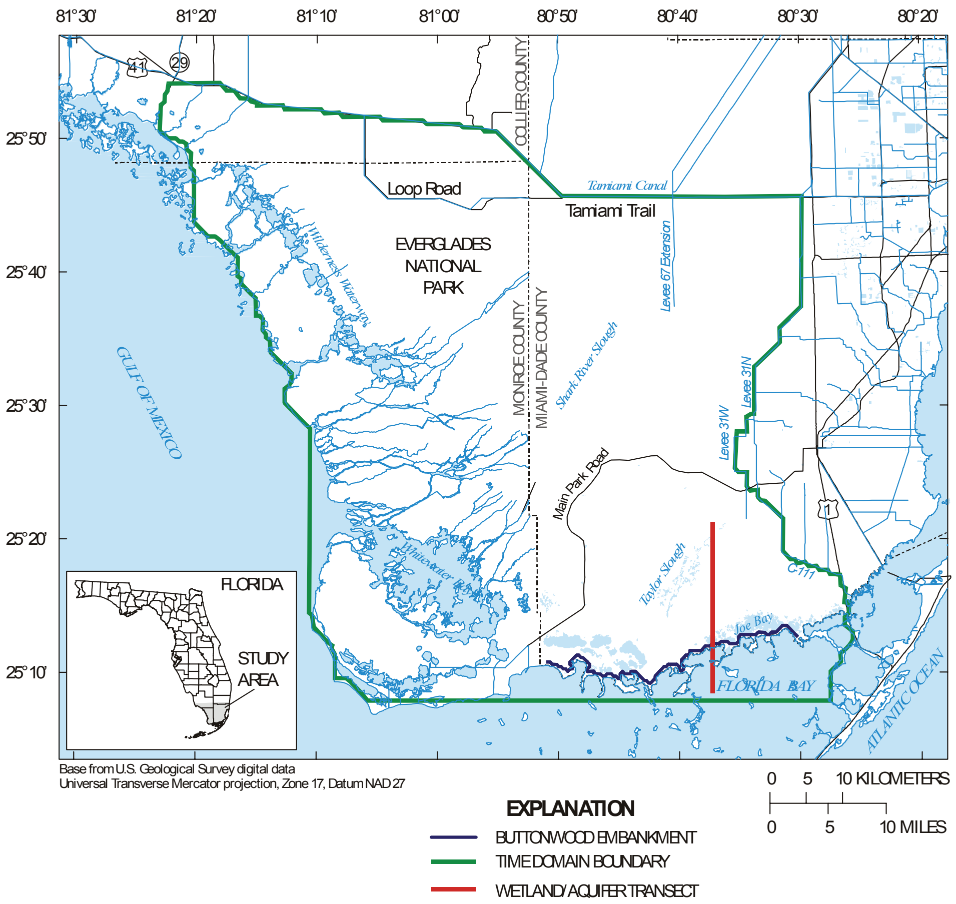

Fig. 2 Location of the Tides and Inflows to the Mangrove Everglades (TIME) domain, geographic features and water management features.

some areas. The surficial aquifer system generally thins towards the west in the study area. Leakage between surface water and groundwater is affected by the surficial peat layer over the majority of the domain (Harvey *et al.*, 2000).

APPLICATION

Because the TIME application involves a hydrodynamic surface-water model, a three-dimensional groundwater model, and the coupling between the two, a large amount of field data is needed; much of which was collected specifically for model development. These data include information pertaining to topography, rainfall, frictional resistance of vegetation, evapotranspiration rates, water level, inland and coastal discharge, and aquifer properties. Model development is described in Swain *et al.* (2004), Wolfert *et al.* (2006) and Wang *et al.* (2007). The primary purpose of the TIME development is to represent the coastal Everglades flow regime for discharges to Florida Bay (Fig. 2). To represent this regime's response to ecosystem restoration efforts, however, TIME must have boundary inflows that represent the restoration changes. These simulated inflows are generated by a large-scale regional model of South Florida developed by the South

Florida Water Management District (Wolfert *et al.*, 2004). Using these inflows, a 10-year simulation for 1990–1999 is made with a 10-minute timestep in the surface-water model and a 1-day timestep in the groundwater model. Leakage and salt flux between the surface water and the groundwater is calculated for each 10-minute surface-water timestep, using the current computed surface-water stage and the latest computed groundwater head.

In order to get a reasonable initial condition for the distribution of salinity, the 10-year simulation was repeated a number of times with the final distribution of each run used as the initial condition for the next. After an equivalent total of 160 years, the saltwater interface reaches a relatively constant location. This is the simulation used to examine the configuration of the saltwater interface, and how it varies over time. The groundwater model grid divides the aquifer into 10 layers. This is considered sufficient resolution to represent the vertical variations in groundwater head and salinity to the accuracy needed for the regional restoration simulations. The uppermost layer of the numerical model aquifer has a bottom elevation of –7.0 metres (North American Vertical Datum of 1988; NAVD88), meaning that, at the coastline, the layer is about 7 metres thick. This model resolution was not designed to represent small-scale variations in the salinity interface configuration, but to study major features of the salinity distribution at a larger scale.

RESULTS

Figure 3 shows computed aquifer salinity for the north–south transect shown in Fig. 2. Two simulation dates were chosen that have substantially different salinities under the coastal embankment. Even with the 7-m vertical discretization, sufficient resolution exists to see the effect of the coastal embankment on the salinity in layer 1. Figure 3 indicates, however, substantial salinity variations at the coast over a distance of several model grid cells, so a higher resolution groundwater simulation should increase the accuracy of the representation and give a better estimate on the actual salinity variation. On both dates shown in Fig. 3, the lower salinity zone under the embankment can be seen with somewhat higher salinities on both sides. This is particularly distinct on 7/30/1999, where salinity at a point over a kilometre inland is on the order of 6 points higher than under the embankment. This distribution differs somewhat from the salinity distribution of 11/18/1995, which corresponds to several months after a particularly wet season, with a larger freshwater zone under the embankment and lower salinity on the inland side. The simulation indicates that the surface-water hydrology causes this phenomenon, which can be loosely visualized as a freshwater "bubble" at the coastline. Other transects in an east–west direction, cutting the western Everglades coast (Fig. 2) did not indicate any such freshwater bubble.

The surface-water stage and groundwater head averaged over the entire simulation along the flow transect are shown in Fig. 4, along with the land elevation. The temporal variability of the surface water produces a more irregular average level than that of the groundwater. It can be seen that the surface-water stage is higher than groundwater head inland from the coastal embankment and lower than groundwater head offshore. Whereas the ground-water gradient is more uniformly downward, the surface-water stage drops abruptly at the coastal embankment.

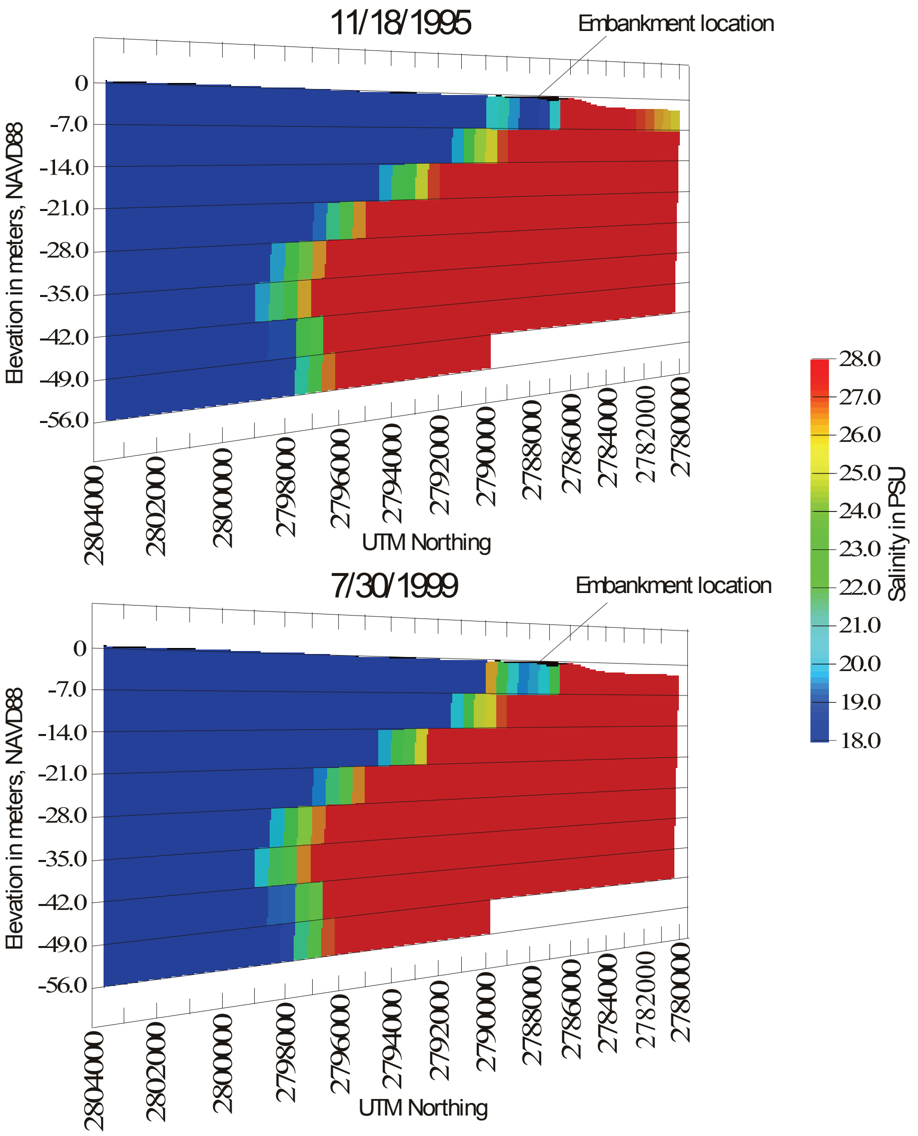

Fig. 3 Computed aquifer salinity showing the effect of the coastal embankment. Transect location shown in Fig. 2.

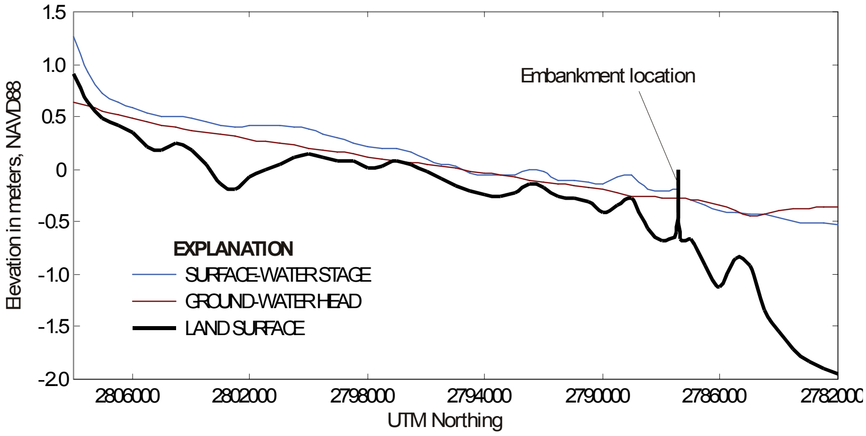

Fig. 4 Average surface-water stage and groundwater head showing effect of coastal embankment.

Further examination of Fig. 4 does not indicate an inland zone where average groundwater head is notably higher than the surface water. At approximately UTM Northing 2794000 in the transect, the average groundwater head is slightly higher. This location in Fig. 3 is inland from where the interface meets land surface, and the groundwater is relatively fresh. With the yearly fluctuations in water levels, groundwater can discharge to the wetland at this location; however, this appears to be a minor effect. The model indicates that, in the coastal Everglades, the wetlands predominantly supply the groundwater, and the tendency of the top of the saltwater interface to intrude inland is offset by recharge from the surface water ponded near the coast.

DISCUSSION

The TIME application is uniquely qualified to simulate a coastal wetland with underlying aquifer. As well as representing groundwater flow and salinity transport three-dimensionally, the wetlands and offshore waters are simulated by a fully hydrodynamic two-dimensional code. In addition, prodigious field measurements of multiple parameters have been used to develop and calibrate the model. It is thus with a high degree of confidence that results of the TIME application are interpreted for the saltwater interface in a coastal aquifer affected by an overlying wetland.

The simulated zone of fresher water in the transect cutting the southern Everglades coast, which is not seen in transects cutting the western Everglades coast, supports the concept that the southern coastal embankment is a controlling feature. The most apparent cause of the freshwater zone simulated in Fig. 3 is the damming and channelization of surface-water flow by the embankment. The simulation indicates that the saltwater interface resembles the situation shown in Fig. 5. The coastal embankment effect is the main phenomenon that differentiates this coastal wetland situation from the classical conceptual model of the salinity interface in a coastal aquifer.

Simulation results indicate that the presence of a coastal embankment produces an aquifer salinity distribution that can be roughly visualized in three zones, as depicted in Fig. 5. The first zone is inland where the surficial groundwater is fresh, and groundwater can discharge to the surface. The simulation indicates predominant recharge of the groundwater from the wetland in this zone, but exchange occurs in both directions. The second zone is at the coast, and the higher salinity groundwater at the top of the saltwater interface is just inland from a “bubble” of fresher groundwater that lies

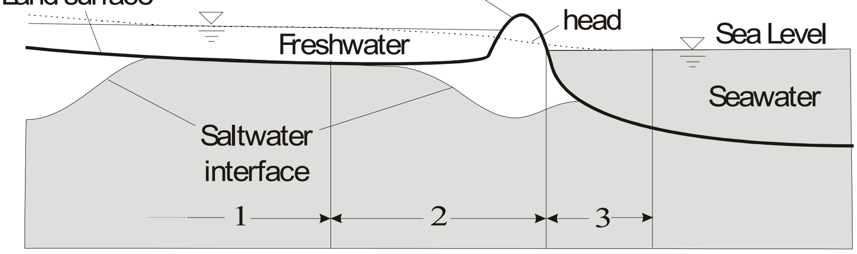

Fig. 5 Saltwater interface in the coastal aquifer where the wetland lies inland of a coastal embankment.

under the coastal embankment. This bubble is apparently induced by recharge from ponded surface water at the embankment. The third zone is offshore, where groundwater becomes more saline and discharges to the sea. The salinity variations induced by the coastal embankment are observed only in the uppermost layer of the model, which is approximately 7 m thick, so a higher resolution model would most likely produce a more accurate picture of the extent and salinity of this phenomenon.

This study indicates a new conceptual model of the configuration of the saltwater interface in coastal wetland environments. The implications affect the development and restoration of coastal wetlands and the associated ecology. The coastal mangroves in the Everglades are significantly affected by the salinity of the shallow groundwater, and changes in the mangrove communities affect other flora and fauna in the area. The TIME simulation indicates that somewhat fresher groundwater along the coastal embankment may be a natural feature of the embankment hydrology, and a feature that is sensitive to the wetland water levels. The location of the saltwater and freshwater marsh can change according to this coastal salinity. Thus, a change in upstream water deliveries can potentially have a complex effect on the configuration of the saltwater interface, salinity of the shallow groundwater, and hence the marsh communities.

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