A modeling study of seawater intrusion in Alabama Gulf Coast, USA

Article *in* Environmental Earth Sciences · March 2009

DOI: 10.1007/s00254-008-1288-y

Environ Geol (2009) 57:119–130
DOI 10.1007/s00254-008-1288-y

ORIGINAL ARTICLE

A modeling study of seawater intrusion in Alabama Gulf Coast, USA

Jin Lin · J. Blake Snodsmith · Chunmiao Zheng · Jianfeng Wu

Received: 12 January 2008 / Accepted: 10 March 2008 / Published online: 26 March 2008

Abstract A numerical model of variable-density groundwater flow and miscible salt transport is developed to investigate the extent of seawater intrusion in the Gulf coast aquifers of Alabama, USA. The SEAWAT code is used to solve the density-dependent groundwater flow and solute transport governing equations. The numerical model is calibrated against the observed hydraulic heads measured in 1996 by adjusting the zonation and values of hydraulic conductivity and recharge rate. Using the calibrated model and assuming all the hydrogeologic conditions remain the same as those in 1996, a predictive 40-year simulation run indicates that further seawater intrusion into the coastal aquifers can occur in the study area. Moreover, the predicted intrusion may be more significant in the deeper aquifer than the shallower ones. As the population continues to grow and the demand for groundwater pumping intensifies beyond the 1996 level, it can be expected that the actual extent of seawater intrusion in the future would be more severe than the model prediction. Better strategies for groundwater development and management will be necessary to protect the freshwater aquifers from contamination by seawater intrusion.

Keywords Seawater intrusion · Groundwater modeling · SEAWAT · Density-dependent flow · Alabama Gulf Coast

J. Lin (✉)
Department of Earth Sciences, Zhejiang University,
Hangzhou 310027, China
e-mail: linjin009671@zju.edu.cn

J. B. Snodsmith
CH2M Hill, Montgomery, AL 36106, USA

J. Lin · J. B. Snodsmith · C. Zheng
Department of Geological Sciences,
University of Alabama, Tuscaloosa, AL 35487, USA

J. Lin · J. Wu
Department of Hydrosciences,
Nanjing University, Nanjing 210093, China

Introduction

Seawater intrusion is a major issue in many coastal regions where over-exploitation of groundwater occurs so that a state of equilibrium originally established between fresh water and salt water under natural flow conditions is disturbed. Fresh water and salt water are miscible fluids, and a transition zone always exists between them in coastal aquifers (Bear 1979; Bear et al. 1999). The transition zone will move landwards when seawater intrusion occurs. To numerically simulate seawater intrusion, a density-dependent groundwater flow simulation model is required to track the movement and change of the transition zone between fresh water and salt water. Sorek and Pinder (1999) provided a summary of 15 computer codes that can be used to simulate density-dependent groundwater flow. The last decade has seen the appearance of several density-dependent simulation codes that are based on the commonly used groundwater model, MODFLOW, developed by the U.S. Geological Survey (McDonald and Harbaugh 1988; Harbaugh et al. 2000). These include SEAWAT (Guo and Bennett 1998a, b; Guo and Langevin 2002; Langevin et al. 2003), MOCDENS3D (Oude Essink 1998), MODHMS (HydroGeoLogic Inc. 2002) and the SWI Package for MODFLOW (Bakker and Schaars 2003). All these codes can be used to simulate seawater intrusion in coastal areas. A summary of these four MODFLOW-based codes was provided by Langevin et al. (2004).

A number of case studies on seawater intrusion in coastal aquifers using different simulation codes have been conducted and reported in the literature. Paniconi et al. (2001) used a finite element model called CODESA-3D (Gambolati et al. 1999) to investigate the occurrence of seawater intrusion in the Korba coastal plain of north-eastern Tunisia. Andersen et al. (1988) numerically simulated salt-water intrusion in Hallandale, Florida by using a finite-element model, SWICHA, described in Huyakorn et al. (1987). Salt water intrusion in a coastal groundwater system in the northern part of the province Noord-Holland, The Netherlands, was modeled in three dimensions by Oude Essink (2001b) with the finite-difference code, MOCDENS3D (Oude Essink 1998) mentioned above. Shoemaker and Edwards (2003) conducted a study to examine the potential for saltwater intrusion into the lower Tamiami aquifer beneath Bonita Springs in southwestern Florida using the SEAWAT code described previously. Additional case studies on seawater intrusion are described in Ma et al. (1997), Oude Essink (2001a), Giambastiani et al. (2007), Dausman and Langevin (2005), Langevin (2003), Langevin et al. (2005), Mao et al. (2006), among others.

This paper discusses a numerical study of seawater intrusion in southern Baldwin County, Alabama, USA, where groundwater is the only source of freshwater for industrial, municipal and private use. To provide useful information to aid in protection of groundwater resources in the study area from contamination by seawater intrusion, a three-dimensional numerical model based on SEAWAT is developed in this study. The numerical model incorporates regional geologic, geographic, and hydrogeologic features. The input parameters to the model are determined from analysis of well logs, well driller's reports, and pumping tests. After being calibrated against head data in 1996, this model is used to predict the extent of seawater intrusion in southern Baldwin County 40 years after 1996 with all the conditions assumed to remain the same as those in 1996. The results show the study area be significantly affected by seawater intrusion in all aquifer units within 40 years.

Site description

Baldwin County, located in southwestern Alabama, is the largest county of the state. The study area is situated in the southernmost portion of Baldwin County, and is bounded by U.S. Highway 98 to the north at Foley, Alabama, Wolf Bay and Miflin Creek to the east, the Gulf of Mexico to the south, and Mobile Bay and Weeks Bay to the west (Fig. 1). This region, lying in the Coastal Lowlands district of the East Gulf Coastal Plain physiographic province, is specifically described as the Southern Pine Hills, a cuesta-like, elevated, southward-sloping dissected plain, developed on sand and gravel deposits of the Pliocene Citronelle Formation (Davis 1987). Elevation in the study area ranges from 24 m above the mean sea level at Foley, Alabama in the north to 0 m along the coastline. Relief in the area is low, with a maximum relief of 19 m per kilometer along eroded stream valleys. Topography in the region is characterized by low rounded hills.

Stratigraphy

The subsurface stratigraphy of southern Baldwin County consists of sedimentary rocks ranging from Jurassic to

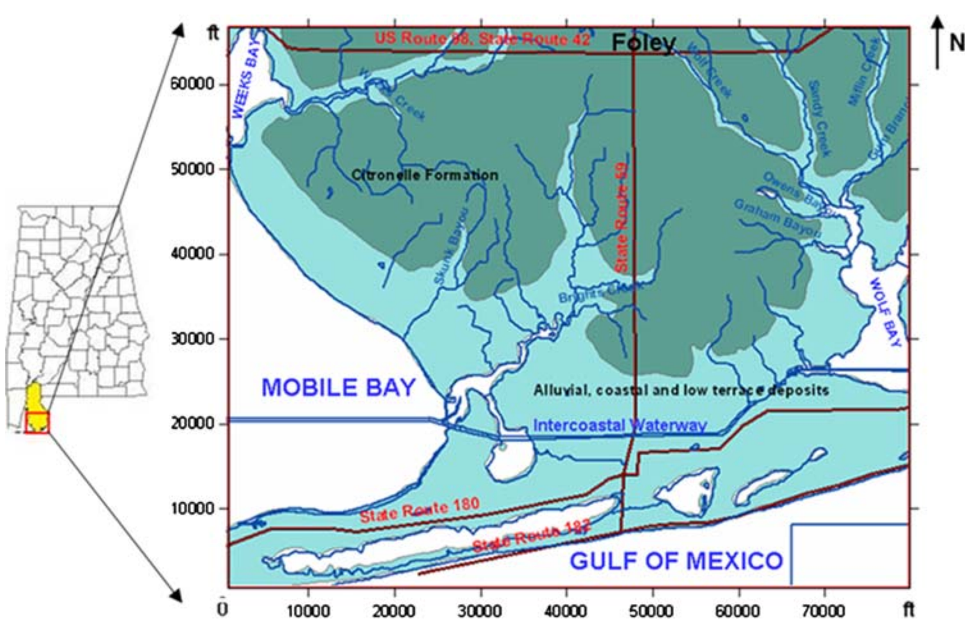

Fig. 1 Location of Baldwin County, Alabama and geographical extent of the study area. One foot is equal to 0.305 m

Holocene in age. Major water bearing zones occur in three intervals, the Pleistocene–Holocene interval, the shallow Miocene–Pliocene interval, and the deep Miocene interval. Generally, these units have a low regional dip to the south toward the Gulf of Mexico, approximately 10 feet per mile (Layne GeoSciences Inc., Layne Inc. 1996).

The surficial sediments are the Pleistocene–Holocene alluvial and terrace deposits, known locally as the Beach Sands, outcropping in the lowland areas along the coast in the southern one-third of the field area. These deposits can be up to 40 m thick. The composition and grain size are highly variable owing to the complex nature of their depositional environments. They consist of a white to pale-orange fine to coarse-grained sand, silt, clay and sea-shell hash. These sediments represent beach dune, lagoonal estuarine, and deltaic deposits. Relatively coarser grained sediments dominate the upper 9–18 m of the unit, while finer grained sediments are predominant in the lower portion. The layers are vertically and laterally discontinuous.

The Beach Sands are directly underlain by the Citronelle Formation, late Miocene to Pliocene in age. It is between 64 and 79 m thick, outcropping in the upper, undissected plains of the northern two-thirds of the field area. Reed (1971) describes it as a reddish-brown, gravelly sand, which locally contains light-gray clay balls and partings, and lenticular beds of light-gray, orange, and brown sandy clay. Layers in this formation are laterally and vertically discontinuous.

The next lithologic unit is comprised of undifferentiated Miocene sediments representing a regressive sequence of marine sediments (Marsh 1964). It is composed of a series of white to light-gray, fine to very coarse-grained sand, silt, sandy clay, and gravel beds, locally up to more than 305 m thick. This unit coarsens upward and is characterized by very abrupt facies changes. Sands usually range from 3 to 34 m in thickness and comprise an estimated 50% of the upper section of this unit. The layers in this unit are more continuous and laterally traceable than those in the Citronelle Formation.

The Miocene Pensacola Clay underlies the undifferentiated Miocene sediments. It occurs at a depth of 229–610 m below mean sea level and is regionally continuous. It is composed of highly impermeable clay.

Hydrogeology

Hydrogeologic units, utilized as freshwater sources in the study area, are described in Table 1. These units are composed of sand and clay, with interbedded silt, gravel, and shell-hash. Water production is from sand layers contained within the units.

Due to the high degree of variability and lateral discontinuity within the geologic units, aquifer zones are determined upon their hydrogeologic characteristics. In this study, the geologic-age, aquifer-zone designation for hydrogeologic units of Chandler et al. (1985) is used. A cross-section through the study area, from Foley, Alabama (north) to the Gulf of Mexico (south), is shown in Fig. 2. Figure 3 depicts an east/west trending cross-section from Bon Secour Bay to the west to Wolf Bay to the east.

The uppermost water-bearing unit is aquifer zone A1. This unit is locally known as the "Beach Sand aquifer". It

Table 1 Hydrogeologic units (adapted from Chandler et al. 1996)

Hydrogeologic unit		Unit character		Recognized individual aquifers
Aquifer zone	Geologic interval (units)	Lithologic	Hydrologic	
A1	Pleistocene–Holocene (alluvial, low terrace, and coastal deposits)	Sand, white to pale-orange, fine- to coarse-grained silt; clay; and sea-shell hash. Finer-grained sediments predominate in lower part of unit as discontinuous layers	Predominantly medium-grained sands in upper 6–18 m of unit comprise principal aquifer. The aquifer is a water-table aquifer and is a potential source of more than 545.1 m^3/day of water per well	Beach sand aquifer (Walter and Kidd 1979)
A2	Shallow Miocene–Pleistocene (Citronelle Formation—Miocene series undifferentiated)	Sand, white- to light-gray, fine- to very coarse-grained, gravelly and carbonaceous in places, interbedded with sandy silty clay	Sand and gravel in unit comprise major aquifers. The lower aquifers are generally semiconfined. Potential soure of 545.1 to 5,451.0 m^3/day of water per well	Gulf shores aquifer (Walter and Kidd 1979)[a]
A3	Deep Miocene (Miocene series undifferentiated)	Same as A2, except sediments for more persistent and traceable layers in the subsurface. The siliciclastics immediately overlie the Pensacola Clay	Major aquifers are semiconfined or confined and yield water to wells under low-head artesian pressure. Potential source of more than 8,176.5 m^3/day of water per well	107- and 152-m aquifers (Walter and Kidd 1979)[a]

[a] Miocene–Pliocene aquifer (Riccio et al. 1973)

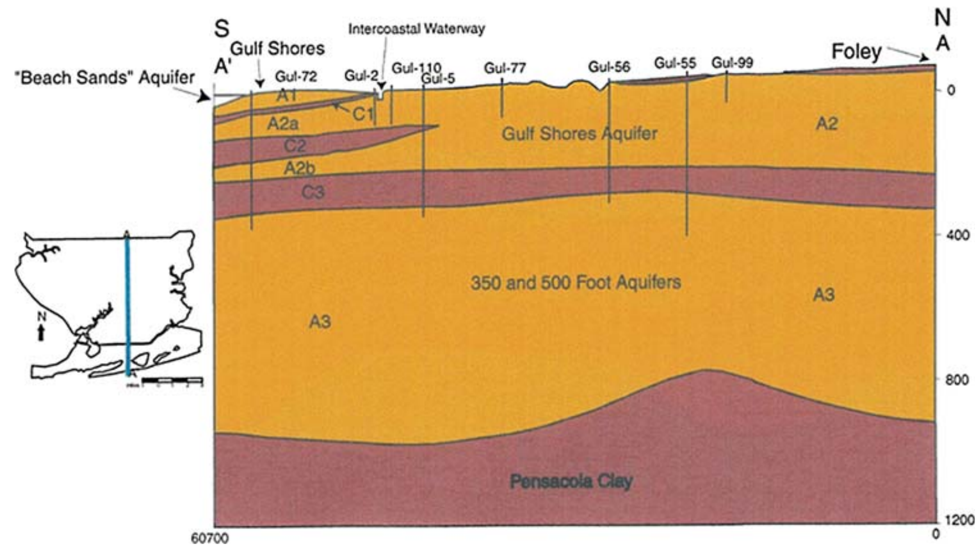

Fig. 2 North to south cross-section through southern Baldwin County showing hydrogeologic units. The *blue line* on the reference map shows the location of the cross-section. The unit of distance and elevation is in feet (1 foot is equal to 0.305 m)

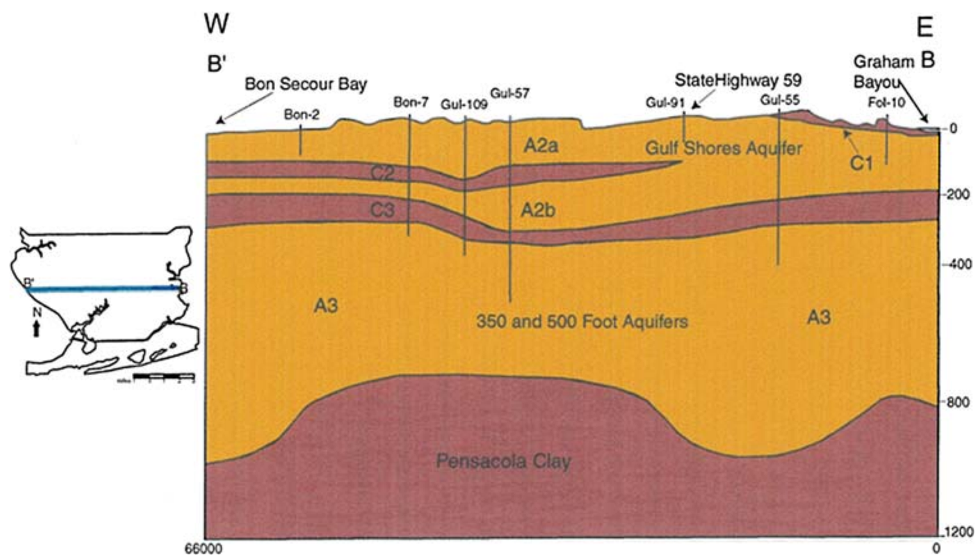

Fig. 3 East to west cross-section through southern Baldwin County showing hydrogeologic units. The *blue line* on the reference map shows the location of the cross-section. The unit of distance and elevation is in feet (1 foot is equal to 0.305 m)

is Pleistocene to Holocene in age and represents alluvial, low terrace, and coastal deposits (Chandler et al. 1996). It occurs in the southern one-third of the study area, generally south of the Intercoastal Waterway and along coastal areas. Thickness of this unit is variable, locally up to 18 m. The unit occurs as an unconfined water-table aquifer, consisting mainly of sand. Fresh-water recharge to the water-table aquifer is predominantly through infiltration of precipitation. The aquifer zone has a potential yield of up to 545.1 m^3/day per well and is not utilized for public supply of freshwater. A confining bed, shown as the C1 aquitard in Figs. 2 and 3, is present beneath the A1 aquifer.

Underlying the A1 aquifer zone is the shallow Miocene–Pleistocene aquifer zone A2. Geologic units in this interval are the Citronelle Formation and the upper portions of the undifferentiated Miocene Series. This aquifer is unconfined in the northern two-thirds of the study area, where it is exposed at the ground surface, and confined where overlain by the A1 aquifer. It is up to 76 m thick and mainly consists of sand and clay with interbedded gravel and shell-hash. Small-scale layering is variable and laterally discontinuous. However, the aquifer is traceable in the Gulf Shores-Orange Beach area, in the subsurface using electric logs of wells (Chandler et al. 1996). It was identified by Walter and Kidd (1979) as the Gulf Shores Aquifer, consisting of two laterally continuous sand beds separated by a locally continuous clay layer. Therefore, this aquifer zone has been subdivided into the A2a aquifer, C2 aquitard, and A2b aquifer (Figs. 2, 3). Aquifer zone A2 is a major source of freshwater in southern Baldwin County, with a potential yield of 545.1 to 5,451.0 m^3/day per well (Chandler et al. 1996). Below the A2 aquifer is the C3 aquitard, a highly impermeable clay layer.

The A3 aquifer zone is present below aquifer zone A2 and consists of sediments of the deeper undifferentiated Miocene Series. This unit is lithologically similar to the A2 aquifer but with individual layers being laterally more continuous and traceable. It is a low-head artesian aquifer with a potential yield greater than 8,176.5 m^3/day per well, making aquifer zone A3 a major source of freshwater in the region (Chandler et al. 1996).

The lower confining unit beneath the A3 aquifer is the Pensacola Clay which is Miocene in age (Raymond 1985). This unit occurs at a depth of 229–305 m below sea level and is highly impermeable.

Recharge to the upper, unconfined aquifers occurs through infiltration of precipitation. Based on annual precipitation, evapotranspiration rates, and surface drainage, it is estimated that the uppermost aquifers gain up to 0.2 m of recharge each year. Stable oxygen and deuterium isotopic evidence from well water samples (Carey et al. 2005) suggest that recharge to the lower aquifers predominantly occurs much farther up-gradient, possibly as far north as Clarke County.

Likely causes of seawater intrusion

The seawater intrusion into the coastal aquifers in southern Baldwin County was first observed in 1985 (Chandler et al. 1985). Generally, in this area, overexploitation of groundwater from the coastal aquifers is considered as the most important factor to cause seawater intrusion, especially in the deep aquifers. However, salt-water spray and coastal flooding of lowland areas as a result of tropical storms and hurricanes in the Gulf of Mexico may increase the salinity of water in the shallow aquifers as well.

As a popular destination for visitors from all over the nation and world, year round because of beautiful beaches, unlimited recreational opportunities and health economy, Baldwin County has attracted a larger and larger residential and industrial population, which contributes to the county's explosive population growth since the 1980s. The population of Baldwin County increased 25.1% from 1980 to 1990, which resulted in a net migration of over 19,000 people into the county. The growth in population was concentrated along the coastline in southern Baldwin County, which was evidenced by a 240% increase in the population of Gulf Shores and a 1,200% increase in the population of Orange Beach over the same period (Remington 1995). The growth in population of Baldwin County has not slowed down since 1990. It was estimated that the population of Baldwin County had increased to 120,198 in July, 1995 from 98,280 by the census in 1990 by 22.3% of change,[1] a majority of which resided along the coastal areas.[2] Obviously, the growth in population has created greater demands on the freshwater from the coastal aquifers in southern Baldwin County. With the population enlarged and subsequently the exploitation of groundwater increased, seawater intrusion in southern Baldwin County has become a serious issue threatening the daily life of people living near the coasts, which urgently requires hydrogeologists and environmentalists to investigate it and find an effective and feasible method to prevent the further intrusion of salt water into the coastal aquifers and remediate the zones already contaminated by the seawater if possible.

Numerical modeling

Simulation code

In this study, the SEAWAT code, capable of simulating three-dimensional variable-density groundwater flow in porous media, is used to simulate the seawater intrusion into coastal aquifers in southern Baldwin County, Alabama. The fundamental concept of this code is to combine the two commonly used groundwater flow and solute transport modeling programs MODFLOW (Harbaugh et al. 2000) and MT3DMS (Zheng and Wang 1999) into a single program that solves the density-dependent groundwater flow and solute-transport equations. The governing equation for density-dependent groundwater flow in terms of freshwater head, which is solved by MODFLOW routines in the SEAWAT code, is derived by Guo and Langevin (2002) as follows:

$$\frac{\partial}{\partial\alpha}\left\{\rho K_{f\alpha}\left[\frac{\partial h_f}{\partial\alpha}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z}{\partial\alpha}\right]\right\}+\frac{\partial}{\partial\beta}\left\{\rho K_{f\beta}\left[\frac{\partial h_f}{\partial\beta}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z}{\partial\beta}\right]\right\}+\frac{\partial}{\partial\gamma}\left\{\rho K_{f\gamma}\left[\frac{\partial h_f}{\partial\gamma}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z}{\partial\gamma}\right]\right\}=\rho S_f\frac{\partial h_f}{\partial t}+\theta\frac{\partial\rho}{\partial C}\frac{\partial C}{\partial t}-\bar{\rho}q_s \quad (1)$$

where α, β, γ are orthogonal coordinate axes, aligned with the principal directions of permeability; $K_{f\alpha}$, $K_{f\beta}$, $K_{f\gamma}$, are equivalent freshwater hydraulic conductivities in the three coordinate directions, respectively [LT^{-1}]; ρ is the fluid density [ML^{-3}]; ρ_f is the density of freshwater [ML^{-3}]; h_f is the equivalent freshwater head [L]; Z is the elevation above datum of the center of a model cell [L]; S_f is the equivalent freshwater specific storage [L^{-1}]; θ is effective porosity [dimensionless]; C is the solute concentration

[1] http://www.usatoday.com/news/states/special/pop/npopal.htm
http://www.usatoday.com/news/states/special/pop/npopal.htm

[2] http://www.co.baldwin.al.us/Pageview.asp?edit_id64
http://www.co.baldwin.al.us/Pageview.asp?edit_id64

[ML^{-3}]; $\overline{\rho}$ is the density of water entering from a source or leaving through a sink [ML^{-3}]; q_s is the volumetric flow rate of sources or sinks per unit volume of aquifer [T^{-1}]; and t is time [T].

The SEAWAT code utilizes MT3DMS routines to solve the following form of solute-transport governing equation (Zheng and Bennett 2002):

$$\frac{\partial C}{\partial t} = \nabla \cdot (D \cdot \nabla C) - \nabla \cdot \left(\vec{v}C\right) - \frac{q_s}{\theta} C_s + \sum_{k=1}^{N} R_k \qquad (2)$$

where D is the hydrodynamic dispersion coefficient [L^{2}T^{-1}]; $\vec{v}$ is the fluid velocity [LT^{-1}]; C_s is the solute concentration of water entering from sources or leaving through sinks [ML^{-3}]; and R_k $(k = 1,\ldots,N)$ is the rate of solute production or decay in reaction k of N different reactions [ML^{-3}T^{-1}].

For a coupled variable-density flow and solute-transport simulation, fluid density is assumed to be a function only of solute concentration; the effects of pressure and temperature on fluid density are ignored (Langevin et al. 2003). A linear equation of state is used by the SEAWAT code to convert solute concentration to fluid density:

$$\rho = \rho_f + \frac{\partial \rho}{\partial C} C \qquad (3)$$

where $\frac{\partial \rho}{\partial C}$ is the slope of the equation. The value for $\frac{\partial \rho}{\partial C}$ is entered by the user and depends on the units used for the simulation. For example, if meters and kilograms are used for the simulation, $\frac{\partial \rho}{\partial C}$ is set to a value of 0.7143, which approximately equals the change in fluid density divided by the change in solute concentration for freshwater and seawater.

The SEAWAT code is a useful tool for simulating various types of variable-density fluid flow through complex geometries and geological settings, including seawater intrusion in coastal aquifers, submarine groundwater discharge, brine transport, and groundwater flow near salt domes. It has been tested with many commonly used benchmark problems (Guo and Langevin 2002; Langevin et al. 2003; Bakker et al. 2004). Two additional verifications, i.e., the modified Henry problem (Simpson and Clement 2004) and the saltpool problem (Johannsen et al. 2002; Oswald and Kinzelbach 2004), have been done by Langevin and Guo (2006) to demonstrate the level of accuracy that can be obtained with SEAWAT. More applications of the SEAWAT code are described in Bakker et al. (2004), Bakker (2003), Bauer et al. (2006), Dausman and Langevin (2005), Langevin (2003), Langevin et al. (2005), Mao et al. (2006), Schneider and Kruse (2006), and Zimmermann et al. (2006).

Model discretization

In the plan view, the model grid consists of 61 columns and 51 rows with a uniform grid spacing of 402.3 m (1,320 feet) in both directions (Fig. 4a). In the vertical direction, the model grid consists of seven layers representing the hydrostratigraphy of southern Baldwin County (Fig. 4b). Layer 1 corresponds to the A1 aquifer. Layer 2 is a confining layer, the C1 aquitard, between the A1 and A2 aquifers. Due to a substantial clay layer that divides the A2 aquifer in the southern half of the study area, the A2 aquifer has been subdivided into the A2a layer, the upper A2 aquifer, the C2 confining layer within the A2 aquifer, and the A2b layer, the lower A2 aquifer. In the model, Layer 3 corresponds to the A2a aquifer; Layer 4 represents the C2 aquitard and Layer 5 corresponds to the A2b aquifer. Layer 6 represents the C3 aquitard, which is the

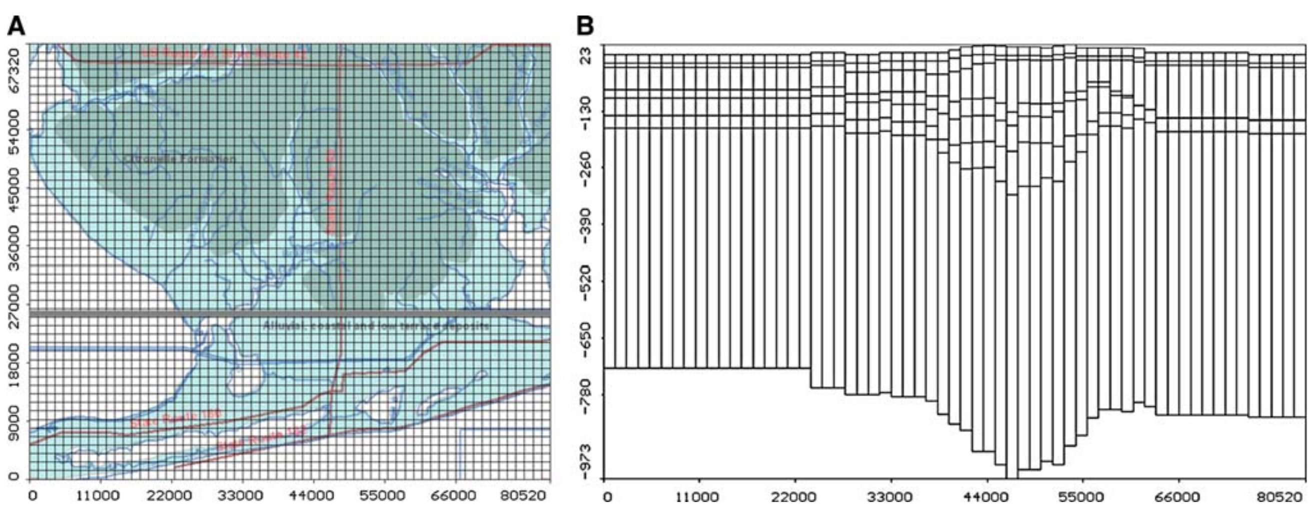

Fig. 4 Spatial discretization for the three-dimensional numerical model (unit in feet): **a** plan view, and **b** cross-section along row 32 as marked on **a**

confining bed between the A2b and A3 aquifers. Layer 7 represents the A3 aquifer.

From the hydrogeology of the study area, it is evident that the flow system consists of both confined and unconfined aquifers. Layers 1 and 3 are unconfined where they are present at the land surface. Layer 3 is confined where overlain by Layers 1 and 2. Layers 4–7 are treated as confined whenever the head is above the top elevation of any particular layer.

Model layer thickness is determined from occurrence of sand and clay layers documented in well driller's reports archived at the Alabama Geological Survey, Hydrogeology Division. Where absent, layer thickness is set to 0.305 m (one foot) and the hydraulic properties of the absent layer are represented by the layer immediately below. For example, north of where the C2 aquitard layer pinches out, layer thickness for Layer 4 is assigned to 0.305 m and the hydraulic properties are the same as those in Layer 5.

Temporally, the simulation model is transient with a total simulation time of 11 years from 1985 to 1996. A total of 11 stress periods is used in the model, with each stress period representing 1 year of simulation time.

Hydrogeologic parameters

Zoned hydraulic conductivity maps are created using hydraulic conductivity values determined from pumping tests conducted at the time of well completion, as described in well driller's logs. All values are averaged for each zone and the mean horizontal hydraulic conductivity is assigned for the entire zone. The size of zones is estimated and then adjusted during model calibration. Hydraulic conductivity of aquitards is determined to be 7.62×10^{-3} m/day in Layers 2 and 4, while Layer 6 is assigned a value of 3.81×10^{-3} m/day. Hydraulic conductivity is assumed to be constant within each aquitard. However, for all the layers, vertical hydraulic conductivity is estimated as 5% of the horizontal hydraulic conductivity.

Streams and rivers are specified with the DRAIN package of the MODFLOW code. Width, depth, and drain stage are determined from topographic maps. Recharge is applied to the uppermost active layer. An average rate of 5.58×10^{-4} m/day is calculated from annual precipitation data, evapotranspiration rates, and discharge rates to streams. A maximum rate of 3.05×10^{-3} m/day and a minimum rate of 3.05×10^{-5} m/day for zones with different recharge rates are applied during calibration. Well locations and pumping rates are given by Chandler et al. (1996). Pumping rates vary throughout the model simulation following changes in withdrawal rates over time at the public supply wells.

Effective porosity is assumed to be homogeneous and set to 0.25 as an initial estimate. Longitudinal dispersivity is also considered to be homogeneous in the flow system and is initially set to 1 m. The ratio of the horizontal transverse dispersivity to the longitudinal dispersivity is assumed to be 0.1, while the ratio of the vertical transverse dispersivity to the longitudinal dispersivity 0.01. As needed, these values are adjusted during model calibration.

Boundary and initial conditions

Since the model is set up to simulate the seawater intrusion into coastal aquifers simultaneously involving both groundwater flow and solute transport processes, boundary conditions for these two processes are required. For the flow model, the boundary conditions are specified-head everywhere (marked by red cells in Fig. 5a and b) except for Layers 1 and 2 which are bounded by no-flow

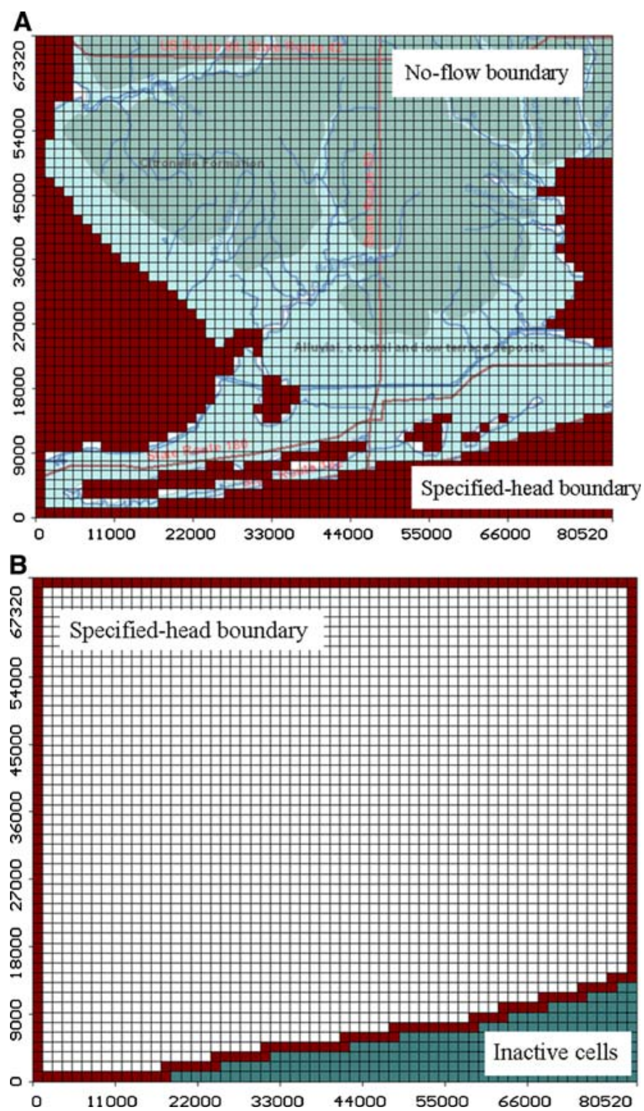

Fig. 5 Flow boundary conditions for each layer of the numerical model (unit in feet): **a** Layers 1 and 2, and **b** Layers 3–7

boundaries at the northern and northeastern edges where the A1 aquifer and C1 aquitard pinch out. The specified-head values are either zero representing the mean sea level or interpolated from the measured heads along the boundaries.

For the solute transport model, chloride is the simulated component. The chloride concentration in seawater is approximately 35 kg/m^3. In Layers 1 and 2, the boundary conditions are specified-concentration wherever the A1 aquifer and C1 aquitard are in contact with surface water, while the boundary conditions are no-mass-flux for the remainder (Fig. 6a). For Layers 3 through 7, the boundary conditions are specified-concentration along the coast, while the boundary conditions are specified-mass-flux elsewhere (Fig. 6b). The chloride concentration value for specified-concentration boundaries are either 35 kg/m^3 along the coast or 17.5 kg/m^3 in the Intercoastal Waterway, Wolf Bay, Mobile Bay and Weeks Bay, which is half of the chloride concentration in seawater and represents a mixing of freshwater with seawater. The mass-flux values for the specified mass-flux boundaries are taken as the product of the inflow or outflow rate multiplied by the inflow or outflow concentration. The dispersive flux across boundaries is assumed to be negligible by default in the SEAWAT code.

The initial condition for the model requires the specification of the chloride concentrations at active model cells at the start of the simulation. For this study the initial concentrations are determined from the figures and plates presented by Chandler et al. (1985) showing the location of saline water in various aquifer layers.

Model calibration

In this study model calibration is achieved through a trial-and-error approach by adjusting the zonation and values of two key parameters, i.e., hydraulic conductivities and recharge rates, until the hydraulic head values calculated by SEAWAT match the observed values to a satisfactory degree. Due to the scarcity of observed chloride concentrations, no attempt is made to adjust several transport parameters including dispersivities and effective porosity. Their values remain the same as initially assigned. Furthermore, because of the lack of continuously monitored head data, the model is only calibrated against the observed heads at the end of simulation. During calibration, a total of 35 observed hydraulic head values measured in 1996 are used. All the observation well locations are shown in Fig. 7 and the observed heads at these locations are taken from

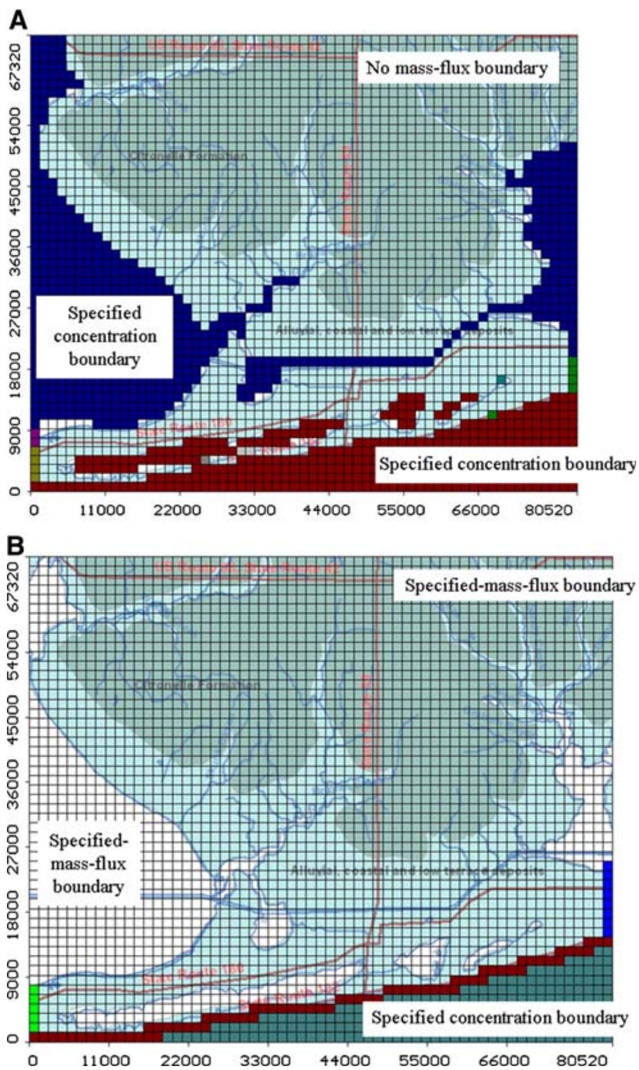

Fig. 6 Transport boundary conditions for each layer of the numerical model (unit in feet): **a** Layers 1 and 2, and **b** Layers 3–7

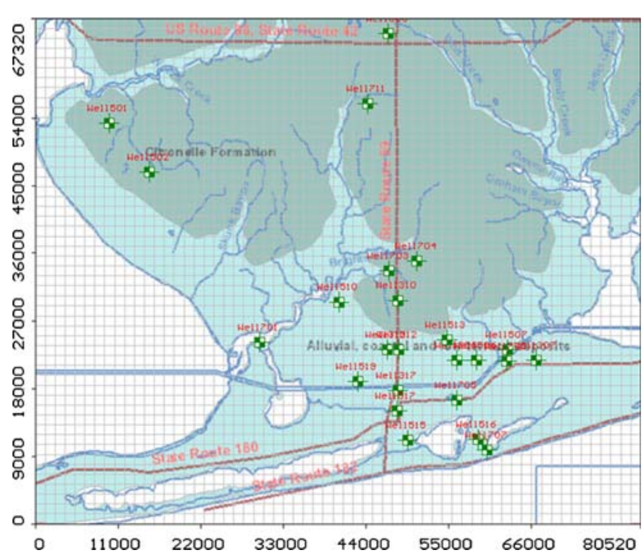

Fig. 7 Location of head observation wells used in model calibration (unit in feet)

Chandler et al. (1996). Model calibration is stopped when a reasonable match between the observed and calculated heads is achieved.

As illustrated in Fig. 8, an overall correlation coefficient of 0.97, a mean error of −0.52 and a root mean square value of 3.71 are obtained when model calibration is finished, indicating a reasonably good match between the observed and calculated heads. Residuals between the observed and calculated heads are also listed in Table 2. After model calibration, the resulting horizontal hydraulic conductivity for Layers 1, 3, 5 and 7 range from 1.52 to 137.16 m/day, while the resulting recharge rates from 3.05×10^{-5} to 3.05×10^{-3} m/day. It is noteworthy that the model calibration performed for this study is of preliminary nature due to the limited number and duration of the observation data. Therefore, additional model calibration should be attempted when more field data become available in the future.

The simulated extent of seawater intrusion into the aquifer Layers 3, 5 and 7 in 1996 is depicted in Fig. 9. Compared with that in 1985, the extent of seawater intrusion was expanded, indicating that further seawater intrusion occurred from 1985 to 1996. As shown in Fig. 9, seawater intrusion in Layer 7 was considerably faster than that in both Layers 3 and 5 during the 11 years. Note that at any specific location of the aquifer, when the chloride concentration rises above 0.25 kg/m^3, the limit for freshwater use set by U.S. Environmental Protection Agency (1973), the location is considered to have been affected by seawater intrusion.

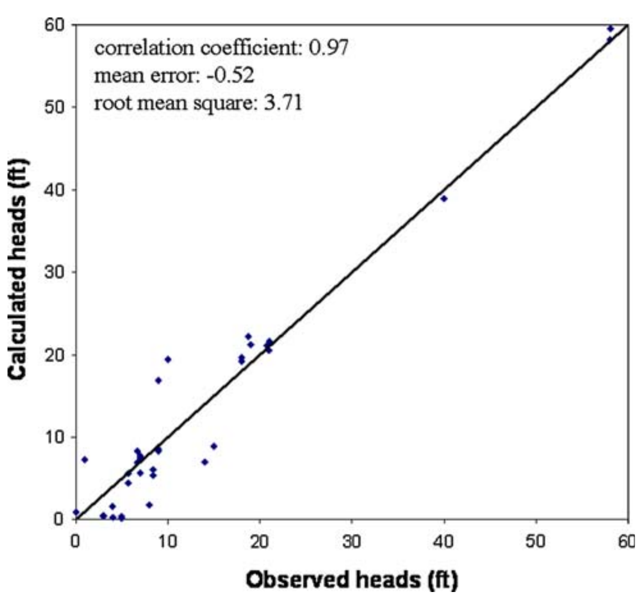

Fig. 8 Scatter diagram showing the goodness of fit between the observed and calculated heads for 1996

Prediction of seawater intrusion

Prediction of the extent of seawater intrusion in coastal aquifers in southern Baldwin County 40 years after 1996 is carried out by running the calibrated model 40-year forwards with all the conditions assumed to remain the same as those in 1996. The predicted extent of seawater intrusion in Layers 3, 5 and 7 is described in Fig. 9 as well, showing further seawater intrusion will occur even if all the hydrogeologic conditions remain the same as those in 1996. Again as shown in Fig. 9, seawater intrusion in Layer 7 will be significantly faster than that in Layers 3 and 5.

Based on model prediction, it is evident that keeping all the conditions unchanged for the next 40 years after 1996 will result in further contamination of the coastal aquifers by seawater intrusion in southern Baldwin County. As the population continues to grow and the demand for groundwater pumping intensifies, it can be expected the actual extent of seawater intrusion in the future will be more severe than the model prediction. In order to protect the freshwater resources in coastal aquifers in the study area from seawater intrusion, adjusting the groundwater pumping scheme for the future is suggested since overexploitation of groundwater from the coastal aquifers is the most important factor to cause seawater intrusion in the study area.

Summary and conclusions

The purpose of this study is to provide useful information to aid in protection of freshwater resources in the Gulf coastal aquifers of Alabama from further contamination by seawater intrusion. A three-dimensional numerical model of density-dependent groundwater flow and miscible salt transport is developed to assess the current extent and predict the future condition of seawater intrusion in the study area. The model incorporates regional geologic, geographic, and hydrogeologic features. The model input parameters are determined from analysis of well logs, well driller's reports, and pumping tests. The SEAWAT code, which is a combined version of the two commonly used groundwater flow and solute transport modeling programs MODFLOW and MT3DMS, is used to solve the numerical model for the coupled density-dependent flow system.

Due to the scarcity of the observed chloride concentrations and continuously monitored head data, the model is only calibrated against the observed heads at the end of simulation. During calibration, a total of 35 observed hydraulic head values for 1996 are used. All the observation well locations and observed heads are taken from Chandler et al. (1996). A reasonably good match between the observed and calculated heads is achieved. However,

Table 2 Observed and calculated heads with residuals at 35 observation points (1 feet = 0.305 m)

Well id	Well name	Column	Row	Layer	Observed heads (ft)	Calculated heads (ft)	Residuals (ft)
Well701	Gul-01	23	33	7	10	19.4245	9.4245
Well703	Gul-97	36	26	7	20.75	21.1385	0.3885
Well704	Gul-53	39	25	7	19	21.1894	2.1894
Well705	Gul-100	43	39	7	9	16.862	7.862
Well707	Gul-36	46	44	7	18.76	22.2162	3.4562
Well709	Gul-23	48	35	7	7	5.6731	−1.3269
Well711	Artificial point	34	9	7	40	38.917	−1.083
Well501	Mag-20	8	11	5	18	19.7065	1.7065
Well502	Bon-10	12	16	5	21	20.5379	−0.4621
Well503	Fol-03	36	2	5	58	58.1901	0.1901
Well506	Gul-46	45	35	5	7	7.494	0.494
Well507	Gul-22	48	34	5	9	8.3167	−0.6833
Well508	Gul-50/Gul-41	43	39	5	5.7	5.5647	−0.1353
Well510	Gul-07/Gul-99	31	29	5	1	7.2929	6.2929
Well512	Gul-05	37	34	5	5	0.4175	−4.5825
Well513	Gul-25/Gul-27	42	33	5	14	6.9674	−7.0326
Well515	Gul-35	38	43	5	8.38	6.0171	−2.3629
Well516	Gul-37	45	43	5	6.67	6.9374	0.2674
Well517	Gul-04/Gul-03	37	40	5	3	0.5474	−2.4526
Well519	Gul-110	33	37	5	4	1.5962	−2.4038
Well301	Mag-20	8	11	3	18	19.2	1.2
Well302	Bon-10	12	16	3	21	21.6336	0.6336
Well303	Fol-03	36	2	3	58	59.5238	1.5238
Well306	Gul-46	43	35	3	7	7.7675	0.7675
Well307	Gul-22	51	35	3	9	8.5742	−0.4258
Well308	Gul-50/Gul-41	43	39	3	5.7	4.4042	−1.2958
Well310	Gul-07	37	29	3	8	1.7785	−6.2215
Well311	Gul-99	31	29	3	0	0.9162	0.9162
Well312	Gul-05	36	34	3	5	0.1348	−4.8652
Well313	Gul-25	42	33	3	15	8.9311	−6.0689
Well315	Gul-35	38	43	3	8.38	5.3318	−3.0482
Well316	Gul-37	45	43	3	6.7	8.3628	1.6628
Well317	Gul-04	37	38	3	6	−0.3851	−6.3851
Well318	Gul-03	37	40	3	3	0.4215	−2.5785
Well319	Gul-110	33	37	3	4	0.2838	−3.7162

additional calibration is necessary when more data become available in the future.

Model prediction is carried out after calibration. The extent of seawater intrusion in the model area 40 years after 1996 is predicted by using the calibrated model and with all the conditions assumed to remain the same as those in 1996. The result shows that further seawater intrusion into coastal aquifers can occur and seawater intrusion in model Layer 7 (aquifer A3) would be considerably faster than that in Layers 3 and 5 (A2a and A2b). As the population continues to grow rapidly and the demand for groundwater pumping intensifies, it can be expected the actual extent of seawater intrusion in the future may be more severe than the model prediction. Since overexploitation of groundwater from the coastal aquifers is the most important factor to cause seawater intrusion in the study area, adjusting the future groundwater pumping scheme and improving groundwater management strategies will be necessary in order to protect the freshwater aquifers from being contaminated by salt water.

This study provides a valuable example for studying seawater intrusion in other coastal aquifers under similar hydrogeologic conditions. The study demonstrates that the SEAWAT code can serve as an effective tool for simulating

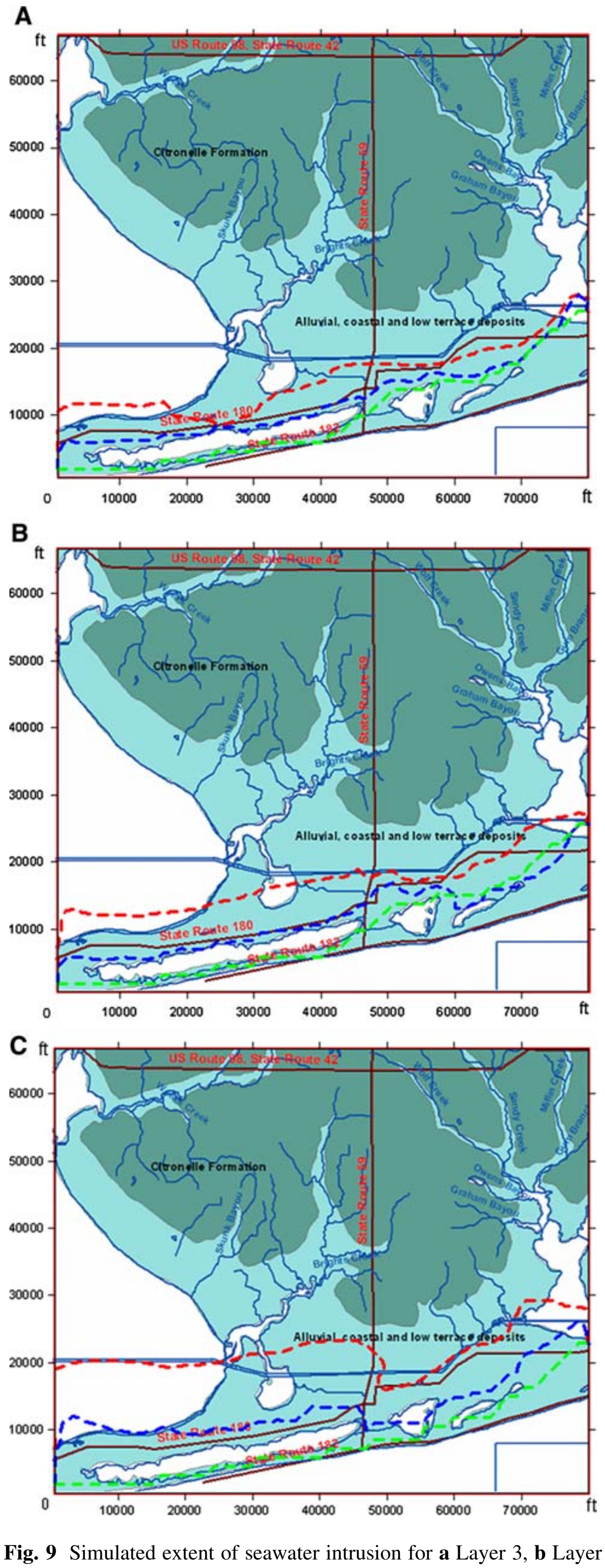

Fig. 9 Simulated extent of seawater intrusion for **a** Layer 3, **b** Layer 5 and **c** Layer 7 in 1996 shown by a *dashed line* in *blue*. Extent of seawater intrusion in 1985 shown by a *dashed line* in *green*. Predicted extent of seawater intrusion by 2036 shown by a *dashed line* in *red*

variable-density flow and transport under complex geometries and geological settings. A three-dimensional regional-scale numerical model, properly calibrated with sufficient data, can provide a powerful management tool for coastal aquifers.

Acknowledgments Funding for this project was provided in part by Award Number NA#17OZ2324 through the Coastal Zone Management Act of 1972 (as amended), administered by the Office of Ocean and Coastal Resource Management, National Oceanic and Atmospheric Administration and in conjunction with the Alabama Department of Conservation and Natural Resources, State Lands Division. The authors are especially grateful to Carl Ferarro of the Alabama Department of Conservation and Natural Resources, State Lands Division, for his support and guidance throughout this study.

References

Andersen PF, Mercer JW, White Jr HO (1988) Numerical modeling of salt-water intrusion at Hallandale, Florida. Ground Water 26(5):619–630

Bakker M (2003) A Dupuit formulation for modeling seawater intrusion in regional aquifer systems. Water Resour Res 39(5):1131

Bakker M, Schaars F (2003) The sea water intrusion (SWI) package manual, version 0.2. University of Georgia, Athens

Bakker M, Oude Essink GHP, Langevin CD (2004) The rotating movement of three immiscible fluids—a benchmark problem. J Hydrol 287:270–278

Bauer P, Held RJ, Zimmermann S, Linn F, Kinzelbach W (2006) Coupled flow and salinity transport modelling in semi-arid environments: the Shashe River Valley, Botswana. J Hydrol 316:163–183

Bear J (1979) Hydraulics of groundwater. Mcgraw-Hill, New York

Bear J, Cheng A, Sorek S, Herrera I, Ouazar D (1999) Seawater intrusion in coastal aquifers: concepts, methods and practices. Kluwer Academic Publishers, Dordrecht

Carey AE, Lyons WL, Poreda RJ (2005) Geochemistry of a gulf coastal aquifer system, Baldwin County, Alabama. Geol Soc Am Abstr Programs 37(7):470

Chandler RV, Moore JD, Gillett B (1985) Ground-water chemistry and salt-water encroachment, southern Baldwin County, Alabama. Ala Geol Surv Bull 126:166

Chandler RV, Gillett B, DeJarnette SS (1996) Hydrogeologic and water-use data for southern Baldwin County, Alabama. Ala Geol Surv Circ 188:124

Dausman A, Langevin CD (2005) Movement of the saltwater interface in the surficial aquifer system in response to hydrologic stresses and water-management practices, Broward County, Florida. U.S. Geological Survey Scientific Investigations Report 2004-5256

Davis ME (1987) Stratigraphic and hydrogeologic framework of the Alabama coastal plain. U. S. Geological Survey Water-Resources Investigations Report 87-4112

Gambolati G, Putti M, Paniconi C (1999) Three-dimensional model of coupled density-dependent flow and miscible salt transport. In: Bear J et al (ed) Seawater intrusion in coastal aquifers: concepts, methods and practices, vol 10. Kluwer Academic Publishers, Dordrecht, pp 315–362

Giambastiani BMS, Antonellini M, Oude Essink GHP, Stuurman RJ (2007) Saltwater intrusion in the unconfined coastal aquifer of Ravenna (Italy): a numerical model. J Hydrol 340:91–104

Guo W, Bennett GD (1998a) Simulation of saline/fresh water flows using MODFLOW. In: Proceedings of MODFLOW '98 conference at the international ground water modeling center, Colorado School of Mines, Golden, Colorado, vol 1, pp 267–274

Guo W, Bennett GD (1998b) SEAWAT version 1.1: a computer program for simulations of groundwater flow of variable density. Missimer International Inc., Fort Myers

Guo W, Langevin CD (2002) User's guide to SEAWAT: a computer program for the simulation of three-dimensional variable-density ground-water flow. USGS Techniques of Water Resources Investigations, Book 6, chap A7

Harbaugh AW, Banta ER, Hill MC, McDonald MG (2000) MODFLOW-2000, the U.S. Geological Survey Modular Ground-Water Model—User Guide to Modularization Concepts and the Ground-Water Flow Processes. U.S. Geological Survey Open-File Report 00-92, 121p

Huyakorn PS, Andersen PF, Mercer JW, White Jr HO (1987) Saltwater intrusion in aquifers: Development and testing of a three-dimensional finite element model. Water Resour Res 23(2):293–312

HydroGeoLogic Inc. (2002) MODHMS—MODFLOW-Based Hydrologic Modeling System: Documentation and User's Guide. Herndon, Virginia

Johannsen K, Kinzelbach W, Oswald S, Wittum G (2002) The saltpool benchmark problem—numerical simulation of saltwater upcoming in a porous medium. Adv Water Resour 25:335–348

Langevin CD (2003) Simulation of submarine ground water discharge to a marine estuary: Biscayne Bay, Florida. Ground Water 41(6):758–771

Langevin CD, Shoemaker WB, Guo W (2003) MODFLOW-2000, the U.S. Geological Survey Modular Ground-Water Model—Documentation of the SEAWAT-2000 version with the variable-density flow process (VDF) and the integrated MT3DMS Transport Process (IMT). USGS Open-File Report 03-426

Langevin CD, Oude Essink GHP, Panday S, Bakker M, Prommer H, Swain ED, Jones W, Beach M, Barcelo M (2004) MODFLOW-based tools for simulation of variable-density groundwater flow. In: Cheng A, Ouazar D (eds) Coastal aquifer management: monitoring, modeling, and case studies. Lewis Publishers, Boca Raton, pp 49–76

Langevin CD, Swain ED, Wolfert MA (2005) Simulation of integrated surface-water/ground-water flow and salinity for a coastal wetland and adjacent estuary. J Hydrol 314:212–234

Langevin CD, Guo W (2006) MODFLOW/MT3DMS-based simulation of variable-density ground water flow and transport. Ground Water 44(3):339–351

Layne GeoSciences Inc., Layne, Inc. (1996) Gulf Shore Utilities Local Wellhead Protection Plan

Ma TS, Sophocleous M, Yu Y-S, Buddemeier RW (1997) Modeling saltwater upconing in a freshwater aquifer in south-central Kansas. J Hydrol 201:120–137

Mao X, Prommer H, Barry DA, Langevin CD, Panteleit B, Li L (2006) Three-dimensional model for multi-component reactive transport with variable density groundwater flow. Environ Model Softw 21:615–628

Marsh OT (1964) Geology of Escambia and Santa Rosa counties, western Florida panhandle. Fla Geol Surv 50:2344–2365

McDonald MG, Harbaugh AW (1988) A modular three-dimensional finite-difference ground-water flow model. U.S. Geological Survey Techniques of Water Resources Investigations, Book 6, chap A1, 588p

Oswald SE, Kinzelbach W (2004) Three-dimensional physical benchmark experiments to test variable-density flow models. J Hydrol 290:22–42

Oude Essink GHP (1998) MOC3D adapted to simulate 3D density-dependent groundwater flow. In: Proceedings of MODFLOW '98 conference at the international ground water modeling center, Colorado School of Mines, Golden, Colorado, vol 1, pp 291–300

Oude Essink GHP (2001a) Saltwater intrusion in 3D large-scale aquifers: a Dutch case. Phys Chem Earth 26(4):337–344

Oude Essink GHP (2001b) Salt water intrusion in a three-dimensional groundwater system in The Netherlands: a numerical study. Transp Porous Media 43:137–158

Paniconi C, Khlaifi I, Lecca G, Giacomelli A, Tarhouni J (2001) A modeling study of seawater intrusion in the Korba Coastal Plain, Tunisia. Phys Chem Earth 26(4):345–351

Raymond DE (1985) Depositional sequences in the Pensacola Clay (Miocene) of southwest Alabama. Ala Geol Surv Bull 114:87

Reed PC (1971) Geologic map of Baldwin County, Alabama. Ala Geol Surv Spec Map 94:5

Remington WC (1995) The atlas of Alabama counties. Geography Department, University of Alabama

Riccio JF, Hardin JD, Lamb GM (1973) Development of a hydrologic concept for the greater Mobile metropolitan-urban environment. Ala Geol Surv Bull 106:171

Schneider JC, Kruse SE (2006) Assessing selected natural and anthropogenic impacts on freshwater lens morphology on small barrier Islands: dog Island and St. George Island, Florida, USA. Hydrogeol J 14:131–145

Shoemaker WB, Edwards KM (2003) Potential fro saltwater intrusion into the lower Tamiami Aquifer near Bonita Springs, southwestern Florida. U.S. Geological Survey Water-Resources Investigations Report 03-4262

Simpson MJ, Clement TP (2004) Improving the worthiness of the Henry problem as a benchmark for densitydependent groundwater flow models. Water Resour Res 40:W01501

Sorek S, Pinder GF (1999) Survey of computer codes and case histories. In: Bear J et al (ed) Seawater intrusion in coastal aquifers: concepts, methods, and practices. Kluwer Academic Publishers, Dordrecht, pp 399–461

U. S. Environmental Protection Agency (1973) Water quality criteria, 1972. Washington, D. C., U. S. Government Printing Office, 594p

Walter GR, Kidd RE (1979) Ground-water management techniques for the control of salt-water encroachment in Gulf Coast aquifers, a summary report. Alabama Geological Survey Open File Report, 84p

Zheng C, Bennett GD (2002) Applied contaminant transport modeling, 2nd edn. Wiley, New York

Zheng C, Wang PP (1999) MT3DMS: Documentation and User's Guide. Contract Report SERDP-99-1, U.S. Army Engineer Research and Development Center, Vicksburg, MS

Zimmermann S, Bauer P, Held R, Kinzelbach W, Walthe JH (2006) Salt transport on islands in the Okavango Delta: numerical investigations. Adv Water Resour 29(1):11–29