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FRESH-WATER LENS FORMATION IN AN UNCONFINED BARRIER-ISLAND AQUIFER[1]

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ABSTRACT: Cone-penetrometer testing and computer modeling were utilized to investigate factors controlling fresh-water lens formation at Grand Isle, Louisiana. Measurements of tip resistance, sleeve friction, and electrical conductivity were recorded with depth to permit classification of sediment type and to determine thickness of the fresh-water lens and transition zone. Cone-penetrometer testing provided virtually continuous determinations of change in sediment type and ground-water salinity at a resolution rarely achieved using conventional drilling and water sampling techniques.

Three sand bodies are present, each separated by a clay layer. The fresh-water lens is thinner in the center of the island than on the flanks. Fresh-water lens thickness is limited by a clay layer which prohibits downward movement of significant volumes fresh water. The transition zone from fresh water to salt water varies in thickness, being thinnest near the Gulf of Mexico and thickest where silt and clay interfinger with the upper sand.

Both the thickness of the fresh-water lens and the shape of the transition zone differ from that predicted by theoretical models. Calibration of SUTRA, a variable-density solute-transport model, indicates that permeability variations are the dominant control on formation of the fresh-water lens.

(KEY TERMS: hydrogeology; barrier island; modelling; fresh-water lens; cone penetrometer.)

INTRODUCTION

Unconfined aquifers typical of barrier islands often contain reserves of fresh water, despite being surrounded by sea water. Precipitation continuously infiltrates permeable island sediments, and a fresh-water lens develops as salt water is displaced. Because of the difference in density between fresh water and salt water, an interface forms. This fresh-water/salt-water interface is sometimes sharp, or it may grade slowly with depth into salt water over a transition zone marked by increasing salinity.

Most theoretical models for predicting depth to the fresh-water/salt-water interface are limited to analytical solutions for idealized aquifers that assume lithologic homogeneity (Hubbert, 1940; Henry, 1959; 1964; Glover, 1959). Attempts to model effects of non-homogeneity on thickness of the fresh-water lens generally have been limited to relatively simple two-layer models of vertically stratified or horizontally layered aquifers (Vacher, 1988) or multi-layer models where hydraulic conductivity was averaged over all layers (Fetter, 1972). Most of these models assume a sharp interface and no effects from dispersion nor density-driven flow. Though some numerical models are better suited for simulating spatial changes in hydraulic conductivity (Fetter, 1972) or allow for a transition zone and the effects of dispersion (Pinder and Cooper, 1970), few data are available for calibration of these models. In most cases, data for calibration are limited to relatively few observation wells scattered over large field areas (Fetter, 1972; Vacher, 1978; Ayers and Vacher, 1986; Anthony *et al.*, 1989).

Cone-penetrometer testing was performed at Grand Isle, Louisiana, to provide detailed data for comparison to standard models. Cone-penetrometer testing allows for nearly continuous determinations with depth of sediment type and electrical conductivity. Water samples were taken in fresh and saline portions of the aquifer for calibration of electrical conductivity to salinity. Because of the heterogeneity of the system, SUTRA, a variable-density solute-transport model, was calibrated to the data for lithology and ground-water salinity. The combination of cone-penetrometer testing and computer modeling enabled us to meet our objective of determining

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factors controlling fresh-water lens formation at Grand Isle, Louisiana.

Fresh-Water Lens Theory

Many investigations have focused upon fresh-water lenses and the position of the fresh-water/salt-water interface in coastal aquifers or in oceanic island settings. The Ghyben- Herzberg equation assumes hydrostatic equilibrium governs the position of the fresh-water/salt-water interface. The equation relates the depth of a sharp fresh-water/salt-water interface with the height of the water table above sea level. The interface is treated as a no-flow boundary so that no mixing occurs between the static fresh-water and salt-water components. The fresh-water lens tapers to an edge at the beach so that no outlet for fresh water exists. A modification by Hubbert (1940) incorporating dynamic modeling dictates that all fresh water flowing to the sea escapes through a narrow gap between the fresh-water/salt-water interface and the outcrop of the water table on the beach. Other modifications have been proposed by several authors (Glover, 1959; Rumer and Shiau, 1968; Van der Veer, 1977) which allow for fresh water to flow to the sea through a subsurface outflow face between the shoreline and some point offshore.

In field observations, the interface between the fresh water and salt water is rarely sharp (Kohout, 1960; Vacher, 1978; Lloyd *et al.*, 1980; Ayers and Vacher, 1986; Anthony *et al.*, 1989; Stoessell *et al.*, 1989; Moore *et al.*, 1992). Mixing occurs across the interface in the form of mechanical dispersion and molecular diffusion. Cooper (1959) proposed a cycle for salt-water flow in coastal aquifers where salt water flows inland from the sea floor and up into a zone of diffusion where it is removed and carried seaward by overlying fresh water. The diluted sea water, being less dense, continues to rise along a seaward path. According to Cooper (1959), sea water under tidal conditions moves further inland in permeable beds than in less permeable beds. The zone of diffusion is then created by flow across these adjacent beds and is maintained by the reciprocative nature of the rising and falling tides.

Kohout (1960) first documented the existence of a zone of diffusion in the Biscayne aquifer near Miami and showed the salt-water front to be stabilized seaward of the position predicted by the Ghyben-Herzberg relationship or Hubbert's modification. Pinder and Cooper (1970) developed a numerical model for determining the transient position of the salt-water front which allowed for the effects of dispersion. In addition, this model was able to simulate irregular island geometry and variable hydraulic conductivity. Vacher (1988) investigated the effects of geological variables through development of a series of analytical solutions in which hydraulic conductivity and recharge were varied. Variation in recharge and hydraulic conductivity were determined to cause formation of asymmetric fresh-water lenses.

Variation in hydraulic conductivity, or permeability, of island sediments is one of the most influential variables capable of affecting the size and shape of the fresh-water lenses. Harris (1967) argued that for non-homogeneous barrier islands like Hatteras, North Carolina, the theoretical position of the fresh-water/salt-water interface as determined from the level of fresh-water head is not valid. Harris (1967) noted 2.4 meters (m) of hydraulic head at Hatteras corresponded to 39.6 m of fresh water below sea level, not 97.6 m below sea level as predicted by the Ghyben-Herzberg relationship. The base of the fresh-water lens was instead limited by a clay layer which prohibited further infiltration of fresh water. Stratification of fresh and saline water above the interface at Hatteras was attributed to flushing of salt water from permeable sediments, while less permeable sediments retained salt water. In contrast, studies in carbonate systems of the effect of permeability on fresh-water/salt-water interfaces (Vacher, 1978; 1988; Cant and Weech, 1986; Ayers and Vacher, 1986; Anthony *et al.*, 1989) have shown fresh-water lens thickness to be greater in lower permeability formations. In higher permeability formations, thickness of the transition zone is greater where mixing is more thorough.

Study Area

Grand Isle is a barrier island located along the north-central coastline of the Gulf of Mexico in southeastern Louisiana approximately 76 km south of New Orleans (Figure 1). Conatser (1969; 1971) described Grand Isle as an elongated barrier island approximately 12 kilometers (km) long and 1.2 km wide with a smooth straight beach and an irregular shoreline. The island trends from southwest to northeast and is the most westerly and last in a chain of islands separating the Gulf of Mexico from Caminada Bay, Bayou Rigaud, and Barataria Bay.

Five geomorphic provinces were identified by Conatser (1969; 1971) at Grand Isle: beach, dune, ridge and inter-ridge, marsh, and wash-over fan. The beach province is generally narrow and parallels the present coastline except where jetties influenced deposition of sand carried by the littoral drift. Dunes, 2 m high, parallel the beach and extend along most of Grand Isle. Approximately 35 separate ridge units

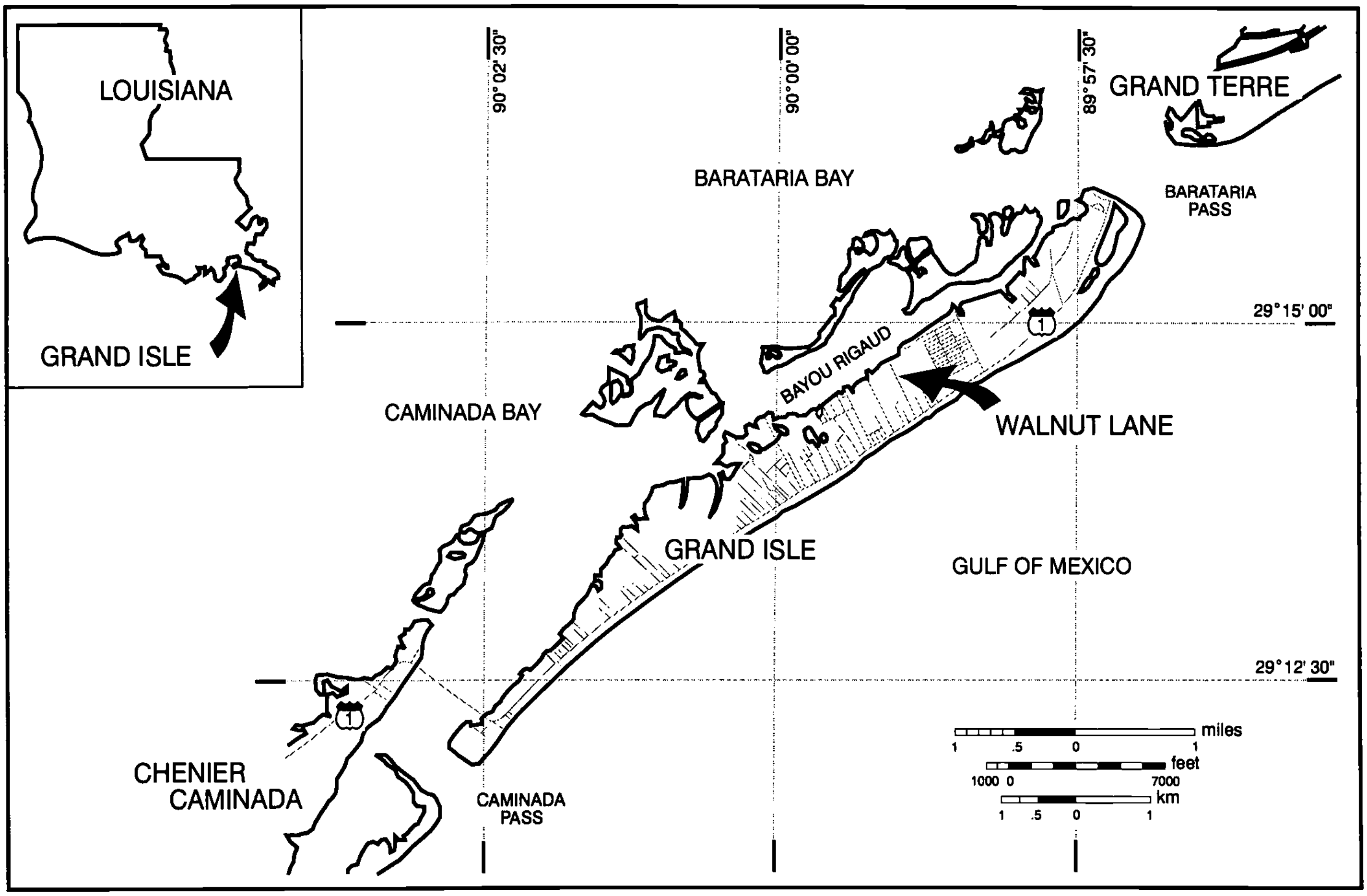

Figure 1. Location Map of Grand Isle, Louisiana (modified from USGS Grand Isle, Barataria Bay, Caminada Bay, and Bay Tambour topographic quadrangles).

were identified. Near the center of the island, 15 complete ridge and inter-ridge suites were delineated ranging from 15 to 50 m apart. The ridge features are generally long and lenticular and originate from the southeast extent of the island where they extend roughly parallel to the present shoreline before curving toward the lagoonal shoreline at their northwest terminus. Ridges represent ancient spring-tide or storm-berm deposits or stranded dune-ridge deposits. The orientation of the ridge features suggests Grand Isle formed from seaward and northeastward accretion of sediments transported by littoral currents from southwest to northeast. Marsh deposits dominate the lagoonal shoreline of the island; whereas, one wash-over fan deposit was identified on the southeast portion of Grand Isle. Conatser (1969; 1971) related changes in grain-size distribution among geomorphic provinces, or between localized environments within a single province, to sediment source, transport distance, and depositional processes.

Four sand bodies were identified at Grand Isle by Conatser (1969; 1971): "A" Sand, "B" Sand, "C" Sand, and "D" Sand (Figure 2). Conatser suggests the subsurface strata delineated at Grand Isle are related to the Mississippi River deltaic progradation and the Holocene marine transgression. The "A" Sand represents the most recent episode of barrier-island and nearshore-marine sand deposition. It was deposited in the last 700 years as sediments eroded from the Bayou Lafourche lobe of the Lafourche delta complex were transported to the northeast via littoral currents. The "B" Sand was deposited approximately 1000 years ago and is related to sediments eroded from the fourth lobe of the Lafourche delta complex. Although no evidence of subaerial exposure exists in the "B" Sand, the elongated geometric distribution of the "B" Sand and marked thickening near the eastern end of the island supports a barrier-island depositional environment. A more planar configuration would be expected if the "B" Sand was deposited exclusively in a nearshore- marine environment. The "C" Sand was deposited approximately 1900 years ago in the nearshore-marine environment immediately offshore from the Bayou Blue lobe of the Lafourche delta complex. The "D" Sand was interpreted to directly overlie Pleistocene-age clay and is considered to represent

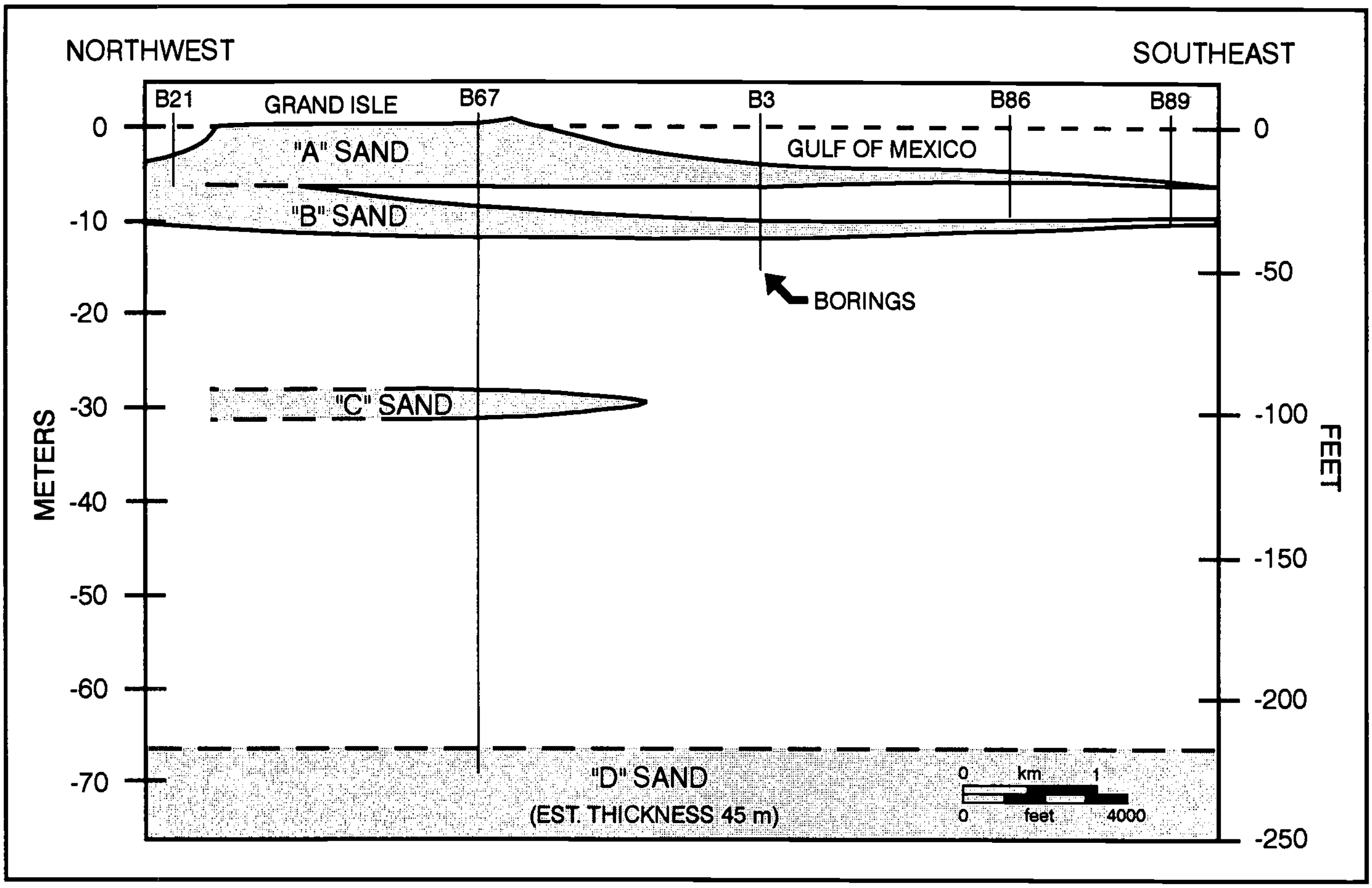

Figure 2. Cross-Section Along the Short-Axis of Grand Isle Showing Holocene Sand Bodies ["A," "B," "C," and "D" Sands (from Conatser, 1969; 1971)]. This cross-section is located near and closely parallels the Walnut Lane study site. Borehole B67 is located near the intersection of Walnut Lane and Highway 1.

the basal sand associated with the marine transgression occurring after the last period of glaciation. Because of the relative depths to the four sand bodies delineated by Conatser (1969; 1971), the "A" and "B" Sands were considered the primary targets of cone-penetrometer testing conducted at Grand Isle in this study.

METHODS

An investigation of the unconfined aquifer at Grand Isle was undertaken involving three main steps: (1) cone-penetrometer testing, (2) water sampling, and (3) development of a variable-density solute-transport model calibrated to the hydrogeologic conditions observed at Grand Isle. Several observation wells provided additional data for verification of data obtained during cone-penetrometer testing.

Cone-Penetrometer Testing

A cone-penetrometer survey was conducted across Grand Isle in October, 1993. A cone-penetrometer rig is a truck-mounted system that hydraulically pushes into the ground a metal rod equipped with geophysical instruments, simultaneously measuring resistance on the tip of the rod and drag along its sleeve. The ratio of tip resistance and sleeve friction, recorded with depth, permit classification of sediment type (Douglas and Olsen, 1981; Robertson and Campanella, 1983a; 1983b). In this survey, the cone penetrometer was also equipped for measuring electrical conductivity with depth so that thickness and extent of the fresh-water lens and transition zone could be delineated. Ten cone-penetrometer soundings were taken along the short-axis of Grand Isle on the city-owned right-of-way of Walnut Lane (Figure 3). The ground elevation at each sounding was surveyed to within 0.003 m of the known elevation of Louisiana Department of Transportation and Development benchmark Z-222.

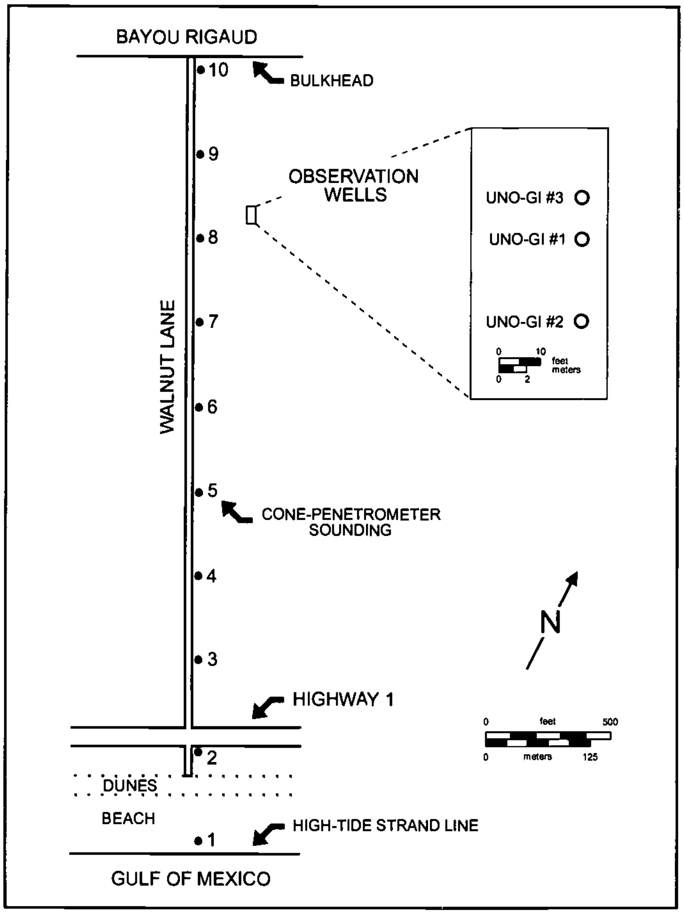

Figure 3. Walnut Lane Study Site, Grand Isle, Louisiana.

Walnut Lane proved to be an ideal location because it allowed for cone-penetrometer testing to be conducted completely across Grand Isle, from the Gulf of Mexico to Bayou Rigaud, at one of the widest parts of the island. Sounding No. 1 was taken on the beach, approximately 15 m from the high-tide strand line of the Gulf of Mexico. Sounding No. 10 was taken approximately 15 m from the bulkhead at Bayou Rigaud. The remaining soundings were equally spaced at 100.5 m except where surface accessibility required Soundings No. 1 and No. 2 to be separated by 106.7 m and Soundings No. 2 and No. 3 to be separated by 111.6 m. Walnut Lane is relatively undeveloped. With the exception of homes along the beach and a number of commercial warehouses servicing the offshore oil and gas industry along Bayou Rigaud, surface conditions and vegetation are relatively unaltered at the study site. Fill material, used when draining marsh land, characterizes the surface in some areas along the lagoonal shoreline of Grand Isle.

Water Sampling

Water samples were collected from the fresh-water and salt-water zones of the unconfined aquifer at Grand Isle as well as from the Gulf of Mexico and Bayou Rigaud. Samples from the aquifer were obtained using a variation of the cone penetrometer known as a push-in well screen. Water samples were recovered from the push-in well screen by lowering a conventional bailer through the hollow push rods. Ground-water samples were obtained to correlate ground-water salinity to electrical conductivity and to verify the presence of separate fresh-water and salt-water zones observed through cone-penetrometer testing. Ground-water samples were also used to establish a relationship between density and concentration required for solute-transport modeling. Ground-water samples from the unconfined aquifer at Grand Isle were obtained at the location of Sounding No. 4. A sample from the fresh-water zone was collected approximately 2.3 m below the ground surface. A sample from the salt-water zone was taken approximately 7.9 m below the ground surface. The Gulf of Mexico sample was collected from the surf zone at the southeastern end of Walnut Lane. The sample from Bayou Rigaud was collected off the bulkhead at the northwestern end of Walnut Lane.

The concentration of total dissolved solids in each sample was determined using standard evaporative techniques (USGS, 1989; I-1749-85). The concentrations of Na^+ and Cl^- in each sample were determined using flame atomic absorption (USGS, 1989; I-1735-85) and titration methods (USGS, 1989; I-1183-85), respectively. The volume and weight of each sample were measured, and the density was determined using a pycnometer. Electrical conductivity of each water sample was measured using a digital conductance meter.

Variable-Density Solute-Transport Modeling

A variable-density solute-transport model was developed, consistent with observed sediment type and positions of the fresh-water lens and transition zone across the island, to understand the flow field and dispersive processes responsible for formation of the fresh-water lens at Grand Isle. In this study, the unconfined aquifer at Grand Isle was modeled using Saturated-Unsaturated-TRAnsport (SUTRA), a ground-water modeling program developed by the United States Geological Survey (Voss, 1984).

SUTRA is capable of simulating fluid movement and transport of a single species of dissolved solids through the saturated or unsaturated subsurface. SUTRA employs two- dimensional hybrid finite-element and integrated finite-difference techniques to determine change in fluid pressure and solute concentration with time throughout the modeled system. Most important to this study is the ability of SUTRA to simulate: (1) density- dependent fluid flow, which varies as a function of solute concentration; and (2) solute dispersion which is responsible for mixing of the fresh water and salt water in the unconfined aquifer at Grand Isle. Because of dependence of fluid flow upon density and solute concentration, SUTRA requires input of pressure and permeability as opposed to hydraulic head and hydraulic conductivity.

A vertical-slice cross-sectional model of the unconfined aquifer at Grand Isle was developed through construction of a mesh of 30 rows and 72 columns (Figure 4). The resulting grid network consists of 2160 elements, the corners of which are defined by 2263 nodes. Each element has dimensions of 12.7 by 0.3 by 0.3 m. The modeled grid is oriented so that the x-axis corresponds to the southeast to northwest trend of the cone-penetrometer survey conducted along the short-axis of Grand Isle. Sea level designates the upper boundary. A depth of 9.15 m below sea level designates the lower boundary of the model. The southeast and northwest lateral boundaries of the model are formed by Soundings No. 1 and No. 10, respectively.

Boundary Conditions. Boundary conditions were specified for lateral, lower, and upper boundaries of the SUTRA model. For nodes defining the lateral boundaries, values were assigned for constant fluid pressure and for solute concentration of any fluid entering the system. Profiles of electrical conductivity at Soundings No. 1 and No. 10 were used to determine depths defining the thickness of the fresh-water lens and transition zone at each lateral boundary. A solute-concentration value equal to that of the

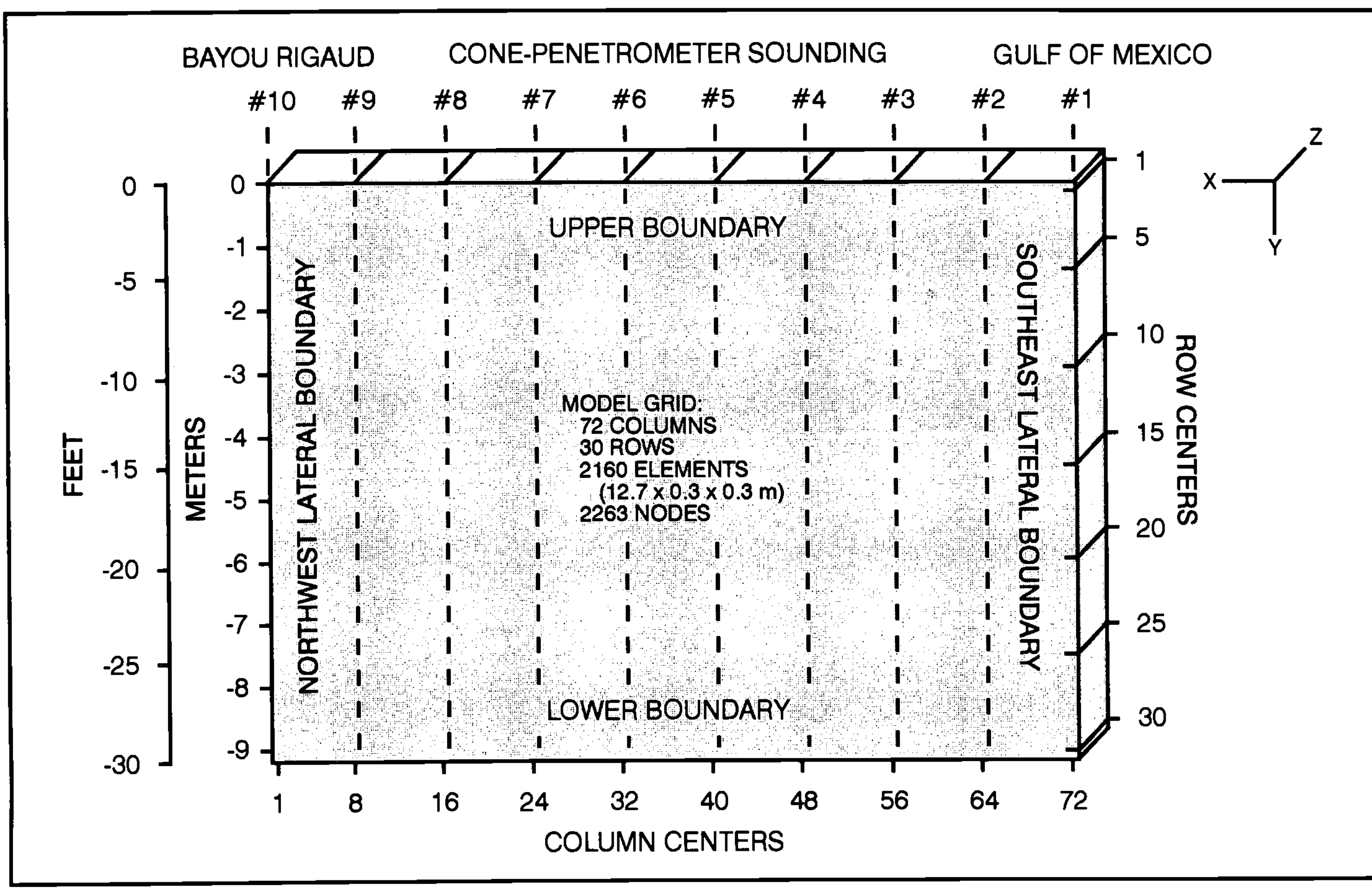

Figure 4. SUTRA Vertical-Slice Cross-Sectional Model of the Unconfined Aquifer at Grand Isle. The model grid is oriented so that the x-axis corresponds to the trend of the cone-penetrometer survey conducted along the short-axis of Grand Isle at Walnut Lane.

fresh-water sample taken from the aquifer, 0.000396 kilogram solute per kilogram (kg_s/kg), was assigned to fluid entering the system at nodes occupying depths from the upper model boundary to the top of the transition zone. A solute-concentration value representative of salt water was assigned to fluid entering the system at nodes occupying depths from the lower model boundary to the base of the transition zone. In these cases, the concentration determined for the Gulf of Mexico water sample (0.030835 kg_s/kg) was used. For fluid entering the system at nodes along the lateral boundaries occupied by the transition zone, a solute concentration value was determined by linear interpolation between the representative fresh-water and salt-water concentration values. Once solute concentration values were determined for each node along the lateral boundaries, corresponding values of fluid density were calculated using the following relationship (Voss, 1984), where concentrations are expressed as mass fraction:

$$\rho = \rho_0 + [(C-C_0)\ \partial\rho/\partial C], \qquad (1)$$

where ρ = fluid density [(kg dissolved solids)/(kg fluid)] at solute concentration C in kg/m^3; ρ_0 = fluid density [(kg dissolved solids)/(kg fluid)] of the base fluid with solute concentration C_0; and $\partial\rho/\partial C$ = constant value of density change with change in concentration, equal to 700 $kg^2/(kg{\cdot}m^3)$ when $\rho_{salt\ water}$ = 1025 kg/m^3, ρ_0 = 1000 kg/m^3, $C_{salt\ water}$ = 0.0357 kg_{salt}/kg_{fluid}, and C_0 = 0 kg_{salt}/kg_{fluid}.

Values of fluid pressure were then calculated for nodes defining the lateral boundaries as follows:

$$P = P_0 + (\rho g \Delta z), \qquad (2)$$

where P = fluid pressure, P_0 = hydrostatic fluid pressure at sea level, ρ = fluid density, g = gravitational acceleration, and Δz = change in elevation.

Values of constant fluid pressure and solute concentration for any fluid entering the system were also assigned to nodes occupying the lower model boundary. Given that profiles of electrical conductivity obtained during cone-penetrometer testing across Grand Isle showed the lower model boundary to be well below the base of the transition zone, a solute concentration value representative of Gulf of Mexico sea water (0.030835 kg_s/kg) was assigned to all nodes occupying the lower model boundary. Because mounding of the water table is expected near the center of the island, the fluid pressure at sea level is also expected to be greater near the center of the island. When hydrostatic conditions are assumed, greater fluid pressure occurs along the lower model boundary near the center of the island. To simulate mounding of the water table, the fluid pressure of greatest magnitude was assigned to the node designating the center of the lower model boundary. The remaining fluid pressure values along the lower model boundary were determined by interpolation in a symmetrical mound-like fashion from the fluid pressure value at the center of lower model boundary to the fluid pressure value determined at the base of each lateral boundary. In terms of hydraulic head, the magnitude of mounding of fluid pressure values at the center of the lower model boundary equals approximately 0.15 m, if fresh-water density is assumed.

The upper boundary of the model is an inflow boundary where recharge of a specified concentration is allowed to enter the system. Fluid entering the system at nodes occupying the upper model boundary were assigned solute-concentration values representative of the fresh-water sample obtained from the aquifer (0.000396 kg_s/kg). Fluid- pressure values were generated for each node along the upper model boundary during each SUTRA simulation.

Initial Conditions. Initial concentration conditions assumed island sediments were deposited completely saturated with salt water. A solute-concentration value equal to that of the Gulf of Mexico water sample (0.030835 kg_s/kg) was assigned to every node in the modeled system. Salinity of the Gulf of Mexico near the Mississippi River varies with river discharge (Cochrane and Kelly, 1982; Rezak *et al.*, 1985). A salinity of 0.030835 kg_s/kg is typical of waters offshore of Grand Isle in December and most likely represents the upper end of the range of seasonal variation in salinity of the northern Gulf of Mexico. Using Equation (1), a fluid density was calculated for the Gulf of Mexico water sample. Assuming salt-water hydrostatic conditions, fluid-pressure values were then calculated for each node using the relationship between fluid pressure and fluid density described in Equation (2). As with boundary conditions, mounding of the water table near the center of Grand Isle, as indicated by estimations of water-table elevation from cone-penetrometer soundings, was simulated by increasing the fluid pressure at the center of the island and interpolating to the initial fluid pressure determined for the uppermost node at each lateral boundary in a symmetrical mound-like fashion.

Aquifer Parameters. SUTRA requires a permeability value as input for each element in the modeled system. Permeability was initially estimated for each element using the variation in sediment type determined by cone-penetrometer testing. Using a range of permeabilities specified by Domenico and Schwartz (1990) for various sediment types, a permeability was assigned to each element of the model. The spatial distribution of sediment type used during SUTRA modeling is represented on Figure 5.

In the absence of field data, reasonable assumptions were made for other aquifer parameters required to perform a SUTRA simulation such as recharge, coefficients of molecular diffusion and dispersivity, porosity, and total simulation period. Given sources (i.e., Manning, 1992) which report both precipitation and evapotranspiration in southeastern Louisiana to average 1.5 meters per year (m/yr), a value of recharge equal to 2.5 centimeters per year (cm/yr), or 17 percent of total precipitation, was assigned initially to the upper model boundary. This parameter required significant adjustment during calibration. The coefficient of molecular diffusion was estimated initially to equal 1.0×10^{-9} meters squared per second (m^2/s) (Voss, 1984; Domenico and Schwartz, 1990). Initial estimates for coefficients of longitudinal and transverse dispersivity were 1 m and 0.5 m, respectively. These values are reasonable given the range of dispersivities of 0.1 to 2 m reported for field experiments over short transport distances (Domenico and Schwartz, 1990). An average porosity value equal to 35 percent was used initially. The total simulation period was set equal to 30 years. Longer simulations were tested for significant differences, but none were found.

Calibration Procedure. Once boundary conditions were established and initial aquifer parameters

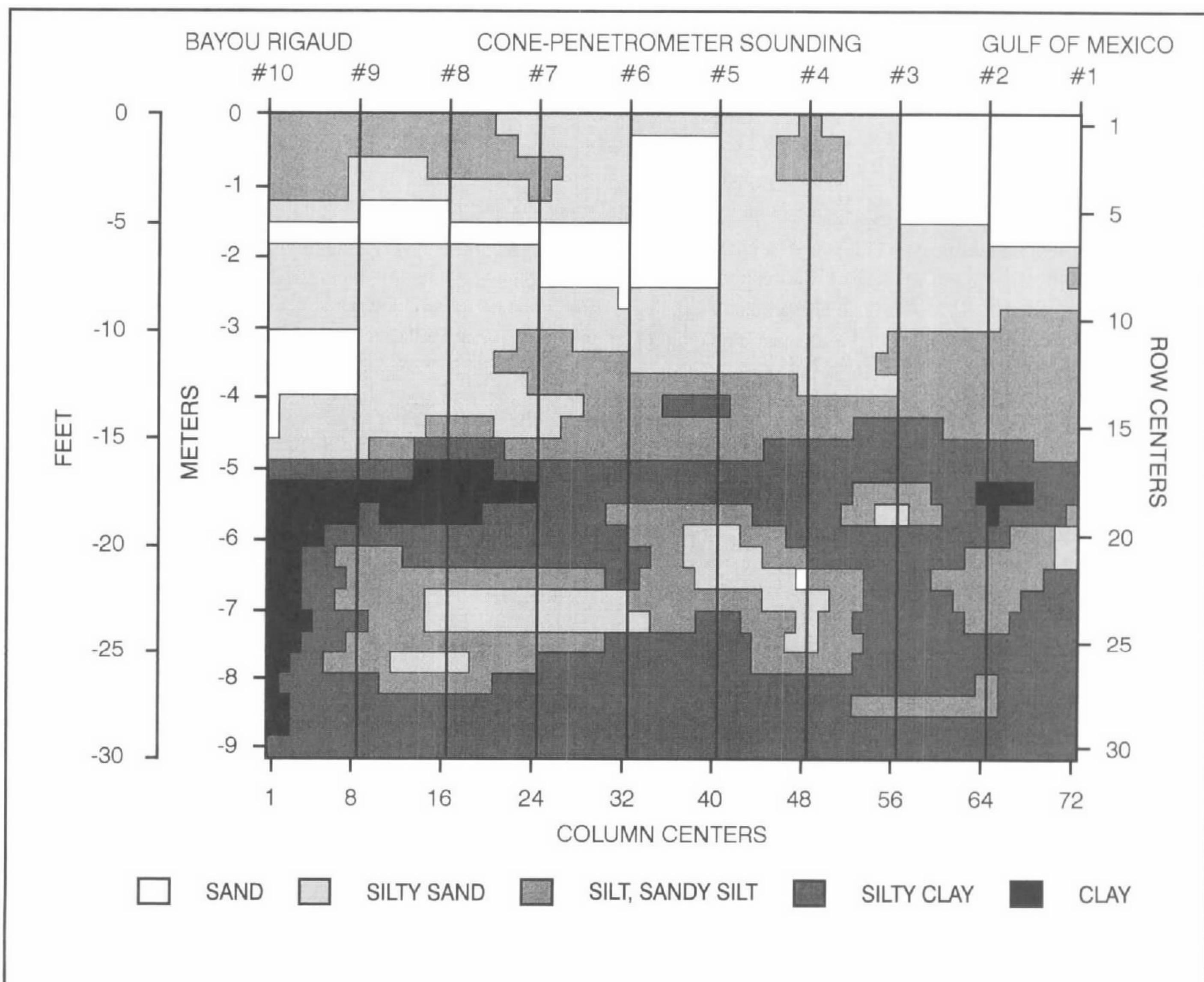

Figure 5. Spatial Distribution of Sediment Type Used During SUTRA Modeling.

were defined, the model was calibrated through a series of SUTRA simulations until reasonable agreement was achieved between the observed and modeled position and shape of the transition zone across Grand Isle. The position and shape of the observed transition zone at Grand Isle were determined using profiles of electrical conductivity with depth which were acquired during cone-penetrometer testing. For each electrical-conductivity profile, elevations defining the top and base of the transition zone across the island were selected. The modeled position of the transition zone was determined using the values of solute concentration which were calculated at each nodal site during each SUTRA simulation. To make comparison between the observed and modeled position of the transition zone easier, the predicted solute-concentration values for each SUTRA simulation were converted to percent salt water and contoured assuming the concentration of sea water equals 0.035700 kg_s/kg. For purposes of calibration, it was assumed that the 10 percent sea-water contour represents the top of the transition zone; while, the base of the transition zone was assumed to be the 80 percent sea-water contour.

The model was calibrated through an iterative process in which permeability, recharge, dispersion, and total simulation time were varied over a range of values. Permeability values of individual elements were always varied within a range of values which reflected the sediment type determined to be representative of a particular element (Figure 5). Recharge into the model was varied to reflect changes in permeability relative to sediment type near the upper model boundary. Dispersivity and molecular diffusion, the variables contributing to total dispersion, were varied to adjust the degree of mixing and to constrain the thickness of the transition zone. For any given combination of these variables, the total simulation time was varied to promote flushing and to allow for complete formation of the fresh-water lens across Grand Isle. Conversion of predicted fluid pressure values along the upper model boundary to hydraulic head provided a final measure of model calibration.

Observation Wells

Three observation wells were drilled in-line and adjacent to the cone-penetrometer survey conducted at Walnut Lane (Figure 3) in April 1994. Although these wells primarily were drilled to study the pumping response of the fresh-water lens and were completed after cone-penetrometer testing, they provided an additional source of data for this study. Sediment samples obtained during drilling were used to verify sediment-type classifications made using cone-penetrometer data. By lowering an electrical-conductivity probe to total depth, changes in groundwater salinity with depth were measured and compared with electrical-conductivity profiles obtained during cone-penetrometer testing. Water-level measurements were taken, and slug tests were performed to determine hydraulic conductivity of the unconfined aquifer immediately around the well bore. These data provided an additional tool for measuring calibration of the variable-density solute-transport model presented in this study.

RESULTS

Profiles of cone-penetrometer data were constructed for each sounding. In Figure 6, the cone-penetrometer data recorded at Sounding No. 1 is plotted versus depth. This plot shows the change in tip resistance, sleeve friction, and electrical conductivity measurements recorded with depth. It also shows change in friction ratio with depth, the basis of sediment-type classification using cone-penetrometer methods (Douglas and Olsen, 1981; Robertson and Campanella, 1983a; 1983b). In the right-hand track, a lithologic profile shows the change in sediment type observed with depth where sand, silty sand, silt, silty clay, and clay are each represented by a different pattern.

Through correlation of individual lithologic profiles for each cone-penetrometer sounding, a cross-section was constructed to show the variability of sediment type with depth and laterally across Grand Isle (Figure 7). Three separate lithologic units, primarily composed of sand and silty sand, were penetrated during cone-penetrometer testing at Grand Isle. Each of these lithologic units are in turn separated from one another by lithologic units primarily composed of silty clay and clay. For purposes of this study, the sand-rich lithologic units are referred to as the Upper, Middle, and Lower Sands; while, the clay-rich lithologic units are referred to as the Upper, Middle, and Lower Clays.

A cross-section of electrical conductivity was constructed to demonstrate the change in thickness of the fresh-water lens and transition zone across Grand Isle (Figure 8). The fresh-water lens is thin near the center of Grand Isle. Along the flanks of the island, the thickness of the fresh-water lens increases significantly. The character of the transition zone also changes along the transect. In some instances, such as at Soundings No. 7 and No. 8, a sharp transition zone is present where the change from fresh water to salt water occurs in less than a meter. At other soundings, such as Sounding No. 4, the transition zone is quite gradual and develops over a distance of several

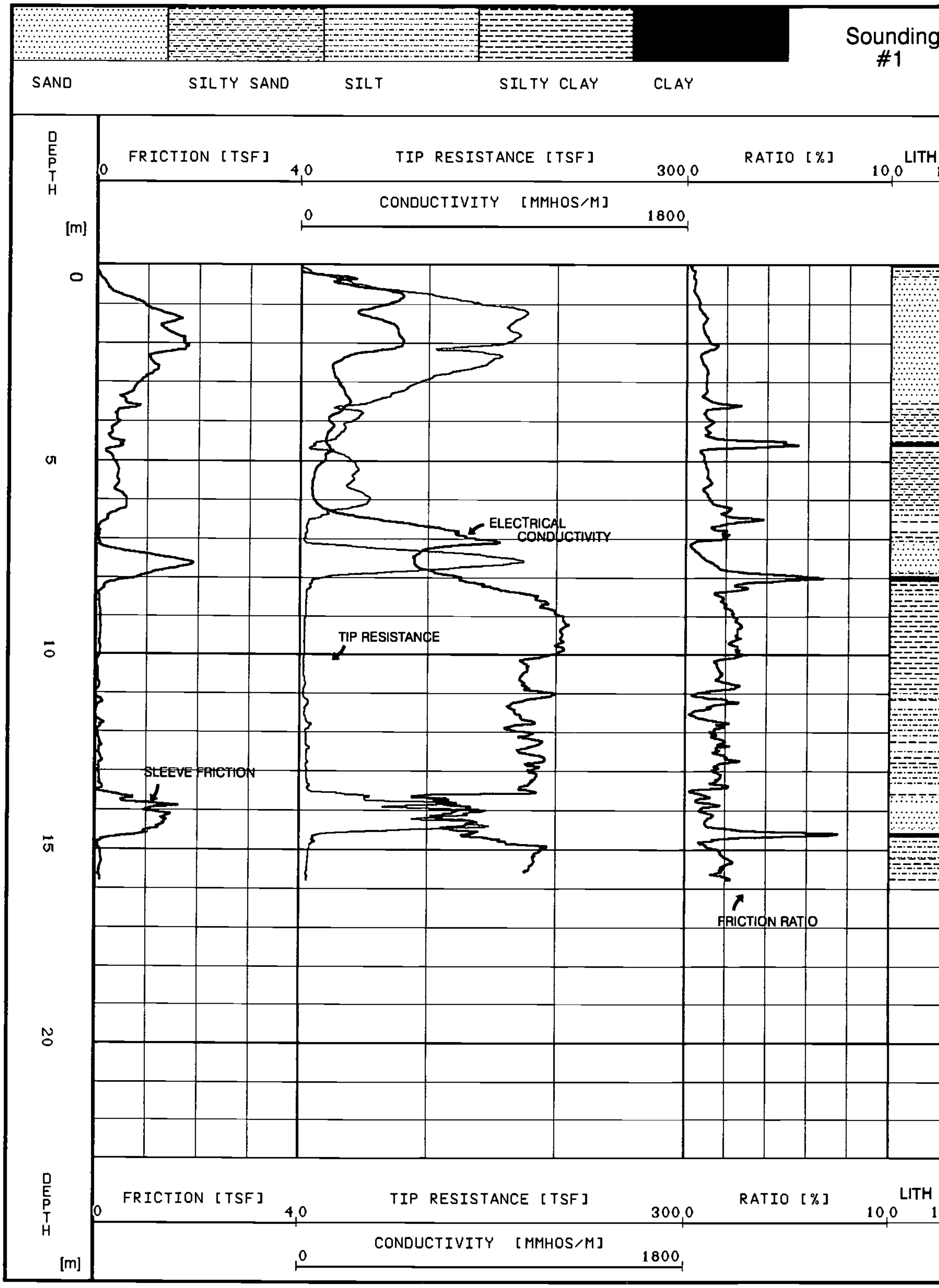

Figure 6. Example of Cone-Penetrometer Log from Sounding No. 1.

meters. Still other soundings are characterized by a transition zone where the rate of change in salinity is not constant but changes several times, such as at Soundings No. 5 and No. 9.

Results of water analyses of samples collected from within the fresh-water and salt-water zones of the unconfined aquifer at Grand Isle and from the adjacent Gulf of Mexico and Bayou Rigaud are presented

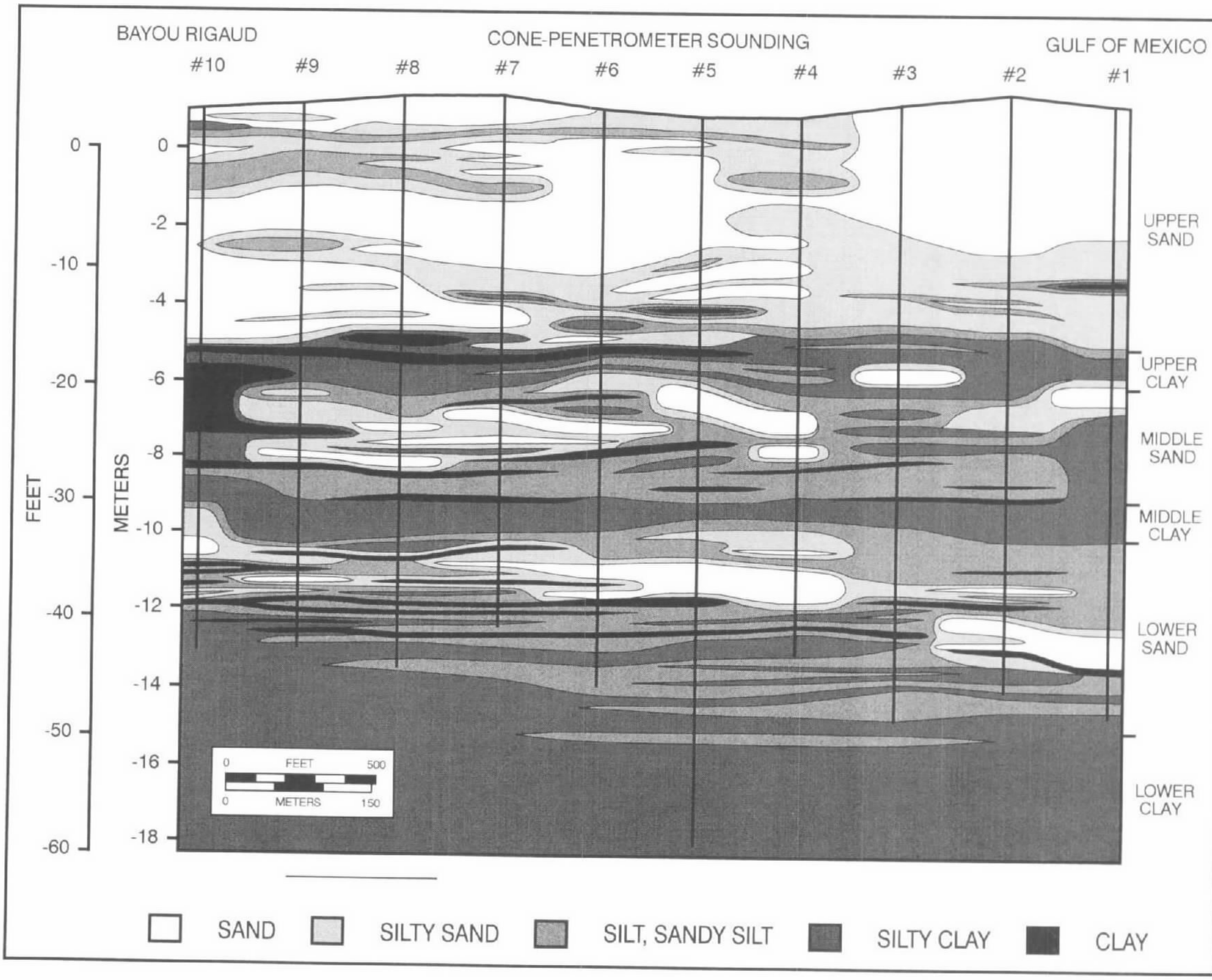

Figure 7. Cross-Section Showing Lithologic Variability Across Grand Isle.

in Table 1. Most important to this study is the measurement of total dissolved solids which directly affects the electrical conductivity of the sample. In terms of percent sea water, assuming the concentration of sea water equals 0.035700 kg_s/kg, the concentration of total dissolved solids in the Gulf of Mexico sample equates to 86 percent sea water at the time of sampling. The Bayou Rigaud sample equates to 54 percent sea water at the time of sampling. Samples obtained from the fresh-water and salt-water zones of the unconfined aquifer at Grand Isle are equivalent to 1 percent and 40 percent sea water, respectively. Nearly identical values of percent sea water are determined using the concentration of Na^+ and Cl^- determined to be present in each sample. The stepwise increase in percent sea water observed to exist among water samples analyzed in this study is also reflected in the measurements of density and electrical conductivity.

The final modeled calibrated match between the observed and simulated position of the fresh-water lens and transition zone across Grand Isle is shown in Figure 9. Contours of concentration in terms of percent sea water define the simulated position of the transition zone. The observed position of the top and base of the transition zone as determined at each cone-penetrometer sounding are annotated for comparison. Values of recharge used to generate the final calibrated model as well as predicted hydraulic head values at each cone-penetrometer sounding location are also denoted along the upper model boundary. The spatial distribution of permeability values assigned to each element within the final calibrated model is shown in Figure 10. Based on the final calibrated

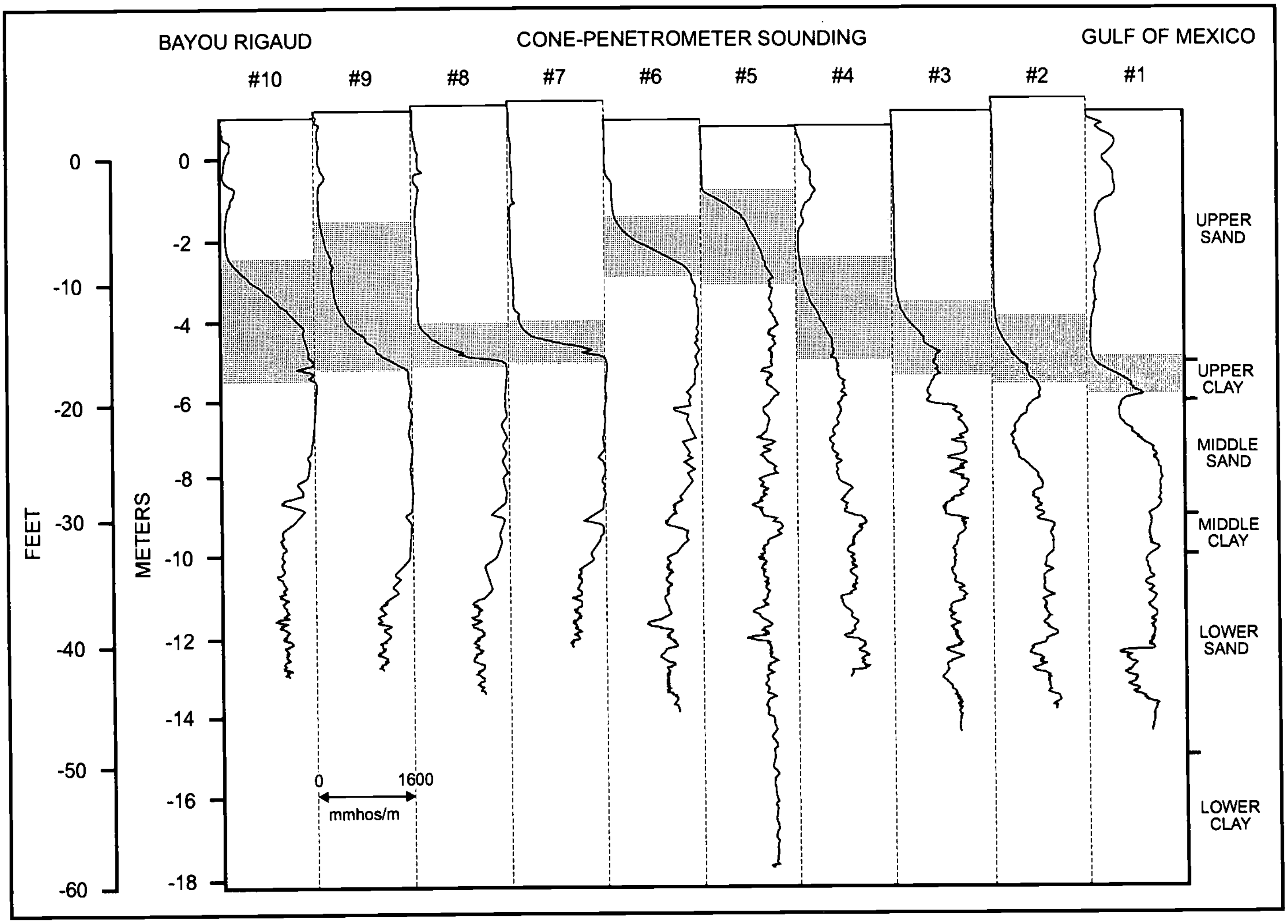

Figure 8. Cross-Section Showing Variation in Electrical Conductivity Across Grand Isle. The shaded area distinguishes the thickness of the transition zone at each cone-penetrometer sounding from the overlying fresh-water lens and underlying salt water.

TABLE 1. Results of Water Analyses for Grand Isle Samples. Samples were taken from the Gulf of Mexico and Bayou Rigaud as well as the fresh-water and salt-water zones of the unconfined aquifer at Grand Isle.

	Total Dissolved Solids				Sodium		Chloride		Density
Sample	mg/L	% Sea Water	ppm	% Sea Water	ppm	% Sea Water	g/cc	ohm-m	mmhos/m
Gulf of Mexico	30,835	86.1	8,900	82.7	16,081	83.1	1.01987	0.19	5270
Bayou Rigaud	19,349	54.2	5,760	53.5	10,175	52.6	1.01219	0.29	3480
Fresh-Water Zone	396	1.1	179	1.7	167	0.9	0.99812	8.85	113
Salt-Water Zone	14,475	40.6	4,315	40.1	7,991	41.3	1.0081	0.4	2516
Average Sea Water	35,700	100	10,760	100	19,350	100	1.025	–	–

model, a vector map showing the pattern of fluid flow is presented in Figure 11, where the relative magnitude of fluid velocity and direction of fluid flow are represented. The vector map depicted in Figure 11 does not account for any effects on fluid flow originating from directions out of the plane of the model, or for any seasonal changes in salinity of Bayou Rigaud or the Gulf of Mexico which may influence the velocity

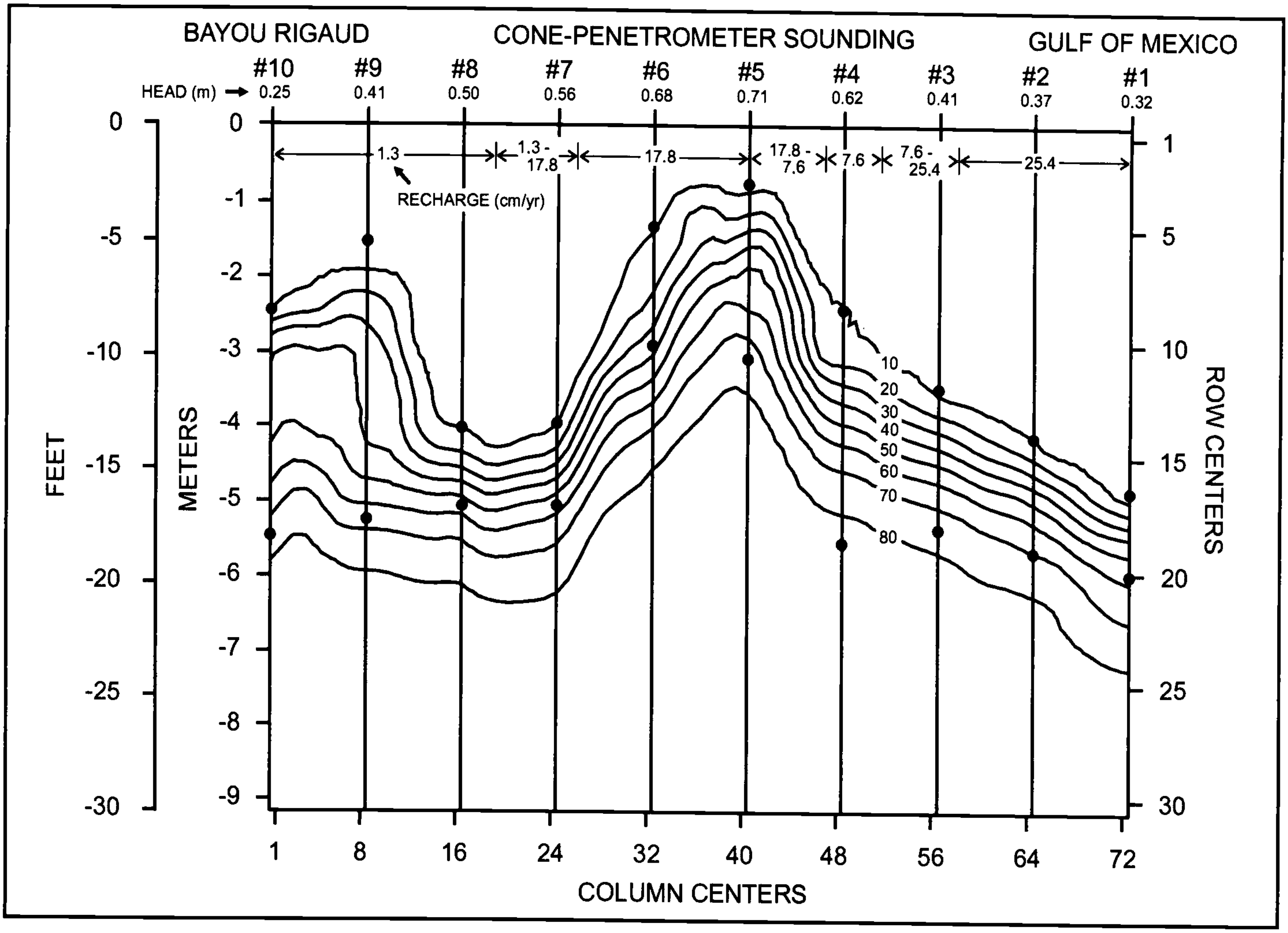

Figure 9. Concentration Cross-Section for Final Calibrated Model Showing the Observed and Simulated Position of the Fresh-Water Lens and Transition Zone Across Grand Isle. Contours are in terms of percent sea water.

at which fresh water discharges from the lateral boundaries of the model.

Water level elevation measured in the observation wells ranges from 0.25 m above sea level in April 1994 to 0.18 m above sea level in May 1994. Permeability values, calculated using the Bouwer and Rice method of slug test analysis (Bouwer and Rice, 1976; Bouwer, 1989), range between 1.14 x 10^{-12} and 2.65 x 10^{-12} meters squared (m^2). Profiles of electrical conductivity measured in each observation well are contained in Figure 12. The top of the transition zone recorded in the UNO-GI No. 2 well compares favorably with that observed in the nearest cone-penetrometer test, Sounding No. 8. A poor completion job resulted in stagnant conditions in the UNO-GI#1 well, and the UNO-GI No. 3 well was not drilled to sufficient depth to show the transition from fresh water to salt water.

DISCUSSION

Cone-penetrometer testing was used in this study to classify sediment type, obtain water samples, and delineate the fresh-water lens and transition zone at Grand Isle. A primary advantage of cone-penetrometer testing over conventional methods is greater resolution of sediment type. Most conventional methods of obtaining samples of soft sediments such as a split-spoon or Shelby tube result in incomplete or partial coverage at best. With cone-penetrometer testing, a determination of sediment type is made for every 2 cm interval, providing a virtually continuous measure of changing sediment type with depth. A second advantage of cone-penetrometer testing is better resolution of the position of the fresh-water lens and nature of the transition zone. Measurements of electrical conductivity were also recorded at 2 cm

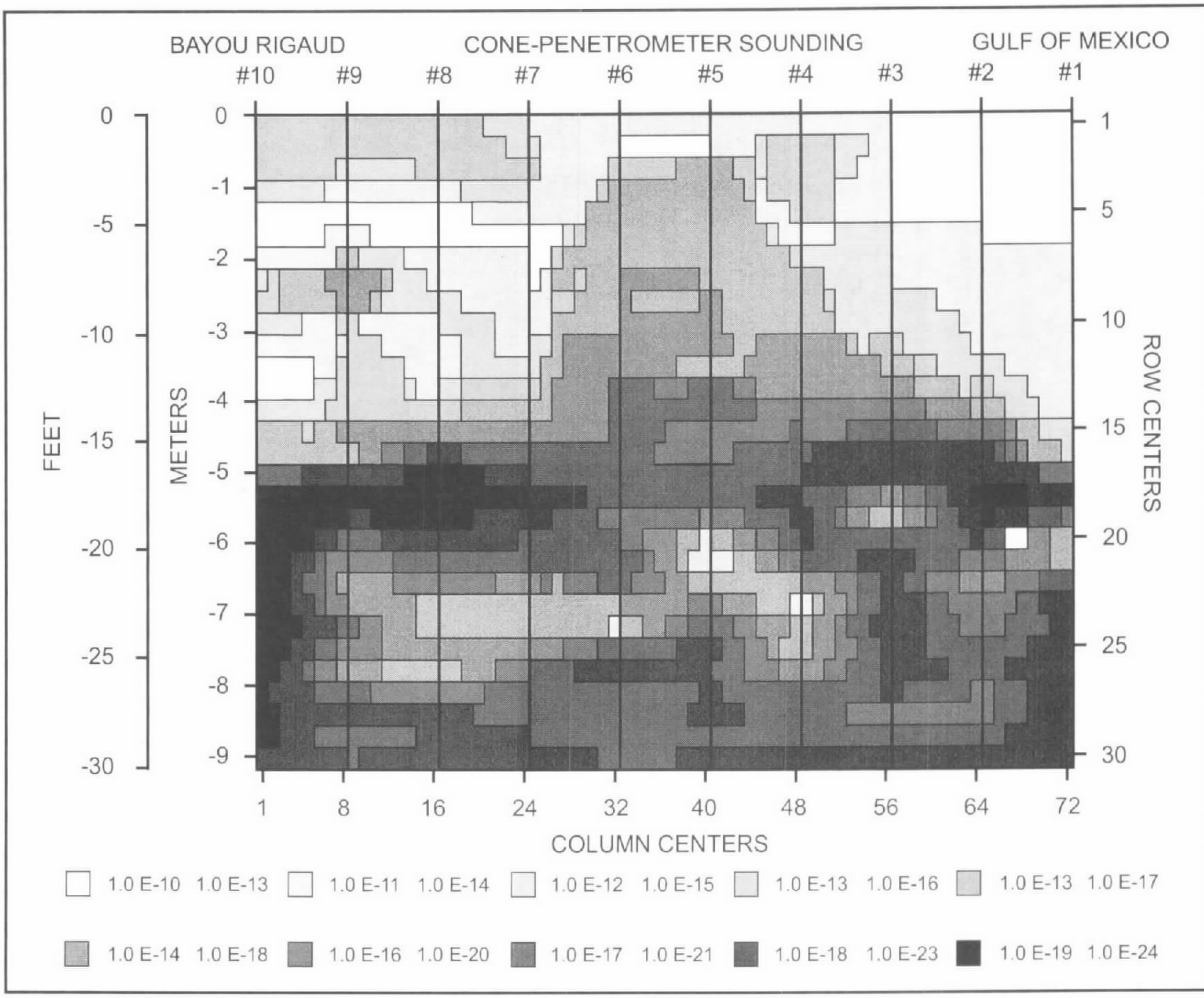

Figure 10. Spatial Distribution of Element-Wise Permeability Values for the Final Calibrated Model. Legend shows permeabilities in the x and y directions.

intervals in each of the ten cone-penetrometer soundings conducted across Grand Isle. As a result, a continuous profile of changing salinity with depth was obtained at each sounding location. Because measurements of electrical conductivity are made in-situ during cone-penetrometer testing, many of the problems encountered while using conventional methods to determine ground-water salinity at discrete intervals are avoided.

Many previous studies of the fresh-water/salt-water interface relied on relatively few observation wells scattered over large field areas (Fetter, 1972; Ayers and Vacher, 1986; Anthony *et al.*, 1989). In a rare case where conditions permitted drilling numerous observation wells (Harris, 1967), all wells were drilled along one side of the island so that across-the-island changes in permeability were not represented. The vertical resolution of change in permeability was also limited by the screened interval used when conducting short-duration pumping tests. Other studies depended on electrical-conductivity profiles obtained in just a few observation wells located outside areas affected by pumping (Vacher, 1978; Rowe, 1984). Where well control was insufficient, Cl^- concentration measured in shallow wells was extrapolated to depth (Anthony *et al.*, 1989), or geophysical methods were used to identify thickness of the fresh-water lens and transition zone (Ayers and Vacher, 1986).

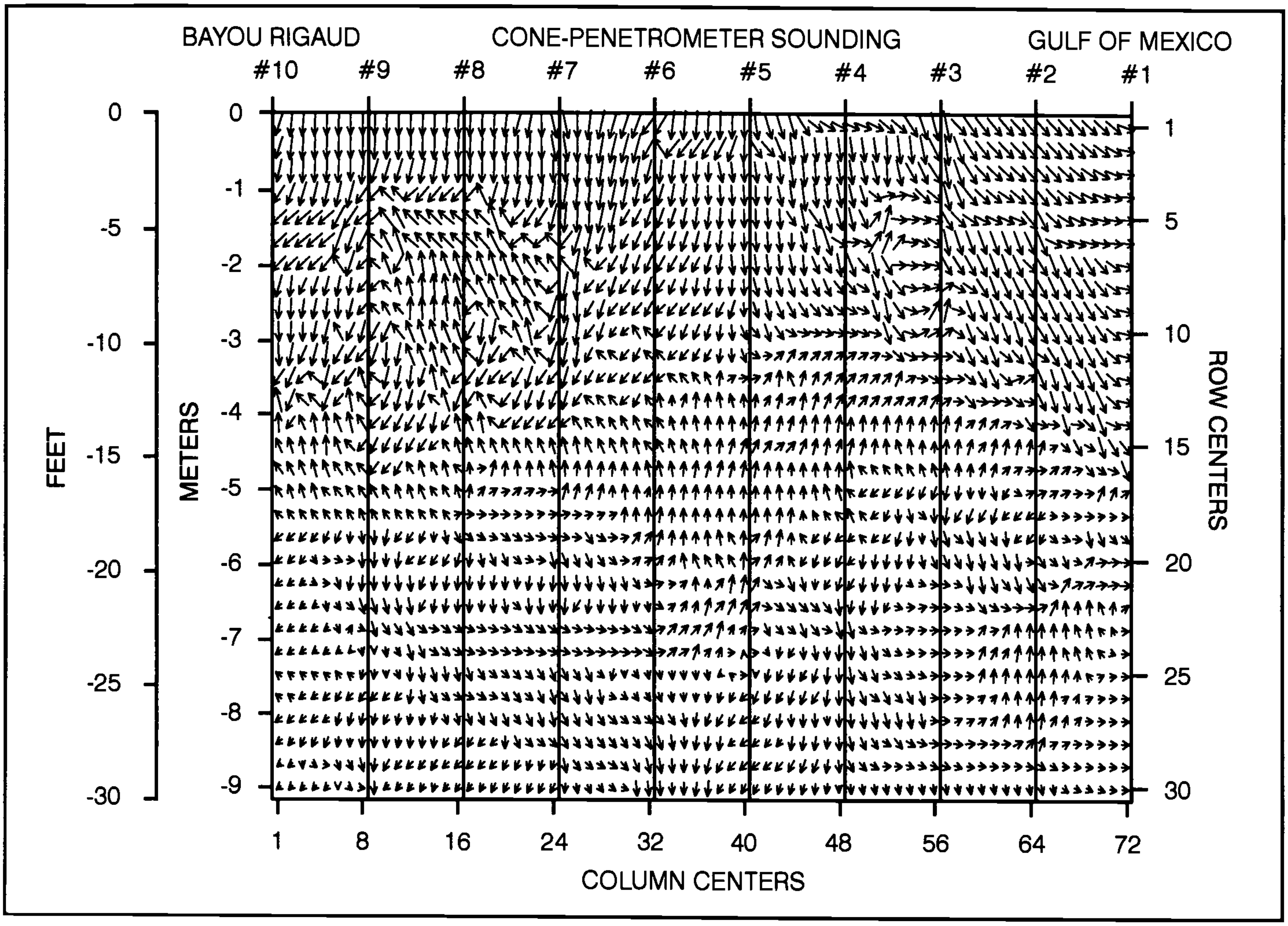

Figure 11. Vector Plot Showing the Pattern of Fluid Flow Across Grand Isle. The arrows indicate the direction of fluid flow. The relative magnitude of fluid flow is represented by the length of each arrow.

Lithologic Variability

The ability to equally space ten cone-penetrometer soundings across Grand Isle provided an opportunity to access stratigraphic variation and to correlate individual lithologic units with confidence across the island. Comparison of the stratigraphy delineated through cone-penetrometer testing in this study with that determined through examination of lithologic logs by Conatser (1969; 1971) results in a better understanding of the geologic history of the island. The Upper Sand defined in this study is undoubtedly the same as the "A" Sand described by Conatser (1969; 1971). Both studies show the uppermost sand body, which is representative of the most recent episode of barrier-island sand deposition, to range in thickness from 4.5 to 6 m across Grand Isle. In addition, the distribution of sand versus finer-grained silty sand determined to be present during cone-penetrometer testing within the Upper Sand supports the conclusion made by Conatser (1969; 1971) regarding the growth pattern of Grand Isle. If Grand Isle grew through seaward and northeastward accretion from an origin located to the southwest as proposed by Conatser (1969; 1971), one would expect the sand-rich beach and dune facies marking the former shoreline of the Gulf of Mexico to migrate through the Upper Sand layer in the same manner. Sounding No. 6 shows an increase of tip resistance with elevation, indicating a gradual upward change in the sand, becoming more dune-like. This pattern of sand deposition is clearly demonstrated in Figure 7 where sand diagonally crosses the Upper Sand. Along the present day Gulf of Mexico shoreline, sand is the predominant sediment type occupying the shallow section of the Upper Sand, while sand dominates the lower section of the Upper Sand in the lagoonward direction along the Bayou Rigaud shoreline. The base of the sand package which cuts across the Upper Sand layer can be thought of as representing the furthest extent of past barrier-island sand deposition into the Gulf of Mexico. Any disruptions to this pattern of sand deposition, such as the isolated lenses of silt penetrated midway through the Upper Sand layer by Sounding No. 9 or at shallow depths by Sounding No. 4, most likely represent channel-fill features cut into the Upper Sand during past storm events. This interpretation seems reasonable considering the shape and limited lateral extent of these predominantly silt lenses.

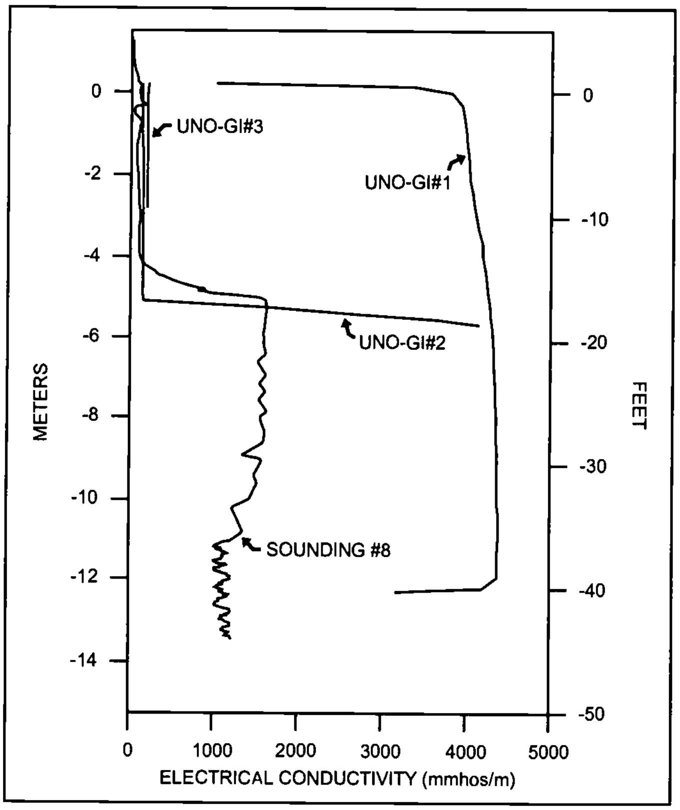

Figure 12. Profiles of Electrical Conductivity Measured in Observation Wells. Shown for comparison is the profile of electrical conductivity obtained at cone-penetrometer Sounding No. 8 which is located nearest the observation wells.

Below the Upper Sand, significant differences were observed between the stratigraphic interpretations of this study and those of Conatser (1969; 1971). Conatser (1969; 1971) described the "B" Sand as ranging in thickness up to 10.5 m and being separated from the "A" Sand by a clay wedge which pinches out toward the lagoonal shoreline so that the "A" and "B" Sands lie directly in contact with one another (Figure 2). No clay wedge was sampled by the cone-penetrometer testing conducted in this study. While the Upper Clay appears to thin in the center of the island, thickness on both flanks of Grand Isle approaches 1.5 m. In addition, two distinct sand bodies, the Middle Sand and Lower Sand, were delineated through cone-penetrometer testing to occupy the interval classified as the "B" Sand by Conatser (1969; 1971). Figure 2 clearly shows the Middle Clay to extend across Grand Isle where it separates the Middle Sand from the Lower Sand. In some areas, thickness of the silty clay which comprises the Middle Clay approaches 1.2 m, which suggests a sustained period characterized by deposition in a low-energy environment. The presence of the Middle Clay suggests that the "B" Sand episode of barrier-island sand deposition described by Conatser (1969; 1971) instead represents two distinct periods of sand deposition.

Fresh-Water Lens and Transition Zone

The most interesting observations afforded through the cone-penetrometer testing conducted at Grand Isle involve the changes in thickness of the fresh-water lens and transition zone across the island (Figure 8). Thickness of the fresh-water lens thins from in excess of 4.5 and 4 m below sea level along the Gulf of Mexico and Bayou Rigaud flanks of the island, respectively, to only 0.75 m below sea level at the center of Grand Isle. Thickness of the transition zone in the unconfined aquifer at Grand Isle is also quite variable across the island. The transition from fresh water to salt water is rarely sharp. In fact, the only area at Grand Isle where the transition zone resembles a sharp interface is at Soundings No. 7 and No. 8 where electrical conductivity increases from 100 millimhos per meter (mmhos/m) in the fresh-water zone to more than 1600 mmhos/m in the salt-water zone over an interval of a meter or less. In most areas of Grand Isle, the transition zone is gradual or there is a change in the rate of increase in salinity with depth. At Sounding No. 4, the transition from fresh water to salt water is at least 3 m thick beginning at approximately 2.5 m below sea level and extending to a depth of approximately 5.5 m below sea level. In fact, an alternative interpretation of the transition zone thickness at Sounding No. 4 could be made where the transition zone extends to approximately 9 m below sea level making the transition zone more than 6.5 m thick. At Sounding No. 9, the rate of increase in salinity with depth changes at least three times before reaching maximum electrical-conductivity values indicative of more saline conditions. Two rate changes are observed in the transition from fresh water to salt water in Sounding No. 5.

When cross-sections showing the variation in sediment type and electrical conductivity across Grand Isle are compared (Figures 7 and 8), both thickness of the fresh-water lens and the shape of the transition zone appear to be influenced by variation in sediment type across the island. At no location across Grand Isle does the fresh-water lens extend below the top of the Upper Clay, though water of moderate salinity may be present below the Upper Clay in the area of Soundings No. 1-No. 4. The correlation between the top of the Upper Clay and the base of the fresh-water lens is well demonstrated along the Gulf of Mexico flank of the island in Soundings No. 1 through No. 3. The relatively sharp transition zone observed in Soundings No. 7 and No. 8 are also attributed to the top of the Upper Clay. Here, the transition zone coincides with the sharp contact between sand of Upper Sand and clay of the Upper Clay. The gradual transition zone as well as the interval of relatively high electrical conductivity penetrated near the surface in Sounding No. 4 coincide with more silt.

Below the transition zone, in what would appear to be within the salt-water zone of the aquifer (Figure 8), electrical conductivity rarely reaches and maintains a constant value with increasing depth. Instead, fluctuations of electrical conductivity of 400 to 700 mmhos/m are common. In some cases, such as at Soundings No. 1 through No. 3, relatively sharp decreases in electrical conductivity by as much as 700 mmhos/m occur over discrete intervals approximately 6 to 7.5 m below sea level, directly below what would appear to be the base of the transition zone. Other fluctuations to lower electrical-conductivity values are also present in these soundings at approximately 12 m below sea level. In other areas of Grand Isle, such as at Soundings No. 7 through No. 10, fluctuations in electrical conductivity below the transition zone are characterized by a gradual decrease in electrical conductivity of 400 mmhos/m which is then maintained with increasing depth.

The fluctuation observed in profiles of electrical conductivity below the transition zone also correlates to changes observed in sediment type across Grand Isle. The sharp decreases in electrical conductivity of 700 mmhos/m immediately below the transition zone in Soundings No. 1 through No. 3 correspond to sand intervals. In fact, many of the sharp and abrupt decreases in electrical conductivity which occur over short intervals of 0.5 m or less correspond to thin sand layers. In cases where alternating thin laminae of sand and clay slowly become more sand-rich at the expense of clay, the fluctuation in electrical conductivity occurs more gradually. Along the Bayou Rigaud flank of Grand Isle in Soundings No. 7 though No. 10, at approximately 10 m below sea level, sand-rich sediments replace clay-rich sediments. Here, the decrease in electrical conductivity of 400 mmhos/m occurs gradually over the interval corresponding to the change from clay-rich sediments of the Middle Clay to more sand-rich sediments of the Lower Sand. Clay exhibits electrical conductivity as a result of both the electrolyte it contains and from ion exchange processes (Schlumberger, 1987). Fluctuations in electrical conductivity below the transition zone (Figure 8) may be related to decreases in salinity of the ground water present in sandy zones or may instead be related to the percentage of laminated or dispersed clay present in the formation. The interval of elevated electrical conductivity penetrated near the surface in Sounding No. 1 (Figure 8), however, should not be confused with the transition zone nor be attributed to a change in sediment type. This anomaly occurs strictly in sandy sediments and most likely represents more saline water associated with the swash zone created as the Gulf of Mexico moves onto the beach with each tidal fluctuation.

The thinning observed in fresh-water lens thickness at the center of Grand Isle and the variation in thickness of the transition zone across the island differ significantly from that predicted by theoretical models or observed in the field at other locations. Predictions of fresh-water lens thickness based on theoretical models which assume lithologic homogeneity and a sharp fresh-water/salt-water interface, such as the Ghyben-Herzberg relationship or Hubbert's modification, predict thickness of the fresh-water lens to be greatest in the center of the island where hydraulic head is at a maximum. Other models based on these principles which attempt to account for variables capable of influencing the position of the interface, such as variable recharge and permeability, also predict a thicker fresh-water lens in the center of the island (Pinder and Cooper, 1970; Fetter, 1972; Vacher, 1978; 1988). Most field observations report thickness of the fresh-water lens to be greatest in the center of the island and thin toward the flanks (Vacher, 1978; Cant and Weech, 1986; Ayers and Vacher, 1986; Anthony *et al.*, 1989). Indeed, few other examples of thinning of the fresh-water lens in the center of islands have been reported. Vacher and Wallis (1992) did report thinning of the fresh-water lens towards the center of Great Exuma, Bahamas; however, it was attributed to upconing of the fresh-water/salt-water interface due to a water deficit and evaporation in inland ponds where the water table was exposed.

Only Harris (1967) reported similar lithologic controls over fresh-water lens formation. As at Grand Isle, the thickness of the fresh-water lens and transition zone at Hatteras, North Carolina, were also complicated by the non-homogeneous anisotropic nature of sediments comprising the island. Thickness of the fresh-water lens at Hatteras was also limited by a clay layer at depth which prohibited further infiltration of fresh water. In addition, more rapid flushing of permeable sand lenses as opposed to less permeable silt lenses resulted in stratified lenses of fresh and salt water at Hatteras. This process of differential flushing may explain the gradual transition zone and increase in electrical conductivity corresponding to the silt lens penetrated near the surface in Sounding No. 4, as well as deflections to higher electrical conductivity observed near the surface in Soundings No. 8, No. 9, and No. 10.

Variable-Density Solute-Transport Modeling

The variable-density solute-transport modeling undertaken in this study was utilized to explain the anomalous shape of the fresh-water lens observed at Grand Isle and to further investigate the controls of variable sediment type and permeability on fresh-water lens formation. Thinning of the fresh-water lens as a result of pumping in the center of the island was quickly dismissed through a field check and review of all wells at Grand Isle registered with the Louisiana Department of Transportation and Development or scheduled through the United States Geological Survey. No evidence of pumping in the center of the island near the study site was discovered. Residents of Grand Isle long ago abandoned shallow wells and cisterns as sources of fresh water with the completion of a pipe line in the late 1960s which brought fresh water from the Lafourche Parish water works. However, some temporal variation is still likely and a possible source of error. The hydraulic heads to which we calibrated the model are representative of springtime conditions. No other head values were available.

Initial attempts to reproduce the observed position of the fresh-water lens across Grand Isle focused upon the thinning observed in the Upper Clay at the center of the island. A simple model was developed where a lower permeability clay layer representative of the Upper Clay was broken in the center of the island. This model resulted in the transition zone being limited to the lower permeability layer with only a slight pull-up of the transition zone near the center of the model where the clay layer was not present. Other modeling attempts were made to simulate upwelling of more saline water confined in the Middle Sand through the break in the Upper Clay layer as a result of subsidence and compaction. To simulate upwelling, the constant pressure values specified along the lower model boundary were increased substantially; however, duplication of the observed position of the transition zone in the center of the island was still unsuccessful.

The observed position of the transition zone across Grand Isle was successfully matched only by varying permeability and recharge within the model as functions of changing sediment type. To obtain a reasonable fit between the observed and modeled position of the transition zone, several modifications were made to initial estimates of permeability. The assumption of isotropic permeability was abandoned in favor of an anisotropic model. This change was prompted when hydraulic head along the upper model boundary grew to excessive values. Apparently, the extreme magnitude of hydraulic head resulted from recharge entering the system through a significantly greater area than that allowed for fluid to exit the system along the lateral and lower boundaries of the model. With each successive time step, more and more fluid entered the system, and fluid pressure continued to build along the upper model boundary, thus creating the unacceptable values of hydraulic head.

Reasonable predictions of hydraulic head at the upper model boundary (Figure 9) were achieved only after the permeability in the y-axis direction of each element was decreased by three to five orders of magnitude from that of the x-axis direction, depending upon sediment type present in each element. The y-axis value of permeability was decreased by three orders of magnitude in elements where sediment type was characterized as sand or silty sand; by four orders of magnitude for elements characterized by silt and silty clay; and by five orders of magnitude for elements characterized as clay. While the need of an anisotropic permeability field was initiated in this study by problems resulting in the dimensions of the grid network, vertical permeability several orders of magnitude less than horizontal permeability is well documented (Domenico and Schwartz, 1990; Weaver and Bahr, 1991) and seems likely where lower permeability clay layers are interbedded with higher permeability sand layers like those observed at Grand Isle.

A wider range of permeability values was also required to calibrate the model. Initial element-wise estimates of permeability, which were based on just five possible values of permeability thought to be representative of the five sediment types determined through cone-penetrometer testing, proved too simple. These estimates did not reflect the range of permeability values representative of a particular sediment type and in some cases lay at the extreme endpoints of the range of permeability values specified for sand to clay- sized sediments by Domenico and Schwartz (1990). Calibration was eventually achieved through expanding the five groupings into ten groupings, which ranged between 1.0×10^{-19} and 1.0×10^{-10} m^2 in the x direction and between 1.0×10^{-24} and 1.0×10^{-13} m^2 in the y direction. Despite the element-wise adjustments made to permeability, the distribution of permeability of the final calibrated model (Figure 9) still reflects the general variation in sediment type determined through cone-penetrometer testing to be present at Grand Isle (Figure 5). Throughout the calibration process, any changes made to element-wise estimates of permeability reflected the range of permeability representative of sediment type characterizing the element. It should also be noted that the permeability value of the unconfined aquifer at Grand Isle determined through slug testing in the nearby observation wells (1.14×10^{-12} to 2.65×10^{-12} m^2) lies well within the range of permeability values used throughout modeling conducted in this study.

Most element-wise adjustments to permeability were required in several distinct areas of the Upper Sand. Along the Gulf of Mexico flank of the model, permeability within the Upper Sand was modeled to simulate the coarsening-upward transition from lower permeability silt and silty sand present in the lower section of the Upper Sand to higher permeability sand representative of the well-sorted beach and dune sediments present at the top of the Upper Sand. The observed thickness of the fresh-water lens along the Gulf of Mexico flank of Grand Isle was duplicated only after permeability of silt and silty sand characterizing the lower section of the Upper Sand was varied in a wedge-like manner increasing in thickness towards the Gulf of Mexico lateral boundary of the model so as to promote flushing. In the center of the model, a similar coarsening up transition from lower permeability silt to sand was modelled, but with lower permeabilities needed in order to calibrate to the higher elevation of the transition zone. As a result, fluid entering the system from the upper model boundary is diverted to either side of model, thus allowing the transition zone to build upward into the center of the island through dispersion in the presence of reduced flushing. The permeabilities of the sand in the middle of the model, though reduced, were still within the ranges reported for sand by Domenico and Schwartz (1990). Permeability was also varied to promote flushing of the silt lens penetrated near the surface in Sounding No. 4. The thickening of the transition zone along the Bayou Rigaud flank of the Grand Isle was duplicated by restricting the flow of fresh water through the bridge of silty sand connecting the silt lenses penetrated midway through the Upper Sand by Soundings No. 7 and No. 9. Through varying the permeability of elements comprising this bridge, the effects of flushing were reduced, and concentration was increased below the bridge.

Adjustments to the variables of recharge and dispersion were also required to calibrate the model. The amount of recharge entering the system at the upper model boundary was varied to reflect changes in sediment type present near the surface of Grand Isle. Recharge was greatest where sand penetrated completely to the surface between soundings 1 and 3. Recharge was lowest between soundings 8 and 10 where multiple clay layers were near the surface, as was the case for the area between soundings 4 and 5. There are no surface streams in the area. Recharge to the upper model boundary of the final calibrated model ranges from 1.3 to 25.4 cm/yr. The positive recharge values and resulting downward flow vectors indicate that the upconing in the center of the island is not controlled by evapotranspiration. A value of molecular diffusion equal to 5.0×10^{-10} m^2/s, approximately one-half order of magnitude less than that reported for Na^+ and Cl^- in Domenico and Schwartz (1990) or Voss (1984), resulted in the best agreement between the observed and predicted thickness of the transition zone across the island. Attempts to further improve the match between observed and modeled thickness of the transition zone through varying initial estimates of longitudinal and transverse dispersivity were unsuccessful.

Comparison of the vector map describing the pattern of fluid flow across Grand Isle (Figure 11) with the distribution of permeability of the final calibrated model (Figure 10) further illustrates the influence of permeability variation on magnitude of fluid velocity and the direction of fluid flow. Where permeability is relatively high, such as in a sandy sediment, the magnitude of fluid velocity approaches the maximum modeled values which exceed 1.0×10^{-6} m/s. The opposite relationship is observed in clay-rich sediments where permeability is less. Fluid velocity in clay-rich sediments decreases to 1.0×10^{-12} m/s. Fluid flows preferentially in the direction of higher-permeability sand-rich sediments and is diverted away from areas of lower-permeability clay-rich sediments.

CONCLUSIONS

Cone-penetrometer testing was successfully used to characterize the unconfined barrier-island aquifer at Grand Isle, Louisiana. The advantages of cone-penetrometer testing are better resolution of sediment type and ground-water salinity than is possible with conventional methods of sediment and ground-water sampling. In many cases, both the quantity of data and level of detail obtained through cone-penetrometer testing in this study exceeded what was available to other studies of fresh-water lenses and transition zones. The ability to closely space ten cone-penetrometer soundings along the short axis of Grand Isle provided a unique opportunity to study the interrelationship between sediment type and formation of the fresh-water lens and transition zone.

Three sand bodies were identified through cone-penetrometer testing at Grand Isle, each separated from one another by a distinct clay layer. Distribution of sand within the Upper Sand, the uppermost of the three sand bodies, supports the theory proposed by Conatser (1969; 1971) suggesting that Grand Isle grew through seaward and northeastward accretion of sediments carried by littoral currents from the southwest to the northeast. The Middle Sand and the Lower Sand bodies are separated by the Middle Clay, a clay layer not recognized previously. The presence of the Middle Clay layer suggests that an interval previously thought to represent one episode of barrier-island sand deposition instead represents two distinct episodes of sand deposition.

At Grand Isle, the observed thickness of the fresh-water lens and the shape of the transition zone differ significantly from that predicted by theoretical models or observed at other locations. The position of the fresh-water/salt-water interface at Grand Isle is not governed by the Ghyben-Herzberg relationship or by any of the modifications to this relationship which assume lithologic homogeneity and a sharp fresh-water/salt-water interface. The fresh-water lens is significantly thinner at the center of the island than on the flanks of the island. Maximum thickness of the fresh-water lens is limited by the Upper Clay which effectively prohibits further infiltration of fresh water.

The transition from fresh water to salt water is rarely sharp as depicted by theoretical models but is instead quite gradual in some areas and is characterized in others by changes in the rate of salinity increase with depth. Where a sharp transition zone exists, it occurs at the contact between the Upper Sand and Upper Clay layers. More rapid flushing of higher permeability sand-rich sediments as opposed to lower permeability silty sediments may explain the gradual transition zones and increases in electrical conductivity observed at some locations within the Upper Sand. Fluctuations in electrical conductivity also occur below the base of the transition zone. These fluctuations may reflect change in ground-water salinity, but may also reflect the percentage of laminated or dispersed clay present in the formation.

Variable-density solute-transport modeling was used to explain the observed position of the transition zone at Grand Isle. The observed position of the transition zone was successfully duplicated only after assuming a vertically anisotropic permeability field and assigning element-wise estimates of permeability and recharge to the upper model boundary as a function of changing sediment type. The model developed in this study was calibrated to the position of the transition zone and changes in sediment type documented to exist at Grand Isle through cone-penetrometer testing. Unlike many models, the effects of dispersion and density-driven flow were also accounted for. A vector map based on the final calibrated model shows magnitude of fluid velocity and direction of fluid flow to be influenced by changing sediment type. Fluid flows preferentially through sand-rich sediments at a higher velocity as opposed to clay-rich sediments. At Grand Isle, fluid entering the system from the upper model boundary is diverted to either side of the island and follows avenues of higher permeability in route to the Gulf of Mexico or Bayou Rigaud.

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