ground water

Hydrogeologic Setting and Ground Water Flow Beneath a Section of Indian River Bay, Delaware

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Abstract

The small bays along the Atlantic coast of the Delmarva Peninsula (Delaware, Maryland, and Virginia) are a valuable natural resource, and an asset for commerce and recreation. These coastal bays also are vulnerable to eutrophication from the input of excess nutrients derived from agriculture and other human activities in the watersheds. Ground water discharge may be an appreciable source of fresh water and a transport pathway for nutrients entering the bays. This paper presents results from an investigation of the physical properties of the surficial aquifer and the processes associated with ground water flow beneath Indian River Bay, Delaware. A key aspect of the project was the deployment of a new technology, streaming horizontal resistivity, to map the subsurface distribution of fresh and saline ground water beneath the bay. The resistivity profiles showed complex patterns of ground water flow, modes of mixing, and submarine ground water discharge. Cores, gamma and electromagnetic-induction logs, and in situ ground water samples collected during a coring operation in Indian River Bay verified the interpretation of the resistivity profiles. The shore-parallel resistivity lines show subsurface zones of fresh ground water alternating with zones dominated by the flow of salt water from the estuary down into the aquifer. Advective flow produces plumes of fresh ground water 400 to 600 m wide and 20 m thick that may extend more than 1 km beneath the estuary. Zones of dispersive mixing between fresh and saline ground water develop on the upper, lower, and lateral boundaries of the plume. The plumes generally underlie small incised valleys that can be traced landward to streams draining the upland. The incised valleys are filled with 1 to 2 m of silt and peat that act as a semiconfining layer to restrict the downward flow of salt water from the estuary. Active circulation of both the fresh and saline ground water masses beneath the bay is inferred from the geophysical results and supported by geochemical data.

Introduction

The Atlantic coast of the Delmarva Peninsula (Delaware, Maryland, and Virginia), like many sections of the east coast of the United States, has had considerable growth in development related to both permanent residence and seasonal tourism. The primary land use of inland areas of Delmarva is agricultural, and the region is one of the leading poultry producers in the country. The coastal zone includes a series of small estuaries, or coastal bays, landward of the barrier islands. Resource managers and policymakers are challenged with balancing priorities of use that affect these estuarine ecosystems, which are an important nursery and habitat for marine organisms, and a valuable asset for commerce and recreation. A key management issue for the coastal bays and their watersheds is controlling the flux of nutrients, specifically nitrogen and phosphorus, into the bays. The results of a U.S. Geological Survey (USGS) study of nutrient inputs to the Delmarva coastal bays by submarine ground water discharge are presented in this and two companion papers.

Setting

The barrier islands along the Delmarva coast enclose a series of shallow coastal bays (generally < 2 m deep) with restricted circulation and limited exchange with the ocean (Figure 1). The form and drainage basins of these bays vary from north to south (Fisher 1961). To the north in Delaware, Rehoboth Bay and Indian River Bay occupy incised valleys that trend nearly perpendicular to the ocean

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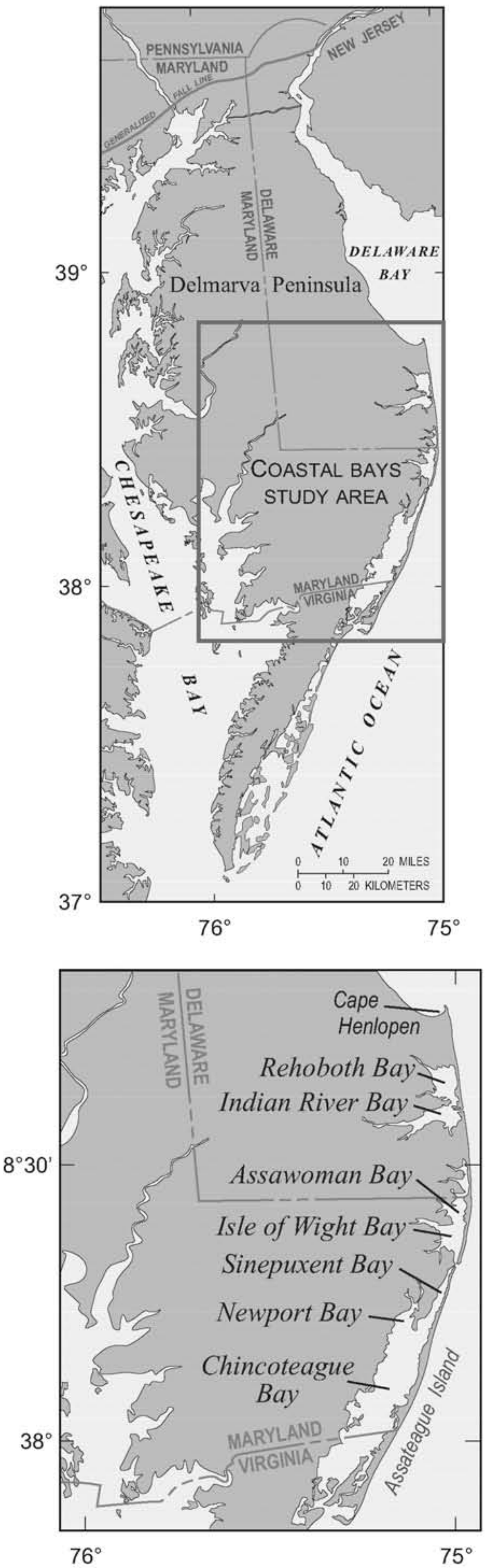

Figure 1. Mid-Atlantic coast and the Delmarva Peninsula, showing the coastal bays along the Delaware-Maryland coast.

shoreline. Farther south, in Maryland and Virginia, Sinepuxent, Newport, and Chincoteague bays trend parallel to the shoreline, occupying a trellis drainage system (Oertel and Kraft 1994). Assawoman and Isle of Wight bays, in the northern section of the Maryland coast, are transitional between the Indian River Bay and Chincoteague Bay geometries. South of Assateague Island, the barrier islands are shorter and separated by moderately large tidal inlets, and the back-barrier lagoons are generally better flushed by tides than those to the north. The ratio of estuary area to drainage-basin area changes dramatically from north to south, with relatively large drainage areas for Rehoboth and Indian River bays, and small drainage areas in Virginia. Salinities in open-bay sections near inlets typically are 28 ‰ to 30 ‰, and become fresh near the heads of tidal tributaries.

Because of the limited circulation, the coastal bays tend to trap fine-grained particles, including organic matter, and sequester and recycle nutrients. Except for sands associated with inlets and overwash sheets, the bays are filled primarily with organic-rich silts (Wells et al. 1994; Wells et al. 1998). The upper reaches of the bays and tributary tidal creeks are particularly vulnerable to eutrophication by input of nutrients (U.S. EPA 1998). Primary productivity in these coastal estuaries tends to be nitrogen limited; however, when surface water nitrogen concentrations remain high, as in the upper Indian River, phytoplankton blooms may be triggered by late-summer releases of phosphorus from anoxic sediments (Ullman et al. 1993). Much of the nutrient load entering the bays comes from nonpoint sources, such as agricultural operations and septic systems, and point sources such as waste water treatment facilities. Transport pathways of anthropogenic nutrients to the coastal bays include atmospheric deposition, overland flow and surface runoff, base flow of streams from ground water discharge, and direct ground water discharge to tidal creeks and bays.

A substantial proportion of the total fresh water flux to the Delmarva coastal bays comes from ground water flowing through the surficial aquifer. In areas with sandy soils, infiltration exceeds surface runoff and a large percentage of annual precipitation enters the ground water (Table 1) (Johnston 1976; Bachman and Wilson 1984). Although ground water transport and discharge may be a primary

Table 1
Hydrologic Partitioning of Annual Precipitation for Stockley Branch, in the Indian River Watershed, Delaware*

Process	Percent of Annual Precipitation
Evapotranspiration from soil	55
Recharge to water table	38
Overland flow (runoff)	7
Evapotranspiration from ground water	7

*From Johnston 1976

pathway for nutrients entering the bays, this process is not well documented or quantified. Total ground water discharge to coastal bays includes base flow of nontidal streams, discharge to tidal streams, and direct discharge to the bay. Estimates of ground water flux to the coastal bays, including those by Andres (1987, 1992) for Delaware, and Dillow and Greene (1999) for Maryland, are based on flownet models. Further, few data are available on the geochemistry of the ground water that discharges to the coastal bays. The distribution of fresh and saline ground water beneath the bays, the flowpaths, ground water ages, nutrient content, and geochemical environment (for example, dissolved oxygen concentrations and redox conditions) were not known previously from direct measurements.

Goals of the Study

The overall objective of this component of the Delmarva coastal bays project is to assess the ground water distribution and flow beneath Indian River Bay. Results reported in this paper include (1) a hydrogeologic framework of the surficial (unconfined) aquifer and the shallow confined aquifers for the study area based on marine seismics correlated with new and existing stratigraphic data from deep boreholes, and (2) verification of the resistivity profiles collected from Indian River Bay (Manheim et al., this issue) with geophysical logs and in situ water sampling from a series of coreholes drilled in the bay. Inferred dynamics of the ground water flow system are further supported by geochemical data reported by Bratton et al. (this issue).

Geologic and Hydrogeologic Setting

The regional stratigraphic and hydrostratigraphic settings of the Delaware coast are documented in Delaware Geological Survey reports (Johnston 1976; Hodges 1983; Andres 1986a, 1986b; Talley 1987; Ramsey 1999). The coast-parallel stratigraphic section presented in Figure 2 depicts the primary sequences that constitute the surficial (unconfined) aquifer and the shallowest confined aquifers; these units also are presented in Table 2 with geologic age,

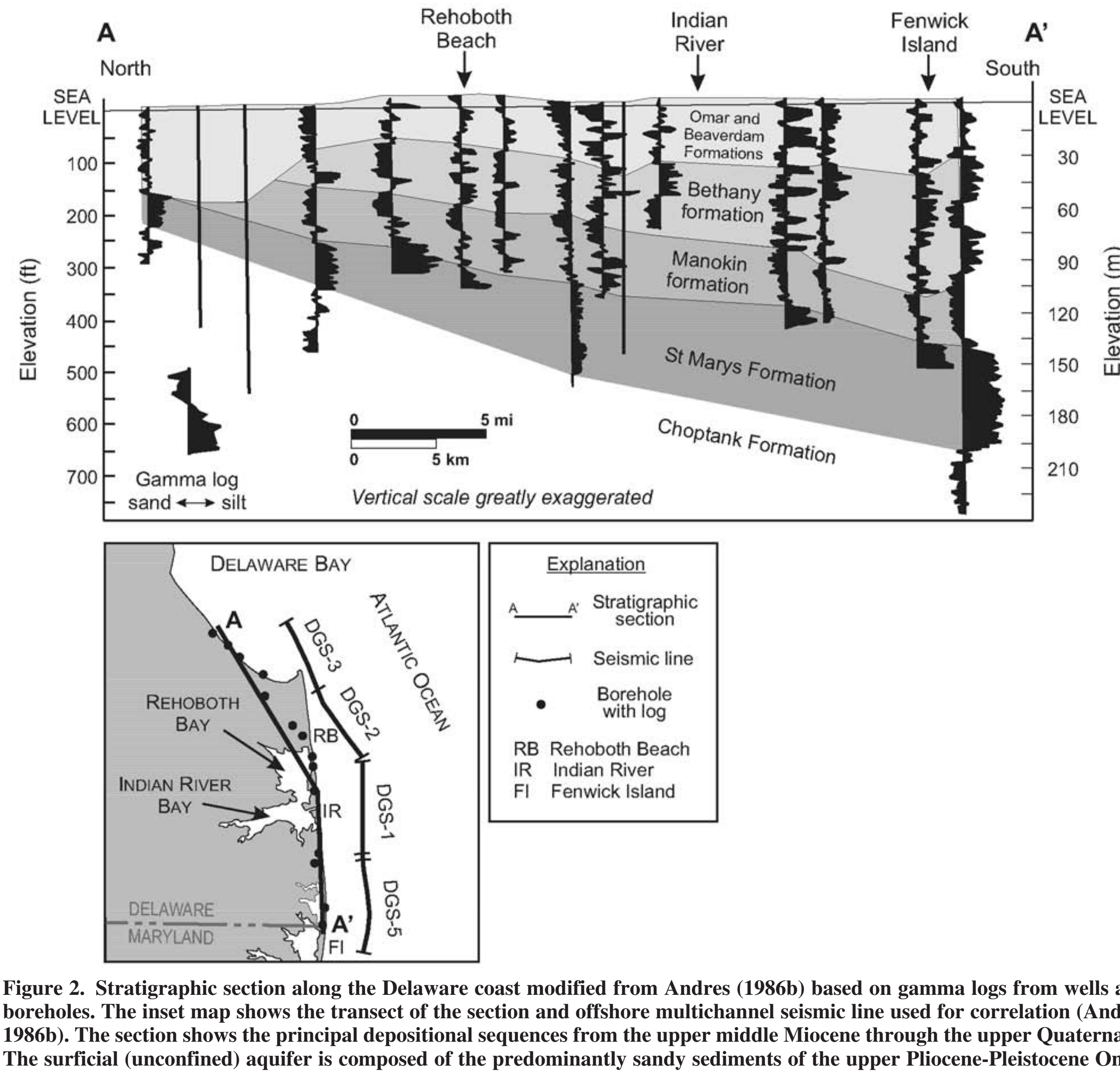

Figure 2. Stratigraphic section along the Delaware coast modified from Andres (1986b) based on gamma logs from wells and boreholes. The inset map shows the transect of the section and offshore multichannel seismic line used for correlation (Andres 1986b). The section shows the principal depositional sequences from the upper middle Miocene through the upper Quaternary. The surficial (unconfined) aquifer is composed of the predominantly sandy sediments of the upper Pliocene-Pleistocene Omar Formation and the Pliocene Beaverdam Formation; marine silts in the upper part of the Bethany formation are a regional confining to semiconfining layer.

lithology, depositional environment, and relative permeability. The upper 200 m of the stratigraphic column are composed of middle Miocene to Recent fluvial, marginal-marine, and marine sediments that dip to the east-southeast. The surficial aquifer in the Delaware coastal bays watershed generally is about 30 m thick and comprises the upper Pliocene and Pleistocene Omar Formation and the underlying Pliocene Beaverdam Formation (Groot et al. 1990). The upper Omar Formation was deposited during a series of Pleistocene sea-level highstands, and preserves sediments deposited in estuarine, back-barrier (lagoonal), shoreline, and inner-shelf environments. Although the Omar Formation is predominantly sand and silty sand, it contains a wide range of lithologies from clayey silts to gravelly coarse sands, with complex bedding geometries. The Omar Formation typically is from 10 to 15 m thick, but may be thicker where it fills incised valleys. The Beaverdam Formation is a thick (typically 15 to 20 m) sequence of coarse sands and gravels deposited in a lower delta plain. The Beaverdam Formation fines upward from fluvial into estuarine deposits (Benson 1990; Andres and Ramsey 1996) and locally contains silt or silt-clay lenses, but generally is highly permeable and is a regional aquifer (Denver 1986).

Below the Beaverdam Formation, the marine silts of the upper Bethany formation form the first regional confining layer and the base of the surficial aquifer. Marine fine sands in the lower Bethany formation constitute the first confined aquifer. The ground water in this confined aquifer has little geochemical interaction or exchange with ground water in the surficial aquifer (Hodges 1983; Denver 1986). A discontinuous confining to semiconfining layer of silt at the top of the Manokin formation separates the sands of the Bethany and Manokin aquifers; both the Bethany and Manokin aquifers are used locally for deep (90 to 140 m) water-supply wells and municipal wellfields. Below the Manokin formation, ~60 m of compacted marine silt and clay of the upper middle Miocene St. Marys Formation is a major regional confining layer. (The Bethany and Manokin formations are informal stratigraphic units recognized by the Delaware Geological Survey [Andres 1986b; Benson 1990].)

During the sea-level lowstand of the last glaciation (18,000 to 20,000 years before present), the local streams flowed into an ancestral Indian River that underlies the modern estuary (Chrzastowski 1986). These streams formed a dendritic drainage network that cut down into the exposed coastal plain. The incised valley of the paleo-Indian River is ~15 m deep in central Indian River Bay, and deepens to 22 to 25 m where it passes beneath the modern barrier island near Indian River Inlet (Kraft 1971; John 1977; Chrzastowski 1986). The larger tributary streams, such as White Creek and Pepper Creek, have incised valleys that are 5 to 8 m deep; the incised valleys of the smaller, first- and second-order streams typically are 2 to 3 m deep. These valleys were flooded progressively during the Holocene sea-level rise and filled with predominantly fine-grained and organic-rich sediments. A typical infill sequence of an incised valley consists of a thin bed (0.5 to 1 m) of fluvial sand overlain by basal peats deposited in a swamp or tidal marsh; this sequence is capped by fine-sandy silts of the estuary (Mixon 1985; Belknap et al. 1994). As the barrier island at the mouth of the coastal bay migrates landward, sand bodies associated with flood-tidal deltas and overwash sheets are deposited over the estuarine silts (Kraft et al. 1987; Oertel et al. 1989).

The thickness and continuity of low-permeability silts and higher-permeability sands in the incised-valley infill sequence and the surficial aquifer largely will determine preferential pathways for ground water discharge to the estuary. Consequently, the development of a hydrostratigraphic framework for the coastal bays includes defining both the geometry of the pre-Holocene sequences that underlie the bays and the facies distribution of the Holocene sediments filling the basin.

Methods

Geophysical Surveys in the Delaware Coastal Bays

Geophysical surveys in the study area included a streaming resistivity survey completed in May 2000, a

Table 2
Regional Stratigraphic Units for the Delaware Coast

Geologic Age	Formation or Unit	Depositional Environment and Lithology	Permeability
Holocene	Modern, incised-valley fill	Estuarine and back-barrier deposits; primarily organic-rich silts and silty sands; highly variable	Generally low permeability
Pleistocene	Omar Formation	Back-barrier, shoreline, and inner-shelf deposits; primarily silty sands and sands	Moderate to high permeability with low-permeability beds
Pliocene	Beaverdam Formation	Lower delta plain coarse sands and gravels; generally fining upward; interbedded silt layers	Very high permeability, with low-permeability beds; regional aquifer
Miocene	Bethany Formation	Marine silt and silty sand	Generally low permeability; regional confining unit

Geopulse (boomer) seismic survey in May 2001, and Chirp seismic surveys conducted by the University of Delaware for the CISNet (Coastal Intensive Sites Network) Project during the summers of 2001 and 2002. The equipment and operating parameters for the resistivity survey are described by Manheim et al. (2002) and Manheim et al. (this issue). The resistivity and Geopulse seismic tracklines were concentrated in Indian River Bay and its tributaries (Figure 3a), but included representative lines in Rehoboth Bay. The resistivity survey included transects parallel to the shorelines in shallow water (< 1.5 m), across the width of the bays, and up several tributary creeks.

The Chirp seismic survey used an EdgeTech SB–216S swept-frequency towfish with an X-Star data-acquisition system operating with a frequency range of 2 to 12 kHz. Penetration typically was 5 to 8 m in silty estuarine sediments, with excellent resolution of bedding. This survey was particularly valuable for defining the base of the Holocene sediments, but deeper reflections in the Pleistocene sequence were imaged in some areas.

A Geopulse boomer plate operated at 105 J was used as the acoustic source for the deeper seismic survey with a Delph Seismic digital-acquisition system collecting single-channel data. The seismic data were filtered for a frequency range of 240 to 2000 Hz, and a logarithmic time-varying gain was applied. The seismic survey retraced the resistivity tracklines and added other lines in key areas. The Geopulse seismic profiles overlap the depth range of the Chirp profiles, so that the entire vertical sequence from the seafloor to ~100 m subsurface is imaged clearly. The Geopulse profiles show distinct reflections typically to 100 to 120 msec (75 to 90 m below the seafloor), and several coherent reflection events in the 150 to 180 msec (112 to 135 m) range. The Chirp survey included most of the same tracklines as the Geopulse survey, but focused more on Rehoboth Bay, because extensive vibracores are available from that bay (Chrzastowski 1986).

Coring Operation in Indian River Bay

Four coring sites off White Neck, along the southern shore of Indian River Bay, were selected based on the resistivity and seismic profiles. The first two coring sites represent end-member conditions interpreted from the resistivity profiles; the third and fourth sites complete an onshore-offshore transect from the margin to the center of Indian River Bay. The three main components of the coring operation were (1) hydraulic vibracoring to recover sediments, (2) geophysical logging of the corehole, and (3) in situ sampling of ground water at the core site. Pore fluids subsequently were sampled from the cores for geochemical analyses (Bratton et al., this issue).

An hydraulic vibracoring rig developed by MPI Drilling (Ontario, Canada) was used for coring, downhole geophysical logging, and ground water sampling. The core barrel was standard NQ steel pipe (70 mm or 2.75 inch outer diameter) in 1.5 m (5 foot) internally threaded sections. The core barrel was fitted with a 10 cm beveled shoe, an inner plastic core liner, and thin aluminum sleeves at the joints to keep the liner from buckling or collapsing during drilling. The drill rig is self-contained on a small trailer that was mounted on the deck of an 18 m (60 foot) construction barge operated by the State of Delaware. The barge can operate in water as shallow as 0.5 m, and has spuds to stabilize the vessel on the drilling site.

The coring operation was conducted in October 2001 at four sites designated WN–1 through WN–4 (Figure 4). Site WN–1, ~150 m offshore from Holts Landing, was centered in a zone of low subsurface resistivity at 2100 m on profile DE-R–05 (Figure 3), which was interpreted as an area with little or no fresh ground water discharge. Sites WN–2 (75 m offshore) and WN–3 (300 m offshore) were in a zone of high resistivity at 2400 m on the profile, interpreted as an area of fresh ground water discharge, which coincided with a small incised valley identified on seismic profiles IR–04 and IR–06. Site WN–4, in the middle of Indian River Bay ~1 km north of Ellis Point, was in the axis of the mainstem incised valley of the Indian River identified on seismic line IR–08. Site WN–4 was occupied for half of a day before demobilizing, and only the borehole geophysical logging was completed at that site.

The order of operation at the first three sites (WN–1 through WN–3) was to recover the core, run a gamma log of the hole, temporarily set PVC casing in the hole to run an electromagnetic-induction (EM) log, evaluate the gamma and EM logs, and choose specific depths for sampling ground water. A 75 mm (3 inch) PVC core barrel with a plastic liner was used to core through the Holocene estuarine sediments, which allowed better recovery of the soft, typically watery sediments than with the metal core barrel because of the wider diameter and narrower walls of the PVC. Deeper cores, below the base of the Holocene sediments, were recovered using the NQ steel core barrel with a core liner. Measurements to the top of the sediment inside the core barrel were made after advancing each 5 foot section, so that percentage recovery and vertical position could be reconstructed accurately. Hydraulic vibracoring recovered three cores as deep as 15.2 m, with 57% to 72% recovery. In general, recovery in the upper three or four rods was > 80%, and drilling was curtailed when recovery dropped much below 50%. Time constraints did not allow reentering the hole to core deeper, although this has been done successfully elsewhere, to a maximum depth of 29 m. Recovered cores were removed from the core barrel in the core liners and transferred to land for geochemical sampling (such as pore fluid extraction) and description.

Geophysical logs down the coreholes were collected using a Mount Sopris Instruments MGX II portable digital logger running MSLog software, with a PGA–1000 gamma-logging tool and a PIA–1000 EM probe. The gamma logs were taken through the steel core barrel, which was advanced with a solid, conical drivepoint. Because the corehole was reentered and drilled to refusal, all of the gamma logs are deeper than the total depth cored at each site. The EM conductivity logs were taken through 5 cm (2 inch) PVC casing. The casing was set by first drilling HQ steel core barrel (89 mm or 3.5 inch outer diameter) with a PVC knock-out drivepoint, inserting the PVC casing and filling it with fresh water, and then retracting the outer steel core barrel. The PVC casing was pulled from the hole after the logging was completed.

Ground water samples for salinity measurements to compare with the EM log and for geochemical analyses

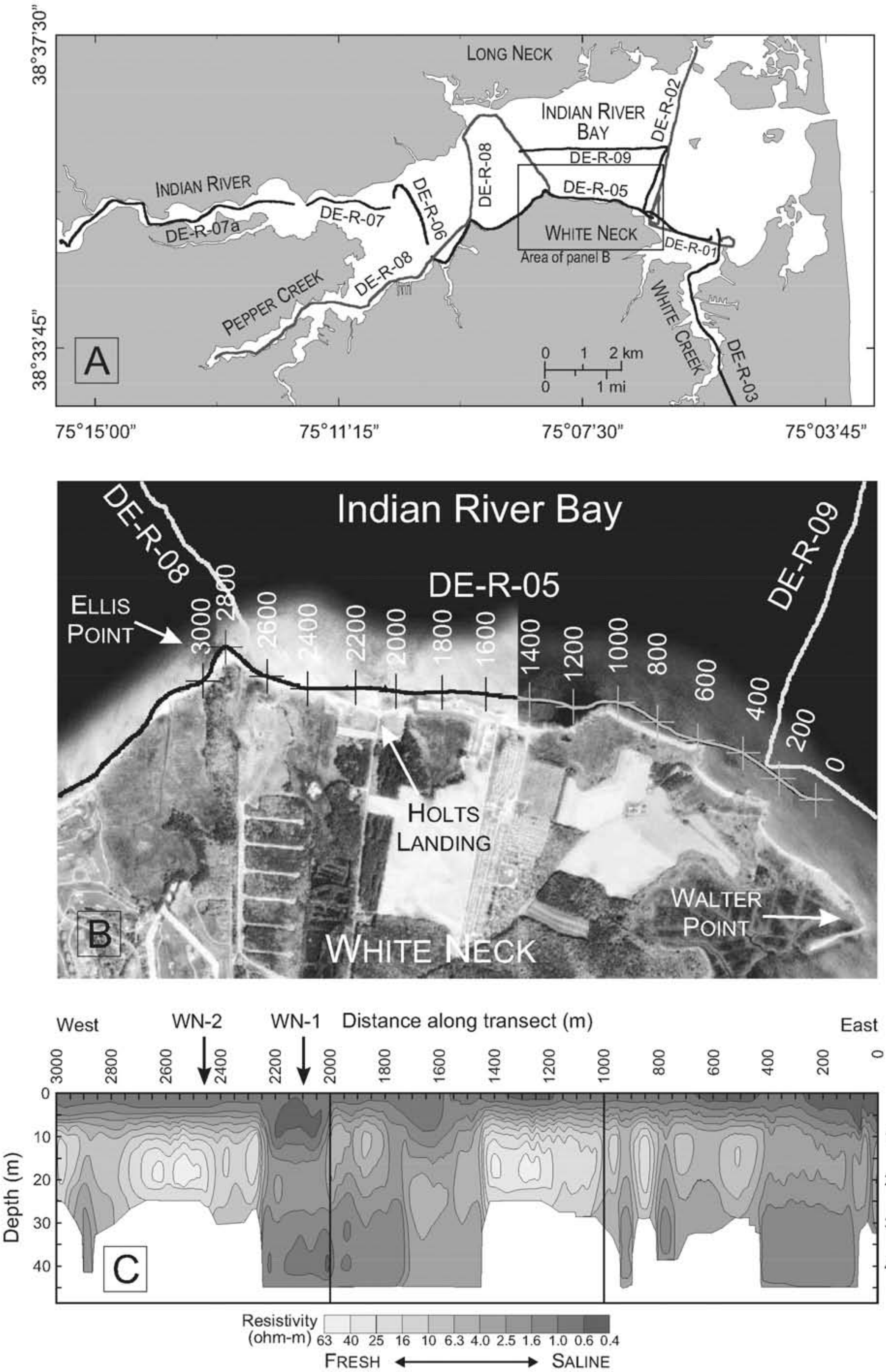

Figure 3. (a) Resistivity tracklines in Indian River Bay and tributaries, Delaware. (b) Resistivity line DE-R–05 around White Neck on the south shore of Indian River Bay. Distances along transect are in meters. (c) Resistivity profile DE-R–05; darker shades are low resistivity values indicative of saline pore fluids in the surficial aquifer; lighter shades indicate high resistivity associated with fresh ground water.

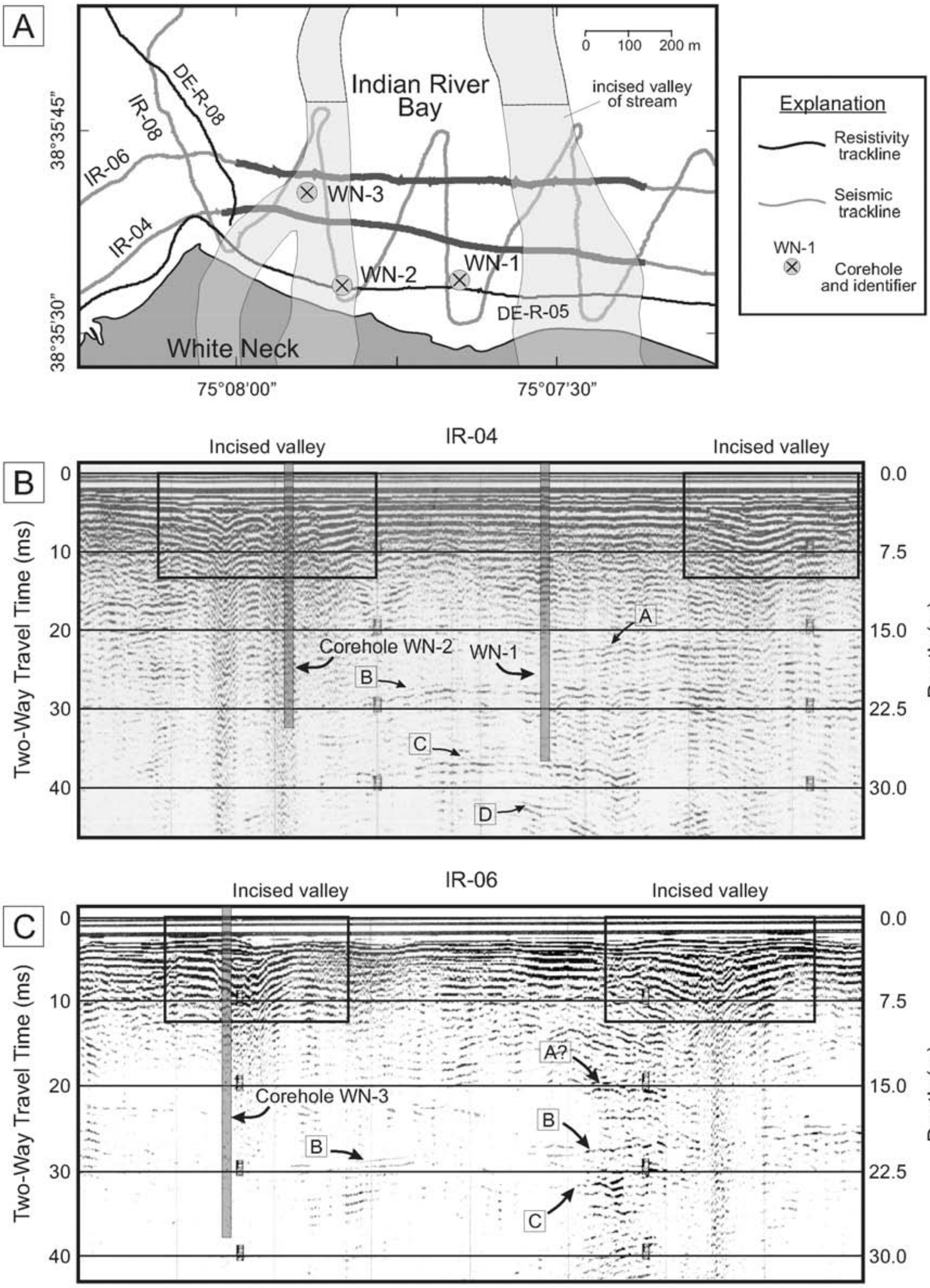

Figure 4. (a) Resistivity and seismic tracklines, and corehole sites off White Neck. Sections of the seismic lines IR–04 and IR–06 shown in panels (b) and (c) are indicated with bold lines. (b) The upper 45 msec of Geopulse seismic line IR–04, showing the buried incised valleys of streams that drained White Neck, the locations of coreholes, and prominent reflection events that may be correlated with the cores and gamma logs. (c) The upper 45 msec of seismic line IR–06; reflections marked A, B, and C are correlated with those on line IR–04. Depths assume a sound velocity of 1500 m/sec through saturated sediments.

were collected by sequentially advancing the NQ core barrel with a 25 cm screened drivepoint to each of three depths selected by reviewing the gamma and EM logs. The temporary well was purged at each depth using a Waterra inertial pump until the water was clear of turbidity. A Bennett pneumatic piston pump and a peristaltic pump were used to collect ground water samples.

Results

The combination of geophysical and geochemical tools used during this study gives a detailed view of the spatial distribution of fresh and saline ground water beneath the coastal bays, and allows inferences to be drawn about the processes of ground water flow and mixing. The initial resistivity survey was an experiment to test this technology in an estuarine environment; however, the results showed such complex and intriguing patterns of ground water distribution beneath the bays that most of the rest of the project was directed toward verifying the resistivity profiles.

Geophysical Surveys off White Neck

A section of the Indian River Bay shoreline, off White Neck on the south shore, was used as a test site to verify the subsurface distribution of fresh and saline waters interpreted from the resistivity profiles. The 3000 m section of resistivity profile DE-R–05 from north of Walter Point to Ellis Point (Figure 3) shows distinct zones of high resistivity, interpreted as fresh ground water flowing offshore, alternating with zones of low resistivity, interpreted as saline water penetrating into the surficial aquifer. The two most prominent fresh water zones, from 1000 to 1450 m and from 2250 to 2800 m along the transect, coincide spatially with the incised valleys that are the offshore extensions of modern tributary streams occupied by tidal marshes. Another small fresh water zone, from 1800 to 2000 m, aligns with a small stream that has been modified for a boat basin. Sections of the White Neck shoreline with low-relief headlands (generally < 2 m elevation) such as Holts Landing from 2000 to 2250 m and a narrow headland between 1450 and 1750 m are characterized by low resistivity (saline) water in the upper 10 to 15 m of the profile. Saline water also may appear deep in the resistivity profiles, for example, below 25 m in the section between 1800 and 2200 m along the profile. Some interfaces between fresh and saline waters are sharp and nearly vertical, such as at 1450 and 2250 m, whereas others are more dispersed and vertically layered, such as west of 2750 m.

Along the margins of Indian River Bay, within 100 m of shore, the Holocene sediments commonly consist of < 1 m of muddy sand. The small incised valleys may be 2 to 3 m deep, and generally are filled with peat overlain by silt, and capped with a thin veneer of muddy sand. The infill sequence thickens appreciably to ~15 m of silt in the incised valley of the Indian River. Below the Holocene sediments, prominent reflections in the seismic profiles (Figure 4) may be traced for hundreds of meters to several kilometers. Many of these reflections have considerable relief over short distances, created by cut-and-fill events over multiple sea-level cycles. Reflections A through D identified on the seismic profiles shown in Figure 4 can be correlated along lines IR–04, IR–06, and IR–08, and with the gamma logs from the four coreholes.

Results from Coring and Borehole Geophysics

Corehole WN–1 reached a total depth of 14.75 m below the sediment surface, with 57% core recovery. The poorest recovery was below 10 m through a series of coarse-sand beds, some with gravel. The gamma log for corehole WN–1 (Figure 5) shows a sequence of silty sands from 2 to 16 m, which is interpreted as the Pleistocene Omar Formation. The upper 0.9 m of the core, with a low gamma signature, has 0.2 m of gray silty sand overlying a well-sorted clean medium sand, which represents Holocene estuarine and bay-beach sediments, respectively. The positive gamma excursion between 0.9 and 1.5 m correlates with a mottled, weathered horizon in the core that is interpreted as the soil horizon of the pretransgressive surface. The unit with low gamma values below 18 m, down to 24 m, is interpreted as the coarse sands and gravels of the Pliocene Beaverdam Formation. The slightly finer-grained unit (higher gamma values) between 16 and 18 m may be silty sands either at the base of the Omar Formation or the top of the Beaverdam Formation.

The EM conductivity log for site WN–1 (Figure 5) starts with high values above 1000 mS/m, and falls rapidly to a minimum approaching 600 mS/m at 2 m. All four of the EM logs have values above 1200 mS/m in the upper 0.5 to 1 m; these high values are not simply the result of saline pore fluids, and values above 2000 mS/m should not be considered equivalent to surface water salinities. EM conductivity depends on the electrical properties of both the pore fluids and sediment, and with the high porosities near the sediment-water interface, the pore fluids have a disproportionately large effect on the EM conductivity. Below ~0.5 m, grains are packed more closely and uniformly, and the range of EM conductivity values is reduced accordingly. Additionally, the dynamic range of the EM instrument was exceeded when the probe was raised above the sediment surface because of the conductivity of the surface water and metal hull of the barge.

The EM conductivity logs for coreholes WN–1, WN–2, and WN–3 were compared with ground water samples pumped from the corehole (Figure 5), and with salinity measurements of pore fluids squeezed from the core (Bratton et al., this issue). Formation factors, which are the ratio of the resistivity of the sediment to the resistivity of the pore fluid, were calculated from resistivity-probe measurements made on the core material and pore fluids (Manheim et al., this issue). Observed formation factors generally ranged between two and five, indicating that variations in the resistivity profiles and EM conductivity logs are controlled primarily by changes in pore fluid conductivity (essentially salinity).

Below the minimum conductivity at 2 m, the EM log for corehole WN–1 remains higher than 1000 mS/m below 3 m, and increases slightly with depth. Pumped ground water samples at 7.6 and 21.6 m had salinities of 25.1 ‰ and 28.5 ‰, respectively, confirming that the EM conductivities above 1000 mS/m indicate saline pore fluids. By comparison, surface water salinities ranged between 29 ‰ and 30 ‰. Pore fluids from the core had salinities between 5 ‰ and 7 ‰ in the low-conductivity section between 1.5 and 2.5 m, rising to 17.6 ‰ in a ground water sample at 3.0 m. This narrow lens of reduced-salinity water appears to be isolated in the coarse sand below the weathered horizon at 0.9 to 1.5 m, which acts as a semiconfining layer to slow mixing with the saline water above.

Most of the upper 1.5 m of core WN–2 is a Holocene peat, deposited in the incised valley, probably in a tidal-marsh setting, overlain by ~5 cm of muddy sand from the bay margin. The peat emits essentially no gamma radiation, as shown by the gamma log (Figure 5). The peat immediately overlies the pretransgressive surface (the Holocene-Pleistocene contact), which is marked by a sharp increase in the gamma response at 1.6 m. In the core, the pre-Holocene sediments between 1.6 and 2.5 m are weathered, mottled, silty sands that are moderately cohesive and represent a

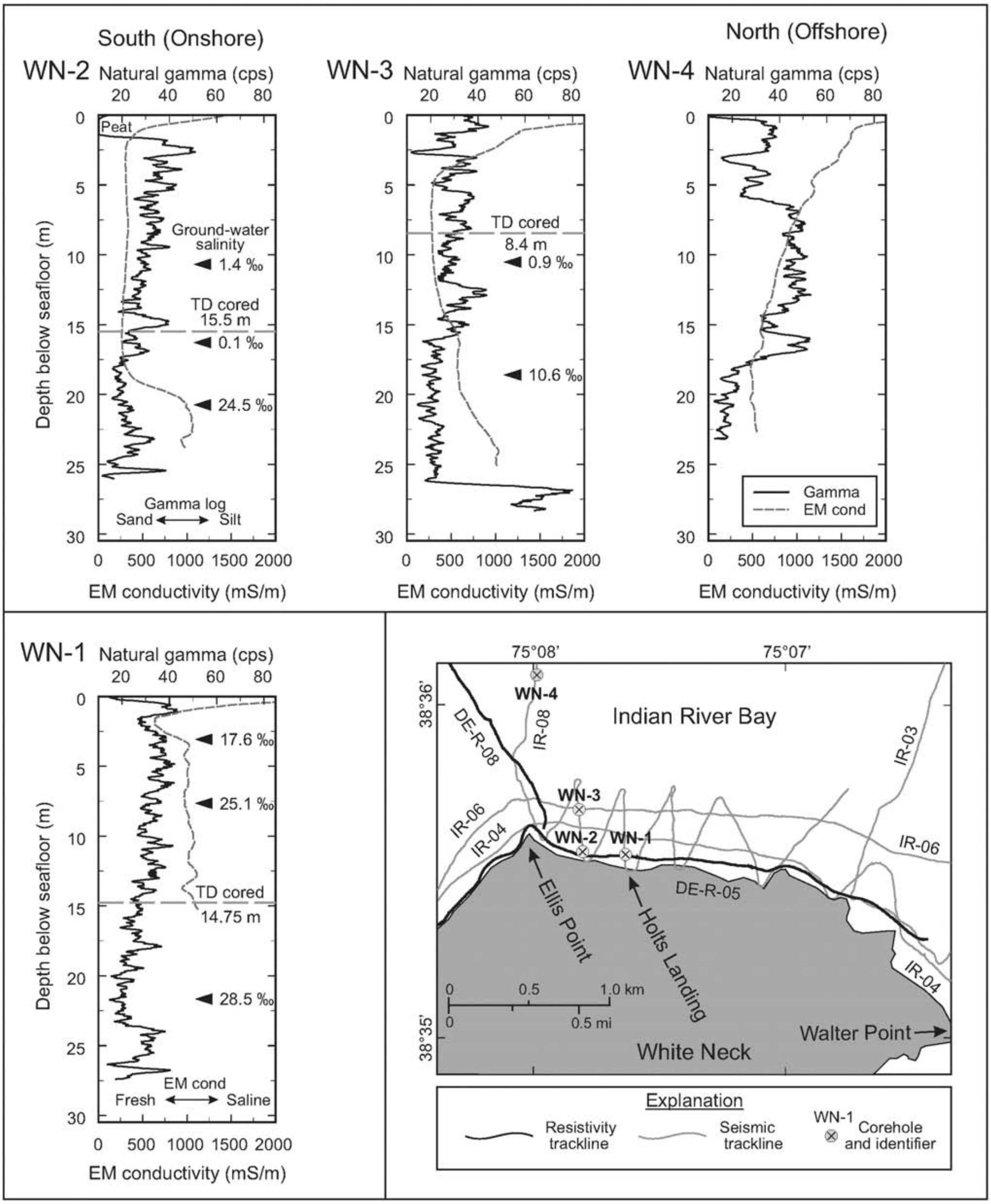

Figure 5. Gamma and EM logs for coreholes WN–1 through WN–4. Inset map shows resistivity and seismic tracklines, and location of coreholes in Indian River Bay off White Neck. Total depth cored and salinities of pumped ground water samples are indicated for coreholes WN–1, WN–2, and WN–3; only geophysical logs were completed at site WN–4.

previous soil horizon. The silty sands from 2.5 to 14 m are the nearshore and back-barrier deposits of the Omar Formation. As in corehole WN–1, the siltier layer between 14 and 17.5 m separates the silty sands of the Omar Formation above from the coarse sands with gravel of the Beaverdam Formation below. In turn, the coarse sands are underlain by slightly finer-grained beds at 23 and 25 m.

The EM conductivity log for corehole WN–2 (Figure 5) shows an abrupt drop from > 1500 mS/m at the sediment-water interface to < 350 mS/m at 2 m. This rapid transition is verified by measurements of pore fluid salinities from the core that decrease from surface salinities near 27 ‰ to < 0.2 ‰ at 1 m (Bratton et al., this issue). The EM conductivity log remains below 350 mS/m from 2 m down to 17.5 m, where it increases sharply to 1050 mS/m at 22 m. Pore fluid samples from the core and pumped ground water samples in the interval between 1.5 and 21 m all have salinities below 1.5 ‰, supporting the evidence from the EM log of a thick layer of fresh ground water at this site. The deepest pumped ground water sample (20.7 m) has a salinity of 24.5 ‰ near the top of the high-conductivity interval below 20 m.

The Holocene estuarine sediments are thicker at WN–3 than at either of the previous two sites. The upper 1.6 m of the sediment is organic-rich, fine-sandy silt deposited in the open bay; this layer overlies a muddy sand between 1.6 and 2.6 m. The abrupt drop in the gamma log at 2.6 m (Figure 5) represents a peat that was deposited in the incised valley. As in core WN–2, the peat immediately overlies a mottled, weathered soil horizon between 3.5 and 4.5 m, which is the pretransgressive surface. Because this site is in the open bay and farther from shore than WN–1 and WN–2, both the Holocene and Pleistocene sediments are generally siltier. In the Pleistocene section, from 3.5 to 12 m, individual silt beds are separated by sands, such as those that appear at 5, 7, and 12 m in the gamma log. As with coreholes WN–1 and WN–2, a siltier unit separates the Pleistocene sequence from the sands of the Beaverdam Formation below 16 m. A very hard, compacted silt at the bottom of the hole, below 26 m in the gamma log, is likely to be marine silt in the upper Bethany formation, but might be a channel-fill unit within the Beaverdam Formation. This same unit stopped drilling penetration in holes WN–1 and WN–2 at similar depths, and is interpreted as a confining bed at the base of the surficial aquifer. With the regional dip, the top of the Bethany formation is 30 to 35 m below sea level 4 km east of the White Neck site, but shallows to 23 m below sea level 9 km to the west.

The EM conductivity log for corehole WN–3 (Figure 5) has more structure than that of WN–2. The estuarine silt in the upper 1.6 m of corehole WN–3 has conductivity values above 1300 mS/m. The transition to low conductivity values at 5 m has several changes in slope that coincide with the lithologic change to muddy sand at 1.6 m, and at the peat overlying the paleosol at 2.6 m. The first truly fresh ground water indicated by the EM log coincides with a gravelly sand at 5 m that is isolated from the overlying saline water by the weathered horizon as a semiconfining layer. Below 12 m, which coincides with the top of the siltier unit, the EM log gradually increases until it reaches fairly constant values around 575 to 600 mS/m between 16 and 20 m; a ground water sample from 18.6 m had a salinity of 10.6 ‰. The conductivity values below 20 m gradually rise to a maximum near 1000 mS/m at 25 m.

The gamma log for site WN–4 (Figure 5) shows a 15 m section comprising several layers of silt or clayey silt, each underlain by sand, that is interpreted as the Holocene infill of the Indian River incised valley imaged in seismic line IR–08 and cored to 6 m previously by Chrzastowski (1986). The thickest of these silt units, from 6 to 14 m, has a negative gamma excursion below it that may be either a peat (with low gamma signature) or a fluvial sand at the base of the incised valley. The silt bed between 16 and 17 m may be a remnant of an older, Pleistocene, infill sequence in the same valley. The sand unit below 18 m correlates with the sands assigned to the Beaverdam Formation in the other coreholes.

The EM conductivity log for corehole WN–4 differs notably from the other three. Conductivity values near 500 mS/m below 18 m appear to indicate the presence of moderately fresh ground water in the lower sands, although this was not verified with water samples. Above 18 m, the conductivity values increase almost linearly to values above 1500 mS/m within 1 m of the sediment-water interface. Slight inflections in the EM log coincide with lithologic changes indicated by the gamma log, such as between 4.5 and 6 m, and at the base of the incised valley at 17.5 m.

The EM-conductivity logs of the coreholes are critical for evaluating the resistivity profiles. The resistivity streamer used for the Indian River Bay survey had 10 m spacing between electrodes measuring potential, which provides deep penetration, but with a loss of vertical resolution. Consequently, the vertical positions of subsurface features in the resistivity profiles, produced by inversion modeling, are not well constrained and do not have the vertical resolution of the EM logs. The effect of the vertical resolution can be seen by comparing resistivity profile DE-R–05 (Figure 3) with the corehole logs (Figure 5). Resistivity profile DE-R–05 suggests that the upper boundary of the fresh ground water plume at site WN–2 (2400 m along the transect) is near 10 m below sea level and the lower boundary deeper than 25 m. In contrast, the EM log for WN–2 places the upper and lower boundaries of the plume at 1 and 17.5 m, respectively. The other resistivity profiles from this survey probably are affected similarly, and vertical positions from the inversion modeling should not be considered absolute. Other investigators in a subsequent project used a different streamer with 2 m spacing between electrodes, which gave much more detail in the upper 10 m, but with loss of penetration (White 2002). As streaming resistivity becomes a standard geophysical tool for this type

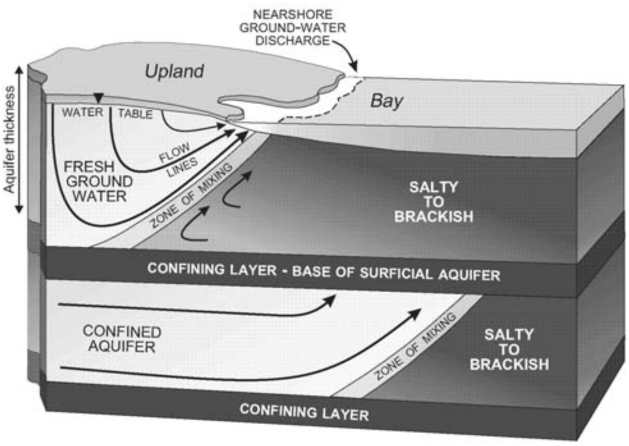

Figure 6. A standard representation of ground water flow and discharge from a layered coastal aquifer system into an estuary (modified from Andres [1987]). Fresh ground water recharged on the upland flows through an unconfined surficial aquifer to discharge in a relatively narrow zone near the shore of the estuary. A wedge of saline water underlies the fresh ground water, and a mixing zone develops between the fresh and saline waters. A second mixing zone that develops in the deeper confined aquifer may be offset seaward from that of the surficial aquifer.

of study, the choice of streamer and electrode spacing should be optimized for the hydrologic setting and research objectives. Alternatives may be to survey the same area using two streamers with wider and narrower electrode spacing, or to develop a streamer with variable electrode spacing for higher resolution at shallower depths and lower resolution at deeper depths.

Discussion

The resistivity profiles from Indian River Bay provide insight into the spatial distribution of fresh and saline ground water beneath the estuary that cannot be obtained readily by other means. The three-dimensional structure inferred from the resistivity profiles and the coring operation is more complex than a simple inclined interface between fresh and saline ground water. The results show the importance of stratigraphic control on the ground water flow and discharge beneath and to the bay, with advective flow of fresh ground water that extends well offshore, vertical flow of sea water from the estuary into the surficial aquifer, and mixing of fresh and saline ground waters.

In simplified, two-dimensional representations of submarine ground water discharge, fresh ground water from the upland flows through the surficial aquifer and discharges near the shoreline into a body of saline surface water (Figure 6) (Freeze and Cherry 1979; Reilly and Goodman 1985). Differences in density between the fresh and saline ground water masses create a wedge, or parabolic, interface that is inclined down and landward from the shoreline. Mixing by hydrodynamic dispersion produces a zone of brackish water along the interface and induces localized circulation of the brackish water upward and seaward (Cooper et al. 1964; Reilly 1993), parallel with the interface, which increases the total volume of discharge. The brackish water that mixes and discharges is replaced by a landward flow of salt water from offshore.

In relatively homogeneous surficial aquifers with moderate to high permeability, flow lines of the fresh ground water converge toward a zone of discharge close to the shore of the estuary (Glover 1964), which commonly is observed to be meters to tens of meters wide (LeBlanc et al. 1986; Reay et al. 1992; Cable et al. 1997; Robinson et al. 1998). Areas of focused discharge along the shore may be created by higher permeability sands surrounded laterally and vertically by muds or marsh peats (Millham and Howes 1994; Howes et al. 1996; Portnoy et al. 1998). Some observations of fresh water discharge (Cable et al. 1997) or reduced-salinity ground water at shallow depths beneath the estuary (Langevin 2001) as far as 300 to 600 m offshore imply hydraulic continuity of permeable layers beneath a low-permeability cap.

Layered coastal aquifer systems, with subaquifers separated by confining or semiconfining layers, have been observed (Lusczynski and Swarzenski 1966; Kohout et al. 1977; Folger et al. 1978; Hathaway et al. 1979) and modeled (Collins and Gelhar 1971; Mualem and Bear 1974; Reilly 1990; Bear 1999). In these layered aquifer systems, a vertical sequence of mixing (or transition) zones can form (Figure 6). In the uppermost aquifer shown in Figure 6, the mixing zone lies above the confining layer, and fresh ground water discharges directly to the bay near the shoreline. In the lower, confined aquifer, the transition zone is displaced offshore by the confining conditions, and fresh water discharges upward through the confining layer and into the overlying saline water (Mualem and Bear 1974; Reilly 1990, 1993; Bear 1999).

On a regional scale, fresh ground water has been observed in layered aquifers beneath the U.S. Atlantic continental shelf (Kohout et al. 1988; Meisler 1989). For example, off the coast of New Jersey, a 200 m thick layer of fresh ground water extends 100 km offshore under the shelf (Hathaway et al. 1979; Kohout et al. 1988). The fresh water layer is 80 to 100 m beneath the seafloor and is protected by a clay or silt-clay confining layer from intrusion of the overlying salt water (Kohout et al. 1988). Because of the rapid rise in sea level during the Holocene, this ground water system is not in hydrodynamic equilibrium, and the fresh ground water is considered relict Pleistocene water from recharge during the glacial lowstand(s) (Meisler and Leahy 1983; Meisler et al. 1984). For most observations of fresh (or reduced-salinity) ground water under the U.S. Atlantic shelf, the aquifers typically are 50 to 200 m thick and the confining layers 10 to 50 m thick (Lusczynski and Swarzenski 1966; Kohout et al. 1977; Folger et al. 1978).

The field observations in Indian River Bay indicate a complex pattern of ground water flow and fresh water/salt water mixing that results from the heterogeneous stratigraphy in the shallow subsurface beneath the bay. The surficial aquifer effectively has a thin semiconfining layer at the seafloor, which restricts downward flow of salt water and allows offshore transport of fresh water. Rather than discharging close to shore, fresh ground water flows beneath Indian River Bay in plumes that are on the order of 500 m wide, may extend 1 km or more from shore, and occupy a substantial vertical section in the surficial aquifer. Adjacent to the plumes off White Neck are nondischarge (or minimal-discharge) zones dominated by saline water from the estuary flowing downward into the aquifer. This alternating pattern of discharge and nondischarge zones commonly was observed in the resistivity profiles, especially those collected along the shores of Indian River Bay and the western shore of Chincoteague Bay. The saline ground water beneath the estuary does not appear to be stagnant, and the geochemical evidence, including ground water age dates, indicates active circulation of the saline waters below, and adjacent to, the fresh water plume (Bratton et al., this issue). Saline ground water near the plume was no older, and possibly younger, than fresh water at the same depth.

Resistivity profile DE-R–08, across Indian River Bay, shows a representative section through two large plumes of fresh ground water extending from the north and south shores (Figure 7) (Manheim et al., this issue). In this area of the bay, the shore-parallel resistivity profiles (such as DE-R–05 in Figure 3) show alternating zones of fresh and saline ground water. On line DE-R–08, the contours indicating fresh water are shallow near each bank, but deepen in the first 100 m offshore. The fresh-saline interface at the top of the plume is inclined bayward rather than landward, deepening gradually toward the center of the bay. Within the two plumes, the fresh ground water becomes slightly

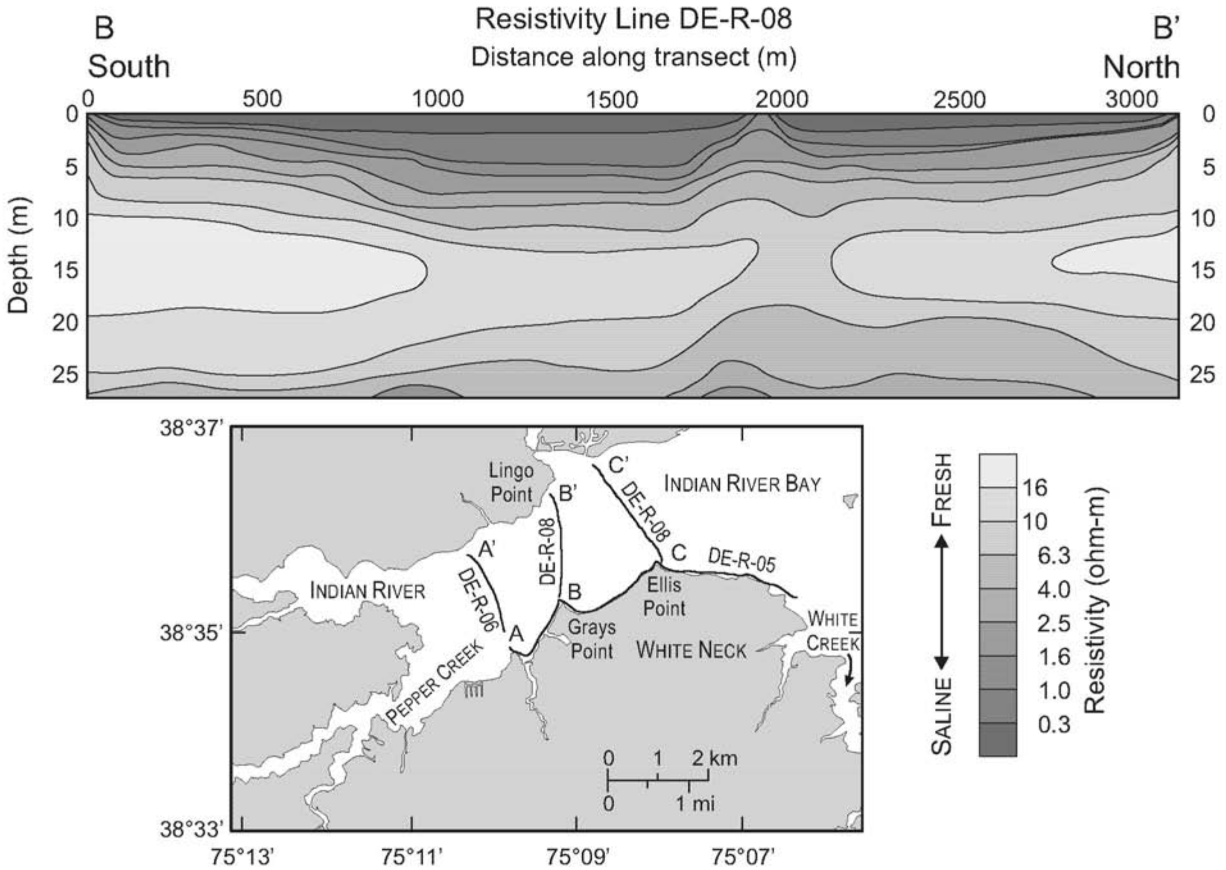

Figure 7. Representative resistivity profile across Indian River Bay—line DE-R–08, section B-B′. As with the profile in Figure 3, high resistivity values are interpreted as fresh ground water beneath the estuary. Fresh water plumes flow from both the south and north shores to discharge near the axis of the incised valley (2000 m along the transect).

more brackish moving offshore as it mixes, and the plume thins to approximately half its initial thickness.

The fresh water plume originating from the south shore flows 2 km beneath Indian River Bay as a coherent ground water mass. Near the axis of the Indian River incised valley, the resistivity contours are convex upward and appear to indicate a vertical component of flow. The plume flowing from the north shore also converges on the incised valley, but is separated from the southern plume. The two plumes probably have similar structure, but may be offset laterally, with the transect running close to the center of the southern plume, but skirting the edge of the northern plume. The spacing of tracklines does not allow an interpretation of the lateral geometry of these plumes, although they likely spread and mix horizontally as they thin and deepen offshore; this possible flow structure is supported by other resistivity lines not presented here. In the shore-parallel lines close to shore, the plumes typically are 300 to 600 m wide. The only shore-parallel line in the survey that is more than 100 m offshore is DE-R–09, which runs west to east through Indian River Bay 1.4 km north of White Neck (Figure 3). Low resistivity sections in line DE-R–09 range from 250 to 750 m wide, and may be the distal ends of discharging plumes.

The onshore-offshore and shore-parallel hydrogeologic sections from White Neck presented in Figure 8 were compiled and interpreted from the resistivity profiles, seismic profiles, cores, and borehole geophysical logs. The compacted silt at the bottom of corehole WN–3 was interpreted as the base of the surficial aquifer. The coarse sands of the Beaverdam Formation form a continuous, high-permeability unit below ~17 m subsurface. A relatively thin (2 to 3 m) semiconfining layer separates the Beaverdam Formation from the overlying silty sand of the Omar Formation. At the top of the sequence, the Holocene organic-rich silts fill the incised valley drainage system created during the last glacial lowstand. The distribution and flowpaths of fresh and saline ground water in these sections were interpreted from the resistivity profiles and the EM-conductivity logs from the coreholes, with supporting evidence from the geochemical analyses (Bratton et al., this issue). Although no water table wells are available on land, the direction of ground water flow on White Neck is interpreted as being toward the streams, with only short, shallow, local flowpaths from the Holts Landing headland flowing directly toward the bay.

End-members in the shore-parallel section are represented by site WN–1 off the Holts Landing headland (an interfluve) and the fresh ground water plume at WN–2; a smaller plume flows offshore east of site WN–1. The nondischarge zone at site WN–1 is interpreted as an area in which saline water from the estuary flows down into the aquifer and beneath the adjacent fresh water plumes. In this case, instead of having a wedge interface nearly parallel with the shoreline, the steepest horizontal gradients of salinity and density are along the lateral boundaries of the plume. The main body of the fresh water plume at WN–2 underlies the incised valleys of two small creeks, which

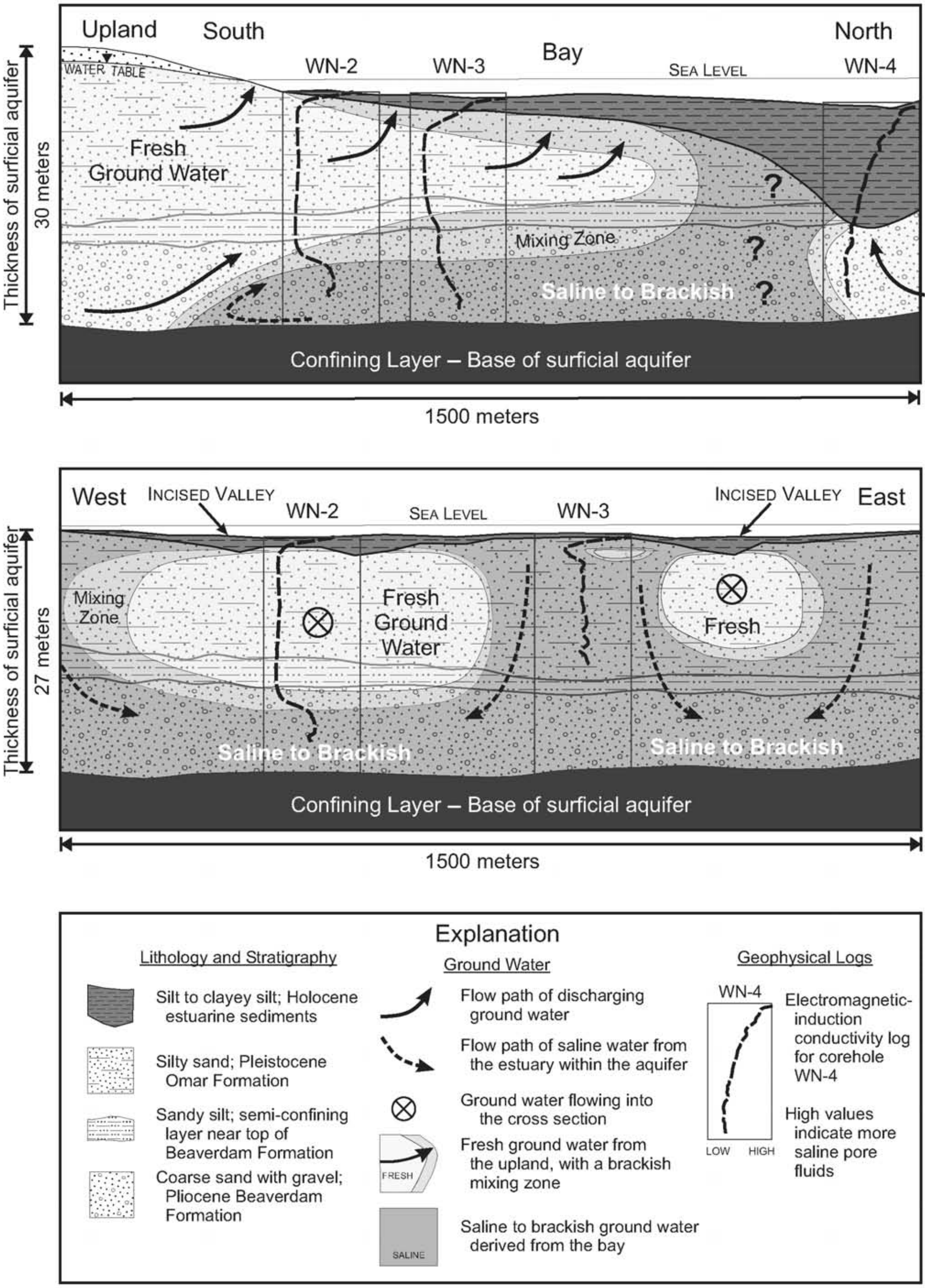

Figure 8. Interpreted sections through the fresh ground water plume off White Neck oriented perpendicular (upper panel) and parallel (middle panel) to shore. Inset map in Figure 5 shows location of coreholes.

converge ~200 m offshore. Although the incised valleys are filled with no more than ~1 m of fine-grained sediment with a basal peat overlying a soil horizon, this permeability contrast appears to be sufficient to separate the fresh ground water from the overlying saline water from the estuary, and to allow the fresh water plume to flow offshore.

The boundaries of the fresh ground water plume show the effects of stratigraphic control on flow and mixing with saline ground water. Near shore, at site WN–2, the upper boundary of the plume is marked by a salinity drop from 27 ‰ to 0 ‰ < 1 m below the seafloor. Farther offshore at site WN–3, this boundary is deeper in the subsurface and the equivalent salinity change is spread over 5 m vertically. Several inflections in the EM log across this transition coincide with lithologic changes indicated by the core and gamma log. Similarly, the lower boundary of the plume shallows and changes structure as it moves offshore. A simple salinity gradient across 5 m vertically at site WN–2 develops into a separate mass of mixed water with 10 ‰ salinity at site WN–3 300 m offshore. At both sites WN–2 and WN–3, the semiconfining layer near 15 m separates the higher-salinity water below from the fresh water plume above.

A fundamental question at the start of the project was how a thick (15 m) sequence of low-permeability silt filling the main incised valley of the Indian River affects ground water flowpaths and discharge. The EM log from corehole WN–4 (Figures 5 and 8), in the axis of the incised valley, is unique among the four sites. The freshest ground water at site WN–4 is in the deep section of the surficial aquifer, in the sand of the Beaverdam Formation. Based on the EM conductivity values between 500 and 600 mS/m, the salinity of this ground water probably is between 7 ‰ and 10 ‰. In contrast, the deep ground water at the other three sites had salinities between ~24 ‰ and 29 ‰. The EM log for site WN–4 shows an almost linear mixing between the low-salinity ground water below 17.5 m and the surface water, through the silt sequence filling the valley. In this vertical section, pore fluid salinity appears to be controlled by relatively slow dispersion through the low-permeability sediments.

The 700 m gap between sites WN–3 and WN–4 does not allow a direct link between the low-salinity ground water at WN–4 and the plume flowing from the south bank. A more likely connection is with a separate plume flowing toward the center of the bay from the north shore, similar to that shown in profile DE-R–08 (Figure 7). Because of the regional dip, the lower section of the aquifer comprising the Beaverdam Formation recharges west and northwest of Indian River Bay (Hodges 1983; Denver 1986), and should have sufficient hydraulic head to drive ground water flow deep in the surficial aquifer beneath the bay. Concentrations of nitrate and chlorofluorocarbons in nearby wells on land show that ground water near the base of the surficial aquifer (depths to 30 m) generally is on the order of 30 to 50 years old (Andres 1991; Dunkle et al. 1993).

All of the data from this study indicate that the large volume of fresh ground water transported by the plumes under Indian River Bay ultimately discharges by dispersion through the fine-grained, organic-rich Holocene sediments. Focused ground water discharge was not observed in this section of Indian River Bay, except locally within ~10 m of shore at the headlands (such as Ellis Point), where sandy Pleistocene sediments have thin or no overlying Holocene material (McKenna 2001). In contrast, aerial thermal-infrared imagery (McKenna 1999) showed areas of focused discharge farther upstream in the Indian River where the adjacent uplands have greater relief than on White Neck (McKenna et al. 2001). The resistivity profiles from these same areas in the Indian River show prominent zones of high resistivity indicating fresh water in the shallow subsurface (Manheim et al., this issue). Because the geophysical results provide only a snapshot of ground water flow, temporal aspects such as tidal pumping over semidiurnal and neap-spring cycles cannot be evaluated. Similarly, these results represent conditions during a dry season following an extended drought, so the water table was lower than the long-term average. Considering the spatial scale of the fresh water plumes and ground water ages on the order of 50 years near the base of the plume (Bratton et al., this issue), it is likely that the overall configuration and dynamics of the flow system are fairly similar through annual or longer wet-dry cycles. However, it is likely that ground water flow rates, particularly for shallow and short flowpaths, would increase with wet conditions and a higher water table.

The surficial aquifer beneath Indian River Bay can be viewed as a layered coastal aquifer with a semiconfining layer of variable thickness at the seafloor and a second semiconfining layer at ~15 m. The spatial scales of stratigraphic control on ground water flow and mixing in this system are intermediate between shallow, local flow systems, such as those observed on Cape Cod (Millham and Howes 1994; Howes et al. 1996; Portnoy et al. 1998), the Virginia Eastern Shore (Reay et al. 1992; Robinson et al. 1998), and the Florida Gulf Coast (Cable et al. 1997), and the regional aquifers beneath the U.S. Atlantic shelf described by Kohout et al. (1988) and Meisler (1989). Many shallow coastal bays on passive margins have a geologic framework similar to Indian River Bay, with a lowstand drainage network of incised valleys that filled with low-permeability peats and fine-grained sediments during the Holocene sea-level rise. Observations of reduced-salinity ground water discharging to, or underlying, coastal estuaries as far as 300 to 600 m offshore (Cable et al. 1997; Langevin 2001) suggest that the structure of the ground water flow system observed under Indian River Bay may be a common mode of submarine ground water discharge to this type of estuary.

Summary

The combined use of a variety of drilling, geophysical, and geochemical methods, including some novel applications, has yielded a detailed view of the distribution of fresh and saline ground water beneath Indian River Bay, Delaware. High-resolution seismics were used to delineate the incised valleys of the lowstand drainage network, the thickness of the Holocene sediments filling the basin, and the internal geometry of the surficial (unconfined) aquifer and the upper section of the confined aquifer system. Streaming horizontal resistivity allowed mapping of the distribution of fresh and saline ground waters beneath this shallow coastal bay by detecting changes in subsurface resistivity to depths of 30 m. The resistivity profiles parallel to the shore of Indian River Bay show alternating subsurface zones of high resistivity, interpreted as fresh ground water flowing offshore, and low resistivity, interpreted as saline water from the estuary moving down into the aquifer. Resistivity lines across the bay show plumes of fresh water emanating from the land margin and flowing beneath the bay to discharge near the center of the bay.

Cores and gamma logs from four sites provided a vertical sequence of lithology to correlate with the seismic profiles and infer permeability structure. EM logs were run to measure pore fluid conductivities for comparison with the resistivity profiles. The gamma and EM logs were interpreted to guide in situ sampling of discrete ground water masses using a screened drivepoint for geochemistry and age dating. The combined results show a complex and dynamic system of ground water flow with appreciable control by stratigraphy. The flow of fresh ground water produces plumes 20 m thick and 400 to 600 m wide that may extend 1 km or more from shore beneath the estuary. The lateral boundaries of a fresh water plume may be abrupt and nearly vertical, or extend horizontally as a diffuse layer for hundreds of meters. The lower boundary of the plume shallows moving offshore and a mixing zone with brackish water develops. The ground water plumes studied follow incised valleys of tributary streams, but the dimensions of the plumes are much larger than the valleys. The fine-grained, low-permeability sediments filling the valleys appear to act as semiconfining layers that restrict infiltration of the overlying saline water of the estuary and permit flow of fresh water far offshore.

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