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The importance of shallow confining units to submarine groundwater flow

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Abstract In addition to variable density flow, the lateral and vertical heterogeneity of submarine sediments creates important controls on coastal aquifer systems. Submarine confining units produce semi-confined offshore aquifers that are recharged on shore. These low-permeability deposits are usually either late Pleistocene to Holocene in age, or date to the period of the last interglacial highstand. Extensive confining units consisting of peat form in tropical mangrove swamps, and in salt marshes and freshwater marshes and swamps at mid-latitudes. At higher latitudes, fine-grained glaciomarine sediments are widespread. The net effect of these shallow confining units is that groundwater from land often flows farther offshore before discharging than would normally be expected. In many settings, the presence of such confining units is critical to determining how and where pollutants from land will be discharged into coastal waters. Alternatively, these confining units may also protect fresh groundwater supplies from saltwater intrusion into coastal wells.

Key words Atlantic; coastal aquifer; confining unit; glaciomarine; groundwater; mangrove; peat; salt marsh; saltwater intrusion; nutrients

INTRODUCTION

As the phenomenon of submarine groundwater discharge has been investigated more intensively over the last decade, several critical data gaps and technological obstacles have emerged (Taniguchi *et al.*, 2002; Slomp & Van Capellen, 2004; Burnett *et al.*, 2006; Gallardo & Marui, 2006). Among these barriers to answering research questions and solving coastal management issues has been the problem of poorly documented submarine stratigraphy and hydrogeology. Many modelling or field studies that initially assumed simple "sandbox" geology at shoreline sites, as suggested by the surficial appearance of many beaches (Fig. 1(a)), had to be modified as field results became available (Fig. 1(b)–(d)) Seepage meter measurements and subsurface sampling have commonly indicated the influence of unexpected lower permeability sediments at depths of less than a metre to several metres beneath the beach and seafloor. Often these investigations have treated the fine-grained units as curious anomalies that complicated experiments which were intended to be more straight-forward. Rarely, however, have investigators attempted to synthesize such phenomena into a coherent typological framework.

For land-based hydrological investigations, stratigraphy of unconsolidated units is normally determined by soil borings. Piezometers or monitoring wells are installed to measure heads, determine flow directions, and collect water-quality samples. In shoreline and submarine studies, these types of investigations become more difficult due to problems associated with accessing the areas with drilling rigs, and installing

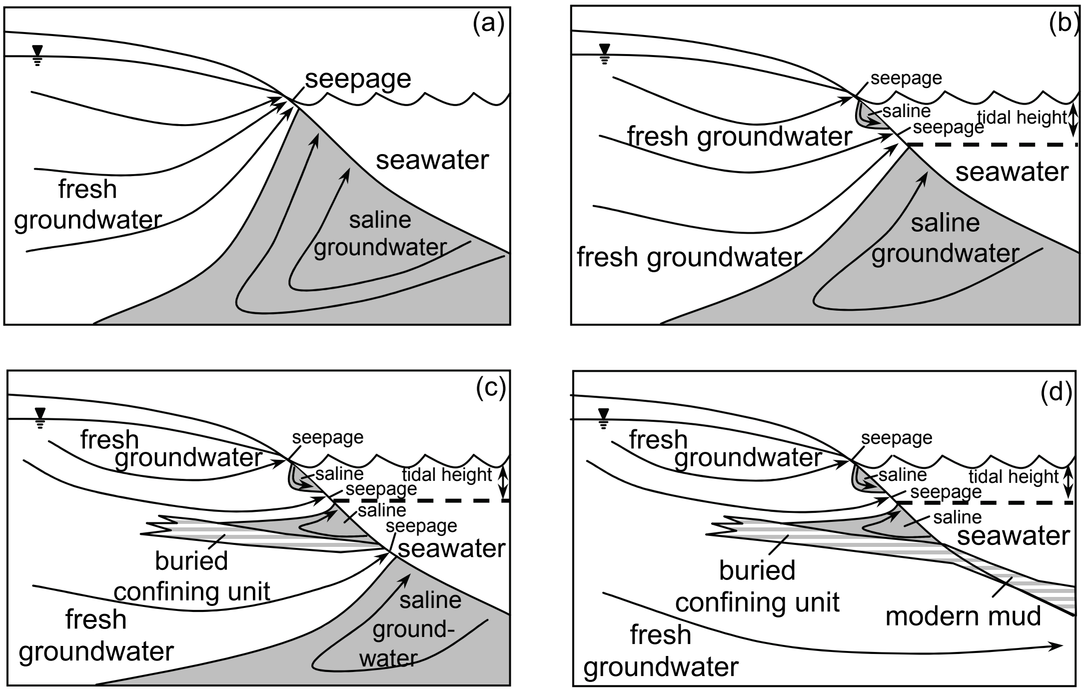

Fig. 1 Schematic diagrams showing: (a) the geometry of a typical fresh–saline interface in a coastal groundwater system, and the circulation within each portion of the aquifer; (b) how the addition of tides can create a shallow saline circulation cell in groundwater beneath the intertidal zone, and two discharge zones, as described in the text; (c) how the presence of a shallow submarine confining unit can create an additional seepage zone and saline circulation cell; and (d) how a more extensive submarine confining unit, formed by the combination of a buried unit and/or fine-grained sediments that are being actively deposited, can create a long (up to kilometres) submarine flow path for fresh groundwater.

wells and piezometers that can withstand the effects of waves, tides, and moving ice. Between 2000 and 2003, six intercomparison experiments were performed using combinations of seepage meters, piezometers, models, geophysical instruments, and other techniques (Burnett *et al.*, 2006). In several of these studies, including sites in Australia, Florida, and New York, discharge patterns were influenced by the presence of shallow confining units. At the Florida site, an anomalous band of discharge was observed between 80 and 100 m offshore (Smith & Zawadzki, 2003) and was attributed to leakage through a "window" in a buried confining unit. Seepage meters deployed during other experiments in Waquoit Bay, Massachusetts (Michael *et al.*, 2005) showed a 15-m wide band of unusually high discharge parallel to the shore, but offset about 15 to 20 m offshore, that may have been influenced by a confining unit. Submarine flow of fresh or brackish water controlled by shallow confining units has also been documented beneath coastal bays in Delaware and Maryland (Bratton *et al.*, 2004; Krantz *et al.*, 2004; Manheim *et al.*, 2004), and beneath the Neuse River Estuary in North Carolina (Cross *et al.*, 2006) and Nauset Marsh in Massachusetts (Bratton *et al.*, 2006).

This paper synthesizes available information on the origins and significance of submarine confining units, with the goal of providing a foundational conceptual model for considering their role in the solution of current scientific and societal problems.

The focus is on examples from the Atlantic coast of the USA. The discussion, however, broadens the application of these examples to other similar coastal settings. The conclusions particularly apply to other passive margin coastlines with active sedimentation, such as those found around much of the Atlantic, Mediterranean, and Arctic basins, as well as the coasts of Australia, eastern Africa, and India.

ORIGINS OF CONFINING UNITS

The ways in which submarine confining units are formed vary both temporally and areally. The process that indirectly produces most of the conditions necessary for formation of such deposits is global climate change. Climate-driven cycles of ice sheet growth and retreat cause vertical sea-level fluctuations and lateral shoreline migrations. As described by Walther's law (Middleton, 1973), lateral movement of adjacent high-energy and low-energy environments, such as sandy beaches and muddy lagoons, results in the stacking of sediment units with different permeabilities. Sands and gravels from high-energy environments act as conduits for groundwater flow. Fine-grained sediments, which are generally deposited in sheltered embayments or depressions during sea-level stillstands and highstands, are barriers to groundwater flow.

The most extensive coastal confining units in many modern systems were deposited between glaciations, particularly during the last interglacial (Marine Isotope Stage [MIS] 5, especially 5e [i.e. Eemian, Ipswichian, or Sangamon age]). Deposits of this age are found throughout tropical and mid-latitude coastal areas, except where they have been eroded away during intervening glacial periods with corresponding low sea levels and subaerial exposure of highstand deposits. In many high-latitude coastal areas such deposits were removed by glacial scour during the last ice age.

There are many regionally extensive deposits of fine-grained sediments from interglacial highstands, or from relative highstand deposits that have been subsequently uplifted. These formations commonly form shallow onshore confining units that extend offshore (Fig. 1(c)). Examples include shallow marine or back-barrier deposits found around the shore of Chesapeake Bay, the Virginia and North Carolina coasts, the northern Gulf of Mexico, and the southern Baltic Sea and North Sea of northern Europe.

The second major category of modern submarine confining unit is deposits formed during the late Pleistocene or Holocene transgression. These units consist of latitudinally distinct biogenic deposits, proglacial deposits, and common estuarine and marine muds (Fig. 1(d)). The biogenic deposits are peats formed at the shoreline, or slightly inland, and derived from mangroves or sawgrass in the tropics, and salt marshes and coastal freshwater marshes and swamps at higher latitudes (Fig. 2). Many such deposits that are no longer actively forming are now submerged below sea level and either exposed on the seafloor, or buried at shallow depths along the coast and offshore.

Mangroves are present along modern tropical and subtropical shorelines up to approximately 28°N and S latitude on western margins of ocean basins, and about 15 to 20°N and S along eastern margins (Fig. 2). In the mid-1990s the total surface area covered by mangroves was 181 000 km^2, or about 8% of the global coastline and 25% of tropical coastlines (Spalding *et al.*, 1997). Submerged mangrove peats have been

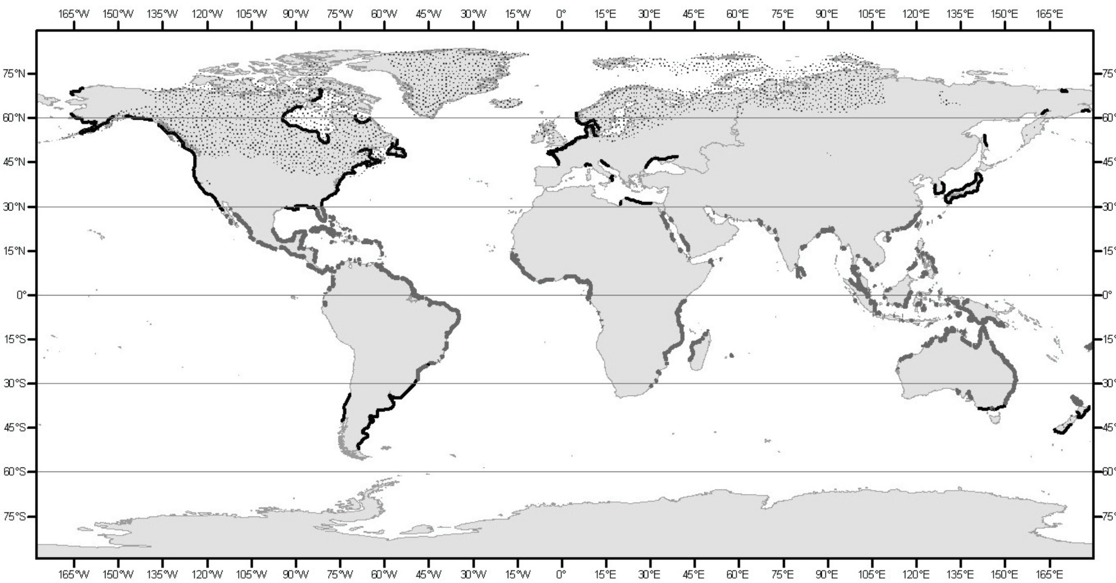

Fig. 2 Map showing global coastlines where mangrove swamps (heavy grey lines) and salt marshes (heavy black lines) are present. The stippled area was covered by ice at the last glacial maximum. Salt marsh and mangrove information is modified from Sumich (1999) and Spalding *et al.* (1997). Glacial limits are from Ray & Adams (2001).

observed around the world at sites including Florida (Robbin, 1984), Belize (Macintyre *et al.*, 2004), and the South China Sea (Hanebuth *et al.*, 2000). Where submerged peats from drowned mangroves either extend close enough to shore to intersect the unconfined seepage face, or are laterally continuous with peats beneath living mangroves, conditions are present for these peats to act as shallow submarine confining units. This is particularly true in areas with very low coastal relief, such as the carbonate platforms of Florida or the Bahamas. The tendency of living mangroves to create brines further complicates the groundwater flow systems in these types of settings (Greenwood *et al.*, 2006). In some tropical and subtropical settings, such as the Florida Everglades, areas inland of mangroves are covered by extensive sawgrass (*Cladium* sp.) marshes (Willard *et al.*, 2006), which also form peats. As sea level rises, mangroves may migrate inland, causing mangrove peat to be deposited over marsh peat (Willard & Holmes, 1997). In Belize, mangrove peat up to 10 m thick has been documented (Macintyre *et al.*, 2004).

Mid- to high-latitude coastal plain shores contain intertidal salt marshes dominated by cordgrass (*Spartina* sp.) and other salt-tolerant vegetation (Fig. 2). The range of these marshes (~25°N and S along western ocean boundaries, ~20°N and S on eastern boundaries due to colder boundary currents) overlaps slightly with that of mangroves, and extends into the subarctic. In the United States, submerged peats have been documented along the Atlantic coast in Maryland, New York, Massachusetts, and Maine, among other locations (Emery *et al.*, 1967; Field *et al.*, 1979, Thieler *et al.*, 1999; Buynevich & FitzGerald, 2002; Bratton *et al.*, 2004, 2007). In low-lying coastal areas inland of salt marshes, freshwater marshes of cattails, bulrushes, phragmites, and sphagnum form peats as well. Forested wetlands or swamps in some areas up to about

38°N or S along the western Atlantic coast also contain cypress and gum trees. At higher latitudes, vegetation in coastal swamps is dominated by red maples, oaks, or Atlantic white cedars. Like salt marshes, these swamps can form low-permeability peats that are later submerged and buried as sea level continues to rise (e.g. Dillon, 1970). In the subarctic and arctic, at latitudes higher than about 55°, coastal wetlands are dominated by salt-tolerant grasses and sedges, with muskeg and tundra vegetation further inland. Coastal and submarine permafrost also becomes hydrologically significant in the subsurface in these regions (Gosink & Baker, 1990).

At latitudes north of 40° along the Atlantic coast of North America and 50° along the coasts of Europe, Asia, and the Pacific coast of North America, large areas of fine-grained glaciomarine and glaciolacustrine deposits from the end of the last glaciation are present on the inner continental shelf (Fig. 2, stippled area). Along coasts that were isostatically depressed due to glacial loading and that subsequently rebounded (Barnhardt *et al.*, 1995; Lambeck, 1995), extensive deposits of these silty and clayey sediments are now locally exposed above sea level, such as the Presumpscot Formation of Maine (Bloom, 1963; Fig. 3, hatched area). Other glacially-derived sediments remain submerged, such as the fine sands, silts, and clays deposited in ephemeral proglacial lakes during the late Pleistocene on the inner continental shelf of southern New England (Fig. 3; Uchupi *et al.*, 2001). In areas where these units reach

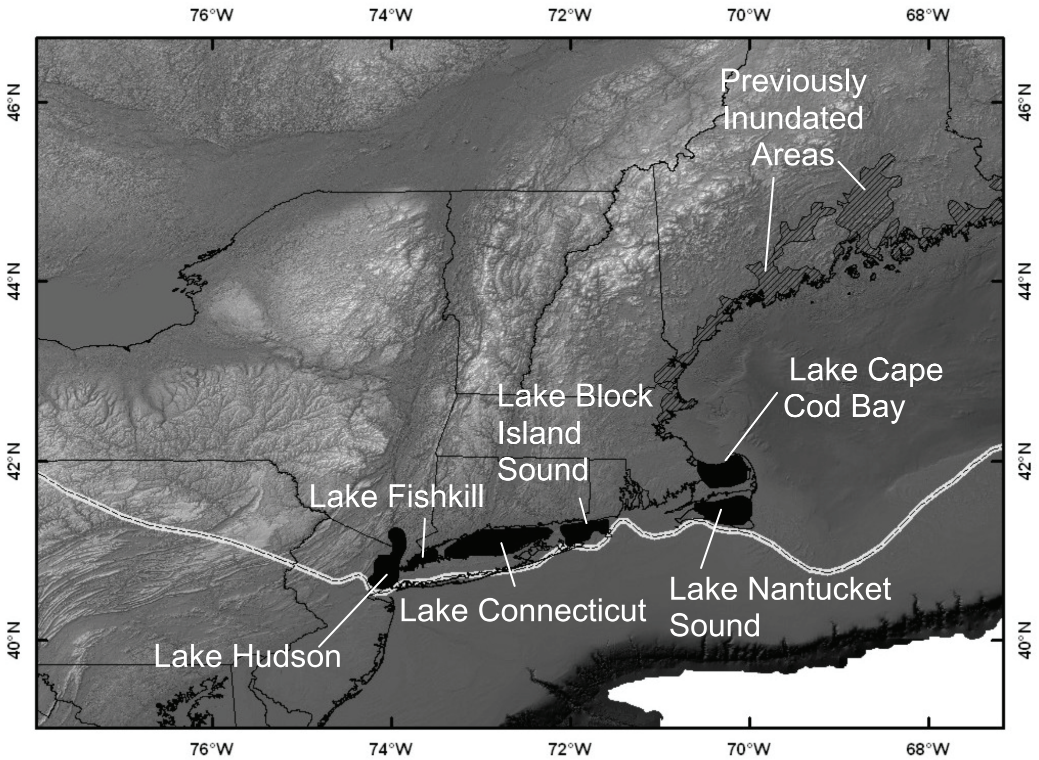

Fig. 3 Shaded relief and bathymetric map of the northeastern United States and Canada showing locations of maximum glacial ice extent during the last Ice Age (dashed white line), proglacial lake beds now mostly submerged (black), and areas of coastal Maine and Massachusetts inundated shortly after deglaciation (hatched area) (modified from Uchupi & Mulligan, 2006).

the nearshore or continue onshore, they serve as very effective confining units. In some locations, fine-grained sediments associated with previous glaciations or marine highstands may also be present beneath late Pleistocene deposits on the inner shelf (Person *et al.*, 2003; Uchupi & Mulligan, 2006).

Estuarine and marine muds, like sediments from previous sea-level highstands such as MIS 5e, are currently being deposited below the wave base and on intertidal mudflats in many coastal areas. This sediment type is especially common in sheltered or deep estuaries, back-barrier lagoons, and near the mouths of large rivers. These surficial confining units can be more than 20 m thick in deep palaeochannels or drowned basins (e.g. Bratton *et al.*, 2003), but are generally much thinner. Thickness often decreases toward the shore where wave action prevents silt and clay from settling out. Although fine grained, the effective permeability of some of these units is increased by bioturbation of infaunal organisms such as bivalves, polychaetes, crabs, and shrimp, some species of which burrow up to 2 m into the seafloor. The uppermost tens of centimetres of estuarine sediments also tend to be only minimally consolidated, with water content values often exceeding 70 percent. Estuarine muds have been observed to overlie buried peats in shallow coastal estuaries (Bratton *et al.*, 2004, 2007; Krantz *et al.*, 2004); and fluvial sand and gravel, beach sand, or oysters (Bratton *et al.*, 2003).

SIGNIFICANCE OF CONFINING UNITS TO SUBMARINE GROUNDWATER FLOW

Historically, coastal and submarine groundwater flow systems have generally been oversimplified. Situations where the groundwater follows a simple Ghyben-Herzberg geometry, with a single wedge of saline groundwater underlying a fresh lens that discharges in a narrow band at the shoreline (Fig. 1(a)), may be more the exception than the rule. Shallow confining units can produce a pattern of two or more discharge zones (Fig. 1(c) and (d)). Permeable shorelines that are subject to significant tides, however, also tend to develop shallow saline flow cells that can mimic the effect of a shallow confining unit by creating two discharge zones (Fig. 1(b)). This was recently observed at a study site in Australia and simulated with a variable-density model (Robinson *et al.*, 2006).

Early variable-density models treated the ocean side of coastal model domains as a simple vertical boundary with hydrostatic saltwater pressure (Dominick *et al.*, 1971). Results of numerous field studies that showed the importance of a more realistic sloping (non-vertical) seepage face subject to tidal pumping are now being incorporated into variable-density models of shoreline aquifer systems (Ataie-Ashtiani *et al.*, 2001). Some modelling studies (e.g. Kooi & Groen, 2001; Bakker, 2006) have also incorporated semi-confined offshore conditions into their analyses; results include migration of the fresh–salt boundary in groundwater farther offshore.

The overall result of these refinements of coastal groundwater flow models is that they are better able to reproduce actual conditions observed in the field. As field measurement techniques have improved, new processes and problems have been identified and models have facilitated more sophisticated quantitative testing of ideas about submarine flow, reaction, and discharge processes. The conceptual framework and instrumental toolkit for approaching submarine geological heterogeneities in something other than case-by-case mode is now starting to emerge. Development of shoreline typologies is likely to be a fruitful approach (Bokuniewicz *et al.*, 2003).

The significance of submarine confining units to submarine groundwater flow and discharge ultimately comes down to questions of scale: How common are these units? How thick are they? How continuous are they? How far onshore and offshore do they extend? How much head is required to establish offshore flow in submarine confined systems? How quickly do these systems respond to changes in recharge? The more prevalent and extensive submarine confining units are, the more they impact coastal aquifers and land–sea interactions. Their primary effect is to broaden or split the zone of contact in the subterranean estuary (Moore, 1999) between land-derived water and ocean water. This, in turn, increases the lengths of submarine flow paths and residence time of water in submarine flow systems. The result is a greater time lag in the response of the groundwater systems to changing surface conditions, and more complicated or substantial submarine biogeochemical reactions.

IMPLICATIONS FOR MANAGEMENT AND SCIENCE

In some estuarine settings, groundwater discharge may be the primary route by which freshwater (and associated nutrients and contaminants) enters the coastal system. Submarine confining units influence discharge patterns in important ways, such as displacing discharge offshore (e.g. seaward of barrier islands rather than into lagoons) or creating conditions conducive to more diffusive rather than advective discharge. In settings where onshore groundwater has been impacted by pollutants, detecting the presence of coastal and submarine confining units is critical to understanding how and where the pollutants will be discharged into coastal waters, and what remedial measures might be appropriate (McCobb & LeBlanc, 2002; Kroeger *et al.*, 2006).

In the particular case of nitrate contamination, the presence of submarine confining units that are enriched in organic matter is likely to increase the amount of nitrate removal from groundwater prior to discharge via denitrification (Capone & Slater, 1990; Bratton *et al.*, 2004, 2007). There are also potential linkages between submarine groundwater discharge and the presence of microbial pathogens at beaches, which would be affected by submarine flow paths (Boehm *et al.*, 2004). Finally, confining units may protect fresh groundwater supplies from saltwater intrusion into onshore wells used for drinking water or irrigation. Such situations would call for the protection of submarine confining units from breaching by dredging and other marine construction (e.g. Foyle *et al.*, 2002).

CONCLUSIONS

It is not surprising that the stratigraphy of coastal aquifers plays a critical role in determining their flow and discharge behaviour. What has been less clear, however, is that offshore stratigraphy may differ significantly from that of nearby onshore areas. Layered sediments with different hydrogeological properties provide many potential pathways for submarine groundwater flow and discharge, as well as for saltwater intrusion. Intensive recent investigations of groundwater systems spanning the shoreline in many settings have shown: (1) that submarine confining units are widespread, and (2) that they can strongly influence patterns of submarine groundwater discharge and associated phenomena such as pollutant discharge, oceanic elemental budgets, microbial contamination of beaches, and saltwater intrusion. Further development of a typological understanding of the eustatic, hydrographic, biogenic, and glaciogenic origins of such confining units will help in predicting where they may be important, both scientifically and societally, in previously unstudied locations.

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REFERENCES

Ataie-Ashtiani, B., Volker, R. E. & Lockington, D. A. (2001) Tidal effects on groundwater dynamics in unconfined aquifers. *Hydrol. Processes* **15**(4), 655–669.

Bakker, M. (2006) How far does a seawater intrusion model need to be extended below the sea bottom? In: *Abstracts, First International Joint Salt Water Intrusion Conference* (1st SWIM-SWICA, Cagliari–Chia Laguna, Italy, September 2006).

Barnhardt, W. A., Gehrels, W. R., Belknap, D. F. & Kelley, J. T. (1995) Late Quaternary relative sea-level change in the western Gulf of Maine; evidence for a migrating glacial forebulge. *Geology* **23**(4), 317–320.

Bloom, A. L. (1963) Late Pleistocene fluctuations of sea level and postglacial crustal rebound in coastal Maine. *Am. J. Sci.* **261**(9), 862–879.

Boehm, A. B., Shellenbarger, G. G. & Paytan, A. (2004) Groundwater discharge: a potential association with fecal indicator bacteria in the surf zone. *Environ. Sci. Technol.* **38**(13), 3558–3566.

Bokuniewicz, H., Buddemeier, R., Maxwell, B. & Smith, C. (2003) The typological approach to submarine groundwater discharge (SGD). *Biogeochem.* **66**(1-2), 145–158.

Bratton, J. F., Colman, S. M., Thieler, E. R. & Seal, R. R., II (2003) Birth of the modern Chesapeake Bay estuary 7,400 to 8,200 years ago and implications for global sea-level rise. *Geo-Mar. Lett.* **22**(4), 188–197.

Bratton, J. F., Böhlke, J. K., Manheim, F. T. & Krantz, D. E. (2004) Ground water beneath coastal bays of the Delmarva Peninsula: ages and nutrients. *Ground Water* **42**(7), 1021–1034.

Bratton, J. F., Colman, J. A., Crusius, J., McCobb, T. D., Massey, A. J., Koopmans, D. J. & Masterson, J. P. (2006) Evidence and implications of a fresh groundwater flow system beneath a shallow coastal estuary in New England. In: *Abstracts, First International Joint Salt Water Intrusion Conference* (1st SWIM-SWICA, Cagliari–Chia Laguna, Italy, September 2006).

Bratton, J. F., Böhlke, J. K., Krantz, D. E. & Tobias, C. R. (2007) Flow of groundwater beneath a back-barrier lagoon: geometry and geochemistry of the subterranean estuary at Chincoteague Bay, Maryland. *Mar. Chem.* (in press).

Burnett, W. C., Aggarwal, P. K., Aureli, A., Bokuniewicz, H., Cable, J. E., Charette, M. A., Kontar, E., Krupa, S., Kulkarni, K. M., Loveless, A., Moore, W. S., Oberdorfer, J. A., Oliveira, J., Ozyurt, N., Povinec, P., Privitera, A. M. G., Rajar, R., Ramessur, R. T., Scholten, J., Stieglitz, T., Taniguchi, M. & Turner, J. V. (2006) Quantifying submarine groundwater discharge in the coastal zone via multiple methods. *Sci. Total Environ.* **367**(2-3), 498–543.

Buynevich, I. V. & FitzGerald, D. M. (2002) Organic-rich facies in paraglacial barrier lithosomes of northern New England: preservation and paleoenvironmental significance. *J. Coast. Res.*, Special Issue **36**, 109–117.

Capone, D. G. & Slater, J. M. (1990) Interannual patterns of water table height and groundwater derived nitrate in nearshore sediments. *Biodegradation* **10**(3), 277–288.

Cross, V. A., Bratton, J. F., Bergeron, E., Meunier, J. K., Crusius, J. & Koopmans, D. (2006) Continuous resistivity profiling data from the upper Neuse River Estuary, North Carolina, 2004-2005. *US Geol. Survey Open-File Report 2005-1306.*

Dillon, W. P. (1970) Submergence effects on a Rhode Island barrier and lagoon and inferences on migration of barriers. *J. Geol.* **78**(1), 94–106.

Dominick, T. F, Wilkins, B. & Roberts, H. (1971) Mathematical model for beach groundwater fluctuations. *Water Resour. Res.* **7**(6), 1626–1635.

Emery, K. O., Wigley, R. L., Bartlett, A. S., Rubin, M. & Barghoorn, E. S. (1967) Freshwater peat on the continental shelf. *Science* **158**(3806), 1301–1307.

Field, M. E., Meisburger, E. P., Stanley, E. A. & Williams, S. J. (1979) Upper Quaternary peat deposits on the Atlantic inner shelf of the US. *Geol. Soc. Am. Bull.* **90**(7), 618–628.

Foyle, A. M., Henry, V. J. & Alexander, C. R. (2002) Mapping the threat of seawater intrusion in a regional coastal aquifer–aquitard system in the southeastern United States. *Environ. Geol.* **43**(1-2), 151–159.

Gallardo, A. H. & Marui, A. (2006) Submarine groundwater discharge: an outlook of recent advances and current knowledge. *Geo-Mar. Lett.* **26**(2), 102–113.

Gosink, J. P. & Baker, G. C. (1990) Salt fingering in subsea permafrost: some stability and energy considerations. *J. Geophys. Res.* **95**(C6), 9575–9583.

Greenwood, W. J., Kruse, S. & Swarzenski, P. (2006) Extending electromagnetic methods to map coastal pore water salinities. *Ground Water* **44**(2), 292–299.

Hanebuth, T., Stattegger, K. & Grootes, P. M. (2000) Rapid flooding of the Sunda Shelf: a late-glacial sea-level record. *Science* **288**(5468), 1033–1035.

Kooi, H. & Groen, J. (2001) Offshore continuation of coastal groundwater systems; predictions using sharp-interface approximations and variable-density flow modeling. *J. Hydrol.* **246**(1-4), 19–35.

Krantz, D. E., Manheim, F. T., Bratton, J. F. & Phelan, D. J. (2004) Hydrogeologic setting and ground water flow beneath a section of Indian River Bay, Delaware. *Ground Water* **42**(7), 1035–1051.

Kroeger, K. D., Cole, M. L., York, J. K. & Valiela, I. (2006) N transport to estuaries in wastewater plumes: modeling and isotopic approaches. *Ground Water* **44**(2), 188–200.

Lambeck, K. (1995) Late Devensian and Holocene shorelines of the British Isles and North Sea from models of glacio-hydro-isostatic rebound. *J. Geol. Soc. Lond.* **152**(3), 437–448.

MacIntyre, I. G., Toscano, M. A., Lighty, R. G. & Bond, G. B. (2004) Holocene history of the mangrove islands of Twin Cays, Belize, Central America. *Atoll Res. Bull.* **510**, 1–16.

Manheim, F. T., Krantz, D. E. & Bratton, J. F. (2004) Studying ground water under Delmarva coastal bays using electrical resistivity. *Ground Water* **42**(7), 1052–1068.

McCobb, T. D. & LeBlanc, D. R. (2002) Detection of fresh ground water and a contaminant plume beneath Red Brook Harbor, Cape Cod, Massachusetts, 2000. *US Geol. Survey Water-Resources Investigations Report 02-4166*.

Michael, H. A., Mulligan, A. E. & Harvey, C. F. (2005) Seasonal oscillations in water exchange between aquifers and the coastal ocean. *Nature* **436**(7054), 1145–1148.

Middleton, G. V. (1973) Johannes Walther's law of the correlation of facies. *Geol. Soc. Am. Bull.* **84**(3), 979–988.

Moore, W. S. (1999) The subterranean estuary: a reaction zone of ground water and sea water. *Mar. Chem.* **65**(1-2), 111–126.

Person, M. A., Dugan, B., Swenson, J., Urbano, L., Stott, C., Taylor, J. & Willett, M. (2003) Pleistocene hydrogeology of the Atlantic continental shelf, New England. *Geol. Soc. Am. Bull.* **115**(11), 1324–1343.

Ray, N. & Adams, J. M. (2001) A GIS-based vegetation map of the world at the last glacial maximum (25,000–15,000 BP). *Internet Archaeology* **11** (http://intarch.ac.uk/journal/issue11/rayadams_toc.html).

Robbin, D. M. (1984) A new Holocene sea level curve for the upper Florida Keys and Florida reef tract. In: *Environments of South Florida: Present and Past* (ed. by P. J. Gleason), 437–458. Miami Geological Society, Memoir 2.

Robinson, C., Gibbes, B. & Li, L. (2006) Driving mechanisms for groundwater flow and salt transport in a subterranean estuary. *Geophys. Res. Lett.* **33**, L03402.

Slomp, C. P. & Van Capellen, P. (2004) Nutrient inputs to the coastal ocean through submarine groundwater discharge: controls and potential impact. *J. Hydrol.* **295**(1-4), 64–86.

Smith, L. & Zawadzki, W. (2003) A hydrogeologic model of submarine groundwater discharge: Florida intercomparison experiment. *Biogeochem*. **66**(1-2), 95–110.

Spalding, M. D., Blasco, F. & Field, C. D. (eds) (1997) *World Mangrove Atlas*. The International Society for Mangrove Ecosystems, Okinawa, Japan.

Sumich, J. L. (1999) *An Introduction to Marine Life*, seventh edn. WCB/McGraw-Hill, New York, USA.

Taniguchi, M., Burnett, W. C., Cable, J. E. & Turner, J. V. (2002) Investigations of submarine groundwater discharge. *Hydrol. Processes* **16**(11), 2115–2129.

Thieler, E. R., Schwab, W. C., Gayes, P. T., Pilkey, O. H., Jr, Cleary, W. J. & Scanlon, K. M. (1999) Paleoshorelines on the US Atlantic and Gulf continental shelf: evidence for sea-level stillstands and rapid rises during deglaciation. In: *Non-steady State of the Inner Shelf and Shoreline: Coastal Change on the Time Scale of Decades to Millennia*, Conference Proceedings (University of Hawaii, Honolulu, November 1999), 207–208.

Uchupi, E. & Mulligan, A. E. (2006) Late Pleistocene stratigraphy of Upper Cape Cod and Nantucket Sound, Massachusetts. *Mar. Geol.* **227**(1-2), 93–118.

Uchupi, E., Driscoll, N., Ballard, R. D. & Bolmer, S. T. (2001) Drainage of late Wisconsin glacial lakes and the morphology and late Quaternary stratigraphy of the New Jersey–southern New England continental shelf and slope. *Mar. Geol.* **172**(1), 117–145.

Willard, D. A. & Holmes, C. W. (1997) Pollen and geochronological data from south Florida: Taylor Creek Site 2. *US Geol. Survey Open-file Report 97-35*.

Willard, D., Bernhardt, C. E., Holmes, C. W., Landacre, B. & Marot, M. (2006) Response of Everglades tree islands to environmental change. *Ecol. Monogr.* **76**(4), 565–583.