

Pleistocene Hydrology of Nantucket Island, Massachusetts

¹Mark Person, ¹Lensyl Urbano, Jim Taylor², Mark Willett³, John Swenson⁴, Brandon Dugan⁵

¹University of Minnesota-Twin Cities Campus, Department of Geology & Geophysics

²Consultant, Yarmouth Maine

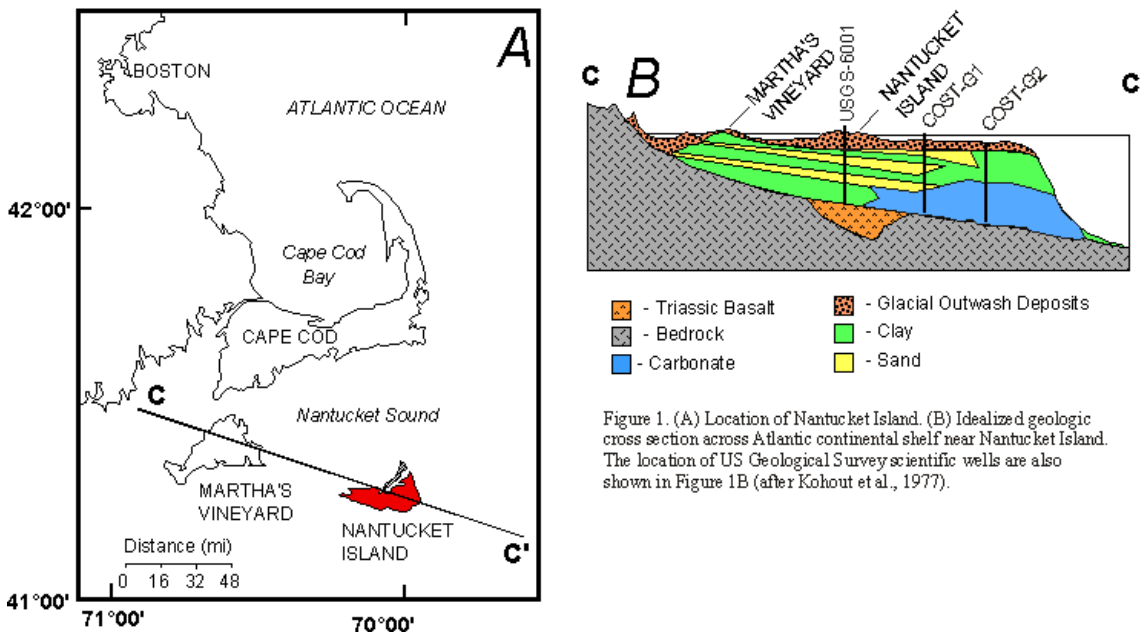
³Wannacomet Water Company, Nantucket Massachusetts

⁴University of Minnesota-Duluth, Department of Geosciences and Large Lakes Observatory

⁵Pennsylvania State University, Department of Geosciences

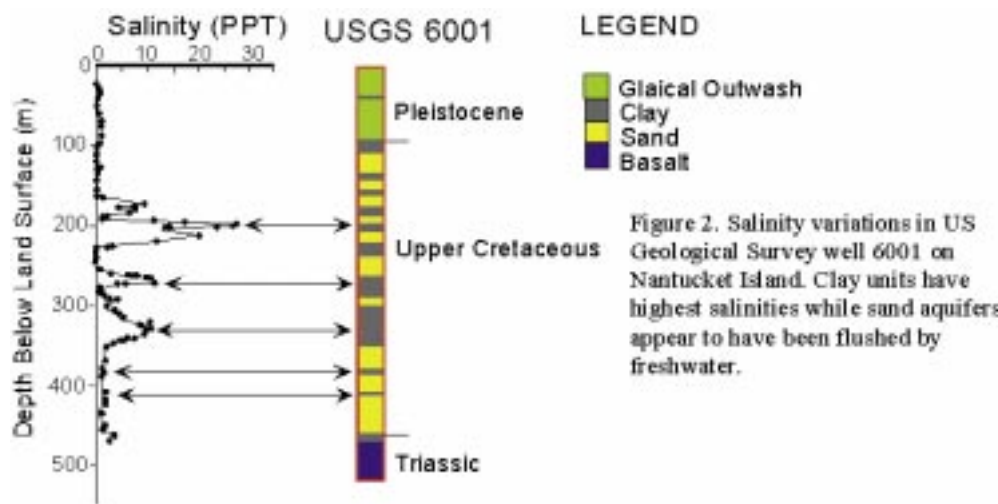
EXTENDED ABSTRACT

In 1975, a 514 meter-deep test well was drilled on Nantucket Island, Massachusetts, by the US Geological Survey to characterize the geology and hydrogeology of the Atlantic continental shelf (USGS 6001, Fig. 1). Unconsolidated deposits on Nantucket Island were found to be composed of Wisconsin-age glacial outwash sands and till up to 91.5 meter thick (Fig. 1). These were underlain by a thick sequence of Cretaceous-age coastal-plain units consisting of sand, clay, and carbonates. Triassic basalts were found at a depth of 488 meters below sea level in USGS 6001. Porefluids salinities were measured at the time of drilling and are reported by Kohout et al. (1977). This well was cased down through the glacial deposits but is open through the Cretaceous section. Because of increased municipal well withdrawals on Nantucket Island over the last three decades, there has been concern regarding saltwater upconing below two municipal well fields (Person et. al., 1998). As a result, new and existing exploration wells were analyzed for salinity and heads. Below we argue that present-day hydraulic heads and salinity patterns are far out of equilibrium with modern sea level conditions. In the remainder of this abstract, we test two hypotheses that could account for these transient hydrologic phenomena.



Analysis of Salinity Data using Analytical Model

In order to assess groundwater flow patterns and saltwater upconing below the island, heads and salinity data were analyzed. In USGS 6001, water levels within the coastal plain sediments were found to be about 3.6 meters higher than surrounding watertable wells. Because the Cretaceous aquifers do not outcrop or subcrop on the mainland, these heads can not be explained by meteoric recharge at higher elevations. Salinity data, analyzed at the time of drilling, indicates that the coastal plain salinity patterns are also far out of equilibrium with modern sea level conditions (Fig. 2). The relatively thick clay layers within the coastal plain deposits have pore fluid salinities between 30% to 70% of seawater values. The salinity patterns resemble diffusional profiles. Two shallower boreholes (~ 100m) drilled in February-March, 2000, into the overlying glacial deposits have salinity values which are also not indicative of modern sea level conditions.



Kohout et al. (1977) proposed that the high heads and low salinity levels within the coastal plain aquifers are due to sea level oscillations during the past 2 million years. In their conceptual model, salinity within the sandstone aquifers are flushed during sea level low stands by meteoric recharge while salinity within the confining units diffuse vertically towards the aquifers. These authors suggest that sea level highstands during the last interglacial period could also account for the anomalous high heads in USGS 6001. Calculations of solute diffusion times were made by us using an analytical solution of the diffusion equation. This model represents transient vertical solute diffusion across a confining unit of constant thickness and uniform diffusivity. At time zero, the salinity in the confining unit is assumed to have seawater salinity (35,000 mg/l). At time greater than 0 years at the upper and lower boundaries of the confining unit, salinity are reduced and maintained at 0 mg/l. Using representative values of diffusivity ($10^{-10} \text{ m}^2/\text{s}$), we found that the salinity profile within the coastal plain confining units is consistent with diffusion time of about 55,000 years (Fig. 3). This time is much shorter than the age of the Pleistocene.

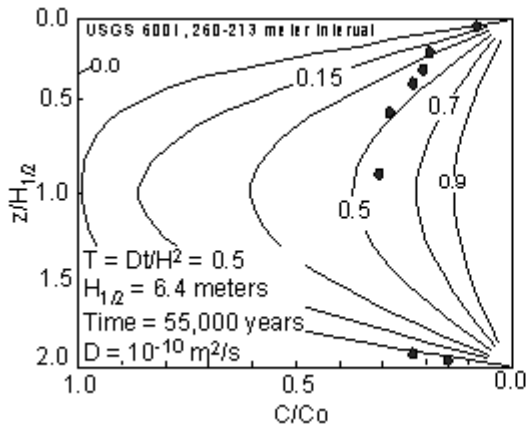


Figure 3. Computed transient profiles of normalized solute concentration (lines) and corresponding observed solute concentrations (circles) from clay layer in USGS well 6001 at a depth of 260-273 meters. The computed concentrations were calculated using an analytical solution assuming solute transport by diffusion. The horizontal axis is normalized concentration while the vertical axis is normalized distance. The variables used in Figure 3 are: $H_{1/2}$, half thickness of layer; C_0 sea water salinity; C , solute concentration in clay bed; T , dimensionless time. The numbers correspond to different dimensionless diffusion times for the analytical solution.

Analysis of Pleistocene Sea-Level Fluctuations and Subglacial Recharge using RIFT2D

We constructed more detailed finite-element models of variable-density groundwater flow, heat transfer, and solute transport (RIFT2D; Person et al., 2001) to further test the hypothesis of Kohout et al. (1977). The geometry of the lithologic units were derived from several deep boreholes completed on the continental shelf (Fig. 1). The hydraulic properties assigned to coastal plain sediments in our cross-sectional model were taken from a number of prior studies and from direct measurements. Permeability for glacial sands were measured using single- and multi-well aquifer tests completed at the municipal well fields on Nantucket Island (Table 1). Pleistocene sea level fluctuations were represented in the model with a sine function using a period of 100,000 years and amplitude of 120 m. On average sea level was 40 m below its current position during the Pleistocene. Off-shore regions surrounding Nantucket Island were often under subaerial conditions. The model was run for 2 million years through 20 cycles of sea level fluctuations. The calculated distribution of salinity after 2 million years within the coastal plain sediments underlying Nantucket shows little variation between the clay and sand layers and is consistent with the above analytical calculations (Fig. 4). While there is more salinity contrast between the coastal plain clay and sand units in Figure 4 further off shore, the contrast is far too low when compared with the observed profile.

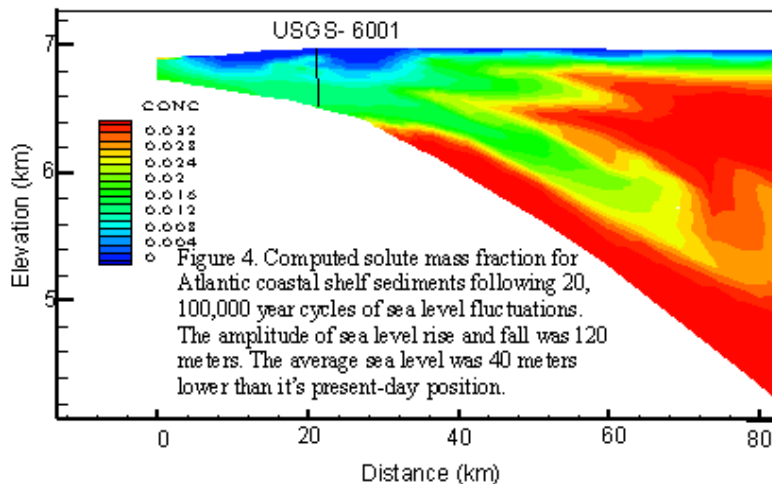


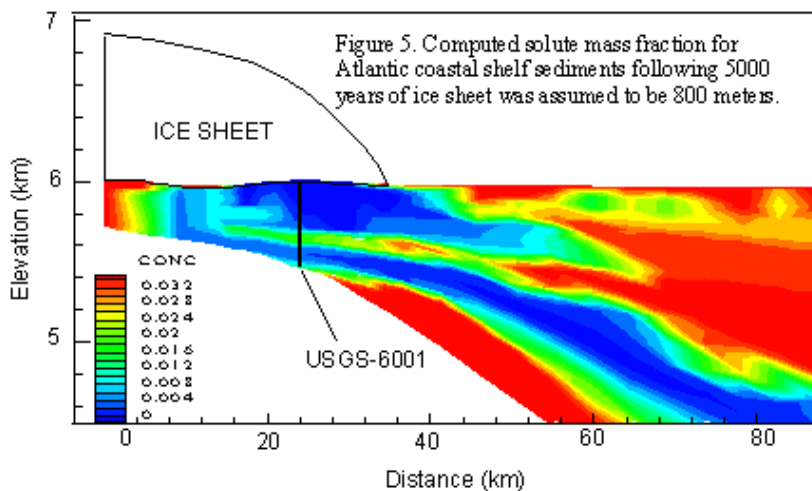
Figure 4. Computed solute mass fraction for Atlantic coastal shelf sediments following 20, 100,000 year cycles of sea level fluctuations. The amplitude of sea level rise and fall was 120 meters. The average sea level was 40 meters lower than its present-day position.

Calculated heads within the continental shelf aquifers were not higher than present-day water table elevations across Nantucket which is not consistent with observed conditions in USGS-6001.

Table 1 Aquifer and Confining Unit Properties used in Finite Element Model.

Unit	Permeability (m ²)	Porosity at Land Surface (unitless)	Sediment Compressibility (Pa ⁻¹)
Coastal Plain Clay	10 ⁻¹⁷	0.4	10 ^{-7.7}
Coastal Plain Sand	10 ⁻¹³	0.5	10 ^{-7.7}
Coastal Plain Carbonates	10 ⁻¹⁵	0.6	10 ^{-7.7}
Glacial Outwash Sands	10 ⁻¹²	0.3	10 ^{-8.0}
Glacial Till	10 ⁻¹⁴	0.6	10 ^{-7.7}

An alternative model, which we advocate here, involves the rapid influx of glacial meltwaters from beneath the toe of the Laurentide ice sheet during Wisconsin Glaciation (between 21-17ka). The thickness of the ice sheet over Nantucket was assumed to be about 900m. Imposed heads below the toe of the ice sheet were assumed to be 90% of the reconstructed ice sheet thickness (Fig. 5). Basal meltwater flowed into the coastal plain aquifers for 5,000 years at the eastern margin of the coastal plain sediments where the sand layers subcropped below pre-Wisconsin till. This was followed by 17,000 years of sea level rise over the area as the glacier receded. During deglaciation, rapid (1 mm/yr) sedimentation was allowed to induce excess heads. This phenomena is thought to be responsible for undercompacted sediments off the coast of New Jersey (Dugan and Flemings, 2000). Results indicate that rapid incursion of freshwater with high velocities resulted in a prominent contrast in salinity between the clays and sand aquifers of the coastal plain consistent with salinity profile in USGS 6001 (Figure 5). Calculated modern heads in coastal plain aquifers are higher than groundwater in the overlying watertable aquifer across the island subsequent to glacial retreat.



Conclusions

This and other recent studies supports the notion that ice sheets have had a major impact reorganizing groundwater flow systems across continents. We argue that aquifer chemistry and isotopic data from regional aquifers, such as presented above, may provide an important

continental archive of climate change. This study may help to constrain the thickness and duration of the Laurentide ice sheet on the Atlantic continental shelf and highlights the importance of ice sheet recharge on modifying the chemistry of continental aquifers during the Pleistocene. Future work should focus on more rigorous coupling of ice sheet/aquifer mechanics. Our work has important implication for defining the freshwater resources on Nantucket Island.

References

- Dugan, B. and P. B. Flemings, 2000, Overpressure and fluid flow in the New Jersey continental slope: Implications for slope failure and cold seeps, *Science*, v. 289, July 14, p. 288-291.
- Kohout, F. A., Hathaway, J. C., Folger, D. W., Bothner, M. H., Walker, E. H., Delaney, D. F., Frimpter, M. H., Weed, E. G. A., and E. V. C. Rhodehamel, 1977, Fresh groundwater stored in aquifers under the continental shelf, Implications from a deep test, Nantucket Island, Massachusetts, *Water Resources Bulletin*, v. 13(2), p. 373-386.
- Person, M., Taylor, J. and S. L. Dingman, 1998, Sharp-Interface Models of Salt Water Intrusion and Well Head Delineation on Nantucket Island, Massachusetts, *Ground Water*, v. 36, p. 731-742.
- Person, M., Neuzil, C., Mailloux, B., Hsieh, P., Mendoza, C., Eadington, P., J. Swenson, and Bekele, E., 2001, RIFT2D: A finite element model for simulating two-dimensional fluid, heat, and solute mass transport in evolving sedimentary basins, US Geological Survey Water Resources Investigation, Water Resources Investigations Report, submitted.