DEFINING FRESHWATER OUTCROPS IN WEST NECK BAY, SHELTER ISLAND, NEW YORK USING DIRECT CONTACT RESISTIVITY MEASUREMENTS AND TRANSIENT UNDERFLOW MEASUREMENTS

Ronald J. Paulsen
Suffolk County Health Services - Bureau of Water Resources
225 Rabro Drive, Hauppauge, NY 11788

Christopher F. Smith
Cornell Cooperative Extension - Marine Program
3059 Sound Avenue, Riverhead, NY 11901-1098

Teng-fong Wong
Department of Geosciences
State University of New York at Stony Brook
Stony Brook, NY 11794-2100

Abstract

Mapping out groundwater discharge zones can be a formidable task due to the highly variable nature of the discharge zone, temporal and spatial variability of seepage rates within the zone, and complications from tidal loading. An integrated approach incorporating direct contact resistivity logging and transient seepage rate measurements was undertaken to delineate the seepage zone and monitor discharge on a bay-wide scale. Conductivity values for the saturated sediments ranged from 280 μS/cm in freshwater zones to 12,800 μS/cm in zones with high salinity. The discharge zone at West Neck Bay, Shelter Island was observed to extend to 10- 75 feet offshore. The groundwater seepage within the discharge zone was measured using a time transient seepage meter that was developed with ultrasonic technology. Seepage velocities in the study area ranged from 1.27×10^{-3} cm/s to 3.94×10^{-5} cm/s, equivalent to a mean value of 16 $\ell/m^2/d$. Integrating over the horizontal extent of the seepage zone, the total daily discharge was estimated to be 1.72×10^6 ℓ/day for the northeast section of West Neck Bay. This estimate of the total discharge due to underflow is comparable to the recharge in the contributing area, estimated to be 1.50×10^6 ℓ/day for this section of the bay.

Introduction

The need to measure and quantify the discharge of groundwater into surface water bodies from inland coastal freshwater aquifers has become increasingly important in Long Island. Several programs have identified groundwater discharge (seepage) as an important key in understanding a surface water's chemical makeup especially as it relates to the nutrient species present. The Brown Tide Comprehensive Management Program, Peconic Estuary Program as well as research performed at Brookhaven National Laboratory (LaRoche et al 1997) have identified groundwater discharge as an important parameter influencing the onset of harmful algal blooms such as *Aureococcus* *anophaefferens* (brown tide). It has been suggested that groundwater discharge can alter the ratio of the nitrogen species in surface waters that receive groundwater discharge. This study is an ongoing collaborative effort to accurately define and measure discharge rates within freshwater discharge zones in the Peconic Estuary System.

During the past four years measurements of groundwater discharge have been made using a newly developed technique capable of transient time measurements of groundwater seepage. The technique employs ultrasonic flow measurement technology to measure freshwater seepage rates through the sediment water interface off shore. This new measurement technique has been field and laboratory tested (Paulsen et al 1997). Although the transient seepage meter is capable of accurately measuring seepage velocity down to 10^{-6} cm/sec, there are still several important variables that exist in fresh water discharge zones off shore that need to be defined before the total seepage inputs can be quantified. One of the most important is the spatial extent of the fresh water discharge zone off shore. In this study direct contact resistivity measurements of bottom sediments and their associated pore water was used to define the size of fresh water discharge zones in West Neck Bay, Shelter Island. Defining the discharge zone in a rapid in situ manner allows for efficient placement of a transient seepage meter within the seepage zone. Integrating data from the two types of measurements provide important constraints on the contribution of underflow to the overall hydrologic budget.

Background

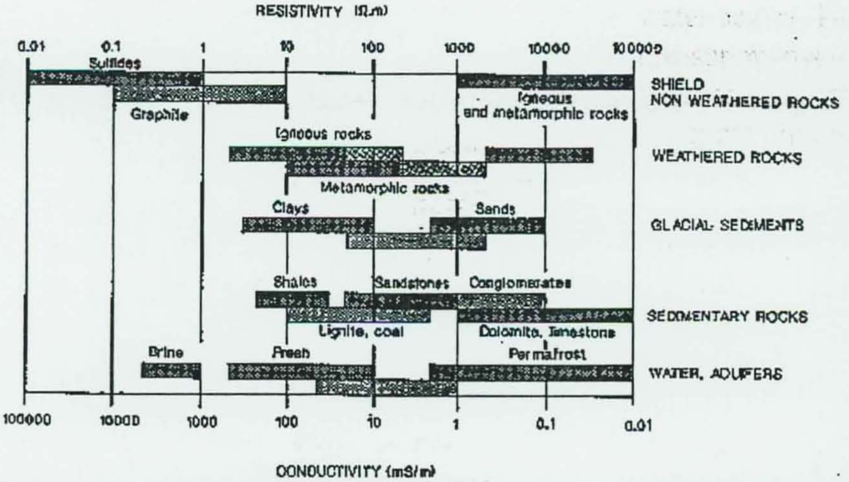

Figure 1. Typical electrical conductivity values of geomaterials.

One approach to identify freshening of bottom sediments requires analysis of sediments recovered from cores (Capone 1985, Aller 1982). Core samples and their associated pore water are analyzed for chloride content and electrical conductivity in the laboratory. This approach can be tedious, expensive and time consuming. When detailed information on porosity, grain size distribution, hydraulic conductivity and chemical constituents of the sediments are required, this approach is warranted. However, it is not practical for characterizing a complex environment on a large scale. To characterize near-shore sediments in a simple and rapid manner, we used geophysical logging to determine the electrical resistivity of surface sediments off shore.

Electrical measurements have been used for some time to characterize the lithology and hydraulic characteristics of geological structures. The basic concept of resistivity logging dates back to 1927 when C.M. Schlumberger made the first well log near Paris (Goldberg, 1997). As indicated in Figure 1, the conductivity generally increases with increasing porosity (Gueguen and Palciauskas, 1994). Archie (1942) invoked laboratory measurement of of conductivity to infer amounts of water and hydrocarbons in the pore space. The electrical conductivity of saturated sediment is commonly analyzed in terms of the formation factor F as a function of the porosity ϕ

$$F = \rho_w / \rho_s = \phi^{-n}$$

where ρ_S is the electrical conductivity of the saturated bulk sediment, ρ_W is that of the interstitial solution, and the Archie exponent $n \sim 1\text{-}2$. Archie's law is applicable when the conductivity of the interstitial solution is much higher than that of the sediment particles, so that surface conduction phenomena are insignificant.

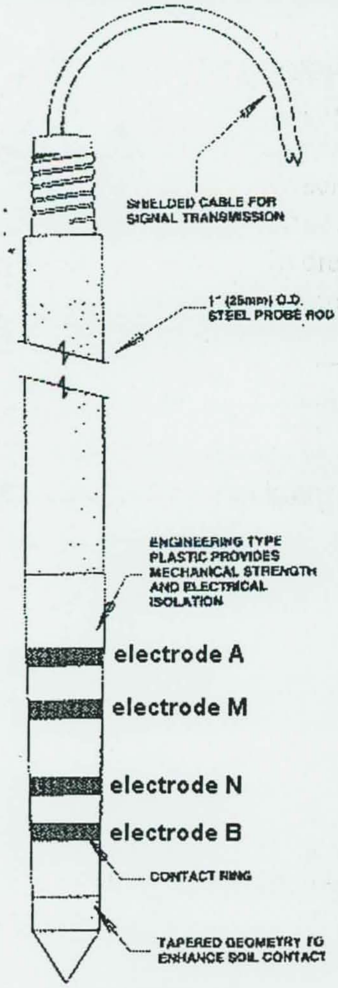

Figure 2.Configuration of the Wenner array.

At off-shore locations where groundwater discharge is negligible, resistivity measurements of the sea water and sediments saturated by water of identical salinity can be used to determine the formation factor and infer the porosity from Archie's law (Aller 1982). In sediments where freshening of the pore spaces has occurred due to groundwater discharge, the measurements usually show a decrease of electrical resistivity with depth, which provides important qualitative constraints on the increase of salinity in the pore fluid and the depth range over which the transition from fresh to sea water occurs. However, the quantitative use of such measurements to infer the salinity or porosity is limited because the porosity may vary with depth and the fresh water may not be sufficiently conductive for Archie's law to be strictly valid.

Several different electrode configurations are commonly used to measure electrical resistivity. Our project employs a direct contact probe arranged in a Wenner array (Figure 2), which is a non-linear array with the potential electrodes placed close together and evenly spaced. This configuration provides discrete measurements even if good contact is not always maintained. The apparent resistivity is given by $\overline{R} = \pi a \, \Delta V / I$, where $a = \overline{AM} = \overline{MN} = \overline{NB}$, and A and B are the positive and negative electrodes that measure the current I, and M and N are the electrodes that measure the voltage drop ΔV (Figure 2).

Direct contact measurements of bottom sediments eliminate the variability commonly associated with resistivity measurements in bore holes filled with drilling mud or interference from well casings and annular spaces (Serra,1984; Christy et al. 1996; Geoprobe technical supplement). The resistivity in a unconsolidated aquifer is controlled primarily by porosity, packing, cementation, resistivity of the pore fluid, degree of saturation and temperature. The use of such logs to identify different lithological zones and hydrological contact zones such as the salt /freshwater interface is well documented (Keys, 1996).

Hydrogeology of the Regional Long Island and West Neck Bay Study Area

The West Neck Bay study area is located in Shelter Island, New York (Figure 3). West Neck Bay has been the focus of many recent investigation because of its vulnerability to brown tide blooms. Since 1982 this bay has been subjected to numerous blooms.

The regional geologic formations underlying Long Island in ascending orders are: 1) the Raritan Formation consisting of the Lloyd sand member and an overlying clay member; 2) the Magothy Formation (Cretaceous deposits); 3) the Upper Glacial Formation (Pleistocene deposits). The Pleistocene marine clays are present beneath the northern and southern margins of the South Fork. There exists various depositional environments within the Upper Glacial aquifer such as several terminal moraines and outwash formations (Nemickas and Koszalka, 1982).

The two key freshwater aquifers in the study area are the Magothy and Upper Glacial aquifers. There is no continuous confining layer between the two formations although the Magothy is composed of layers of clay, sandy clay and silty clay. The hydraulic conductivity of the Magothy aquifer is less than that of the Upper Glacial aquifer which consists of glaciofluvial deposits of mostly fine and coarse sand.

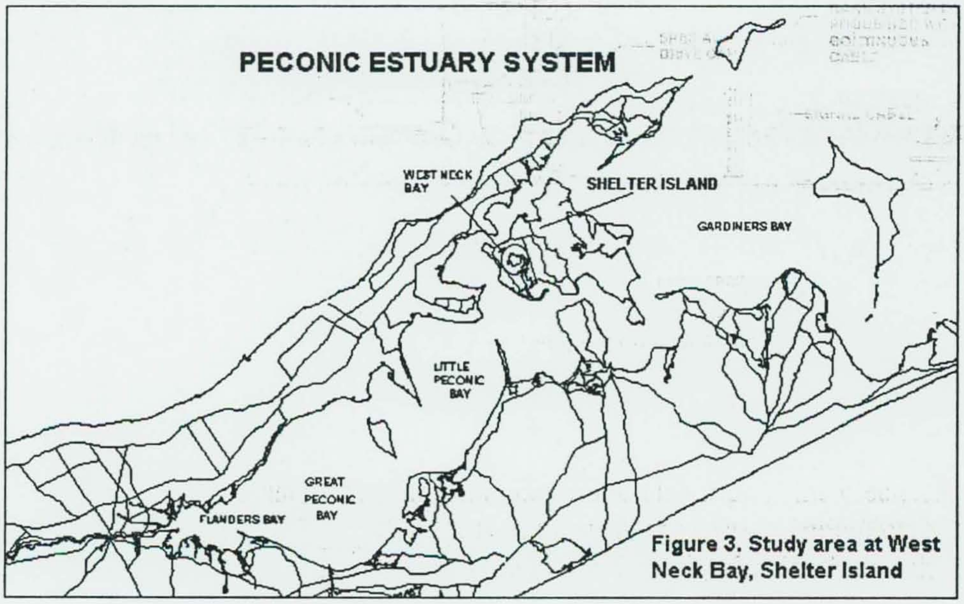

Figure 3. Study area at West Neck Bay, Shelter Island

Natural gamma and driller's logs were used to define lithology in the study area (Figure 3). The West Neck Bay study area contains the same geological formations as the regional Long Island area. The major difference is the absence of a confining layer between the Upper Glacial and the Magothy formations in the study area. On Shelter Island, fresh water is restricted to the Upper Glacial formation that contains a variety of deposits including light to dark brown sands, gray-green to dark-green marine clays and silt (Soren, 1978; Simmons, 1986). The upper glacial formation in the study area contains fine to medium sand to a depth of 97 feet below sea level where a marine gray clay was encountered. The salt/fresh water interface was located using an induction log. The maximum depth of the interface was determined to be 67 feet below mean sea level. The specific area of interest was a 1500-foot section of shore line located in the northwest section of West Neck Bay, that is known to contain an active discharge zone from our previous work.

Methodology

Different geophysical logging tools were used at the shoreline and off shore. At the shoreline, a 2-inch PVC monitoring well was installed to a depth of 110 ft below sea level, and natural gamma and induction logs were used to define the lithology and interface location. For reference, the interface is identified with the contour for a conductivity value 1000 μS/cm, which has been correlated to a chloride value of 250 mg/ℓ on the basis of chemical and electrical analyses of filter press samples (Soren, 1984, Kwader,1986).

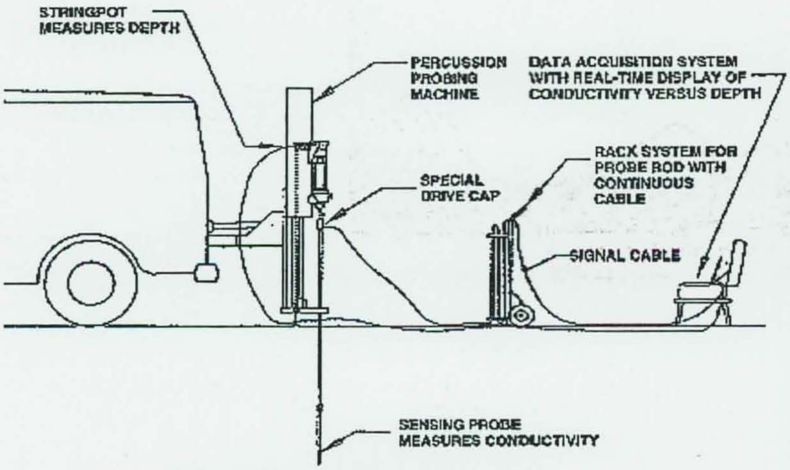

Figure4. Standard setup for the Geoprobe.

The offshore horizontal extent of the interface was delineated by direct contact resistivity measurements, using a probe developed by the Geoprobe Company. As shown in Figure 4, the probe is designed for use in conjunction with a Geoprobe percussion unit, but in this study it was modified to function independently. The resistivity probe was driven manually into bay bottom by scuba divers at six-inch increments. The unit's string pot (that was originally designed to keeps track of the depth measurement automatically and also trigger the electrical measurement) has to be modified accordingly. The string pot was mounted on a jig and manually moved along a displacement that would coincide with the depth that the probe was being driven into the bottom sediments. Resistivity measurements were also simultaneously triggered manually. After the resistivity was logged, the diver then drove the probe into bottom to the next six-inch level. This continued until a freshwater zone was contacted or the probe had been driven to a maximum depth of 4 ft. The diver then moved on to the next off-shore position at a horizontal spacing of ~30 feet, and the manual probing and logging operations were repeated.

During August and September of 1997, measurements were conducted along 8 transects perpendicular to the shoreline (Figure 5). Three resistivity transects (1, 2 and 8) were concentrated in the northeast section of the bay.

Once the groundwater discharge zone had been mapped out, transient seepage meters were installed along the outcrop to monitor seepage velocities. Measurements were made at 10, 50, and 100 ft. from the mean tide mark on the beach. Measurements were recorded on data logger and one-hour averages of rates were analyzed. Synoptic water levels and tide measurements were simultaneously made for one tidal cycle.

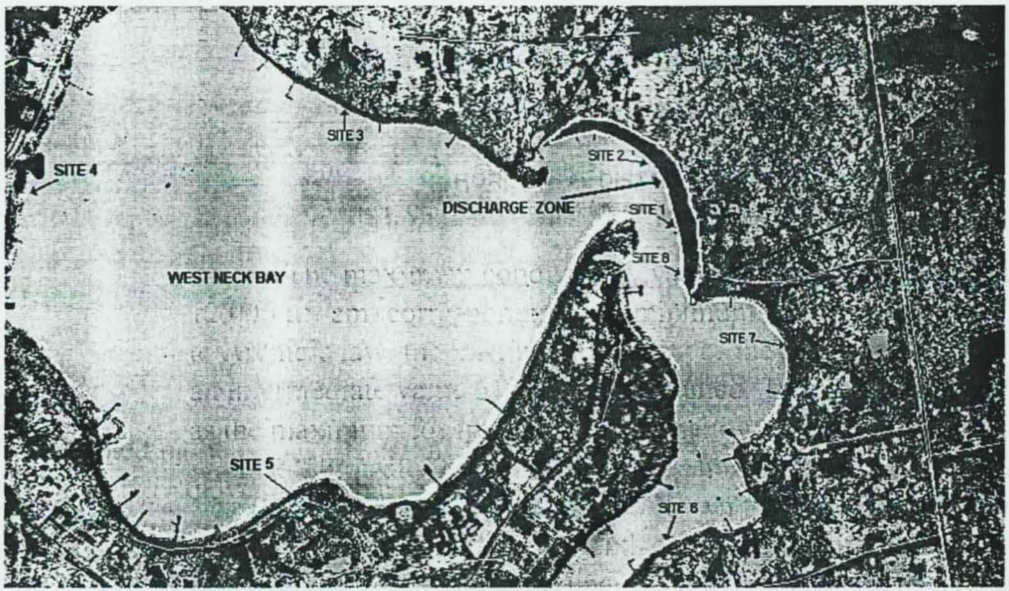

Figure-5 Aerial photo of study sites

Results and Analysis

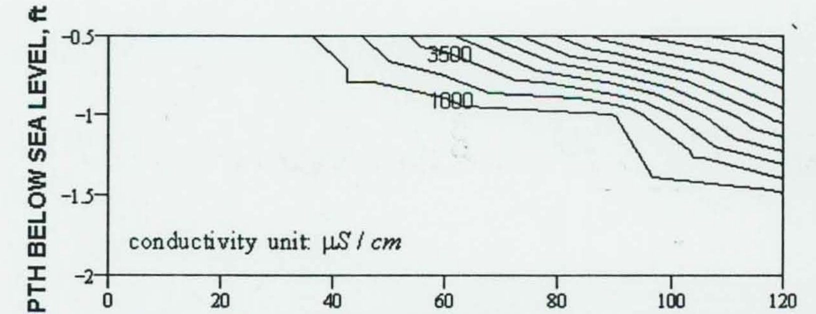

Figure6a. Conductivity profile at site #2. Data were logged at horizontal intervals of 30 ft.

Geophysical logs from monitoring well wn-4 provide information on the coastal lithology at the shoreline. The natural gamma and driller's log indicate that the Upper Glacial aquifer consist of sand, gravel and occasional layers of silty material. A gray marine clay was detected 97 feet below sea level. The induction log indicates the presence of salt water at a depth of 68 feet below sea level. Electrical conductivity profiles for sites 2 and 1 are presented in figure 6a and 6b, respectively. The background value of conductivity for sea water in this study area is ~ 33,000 µS/cm.

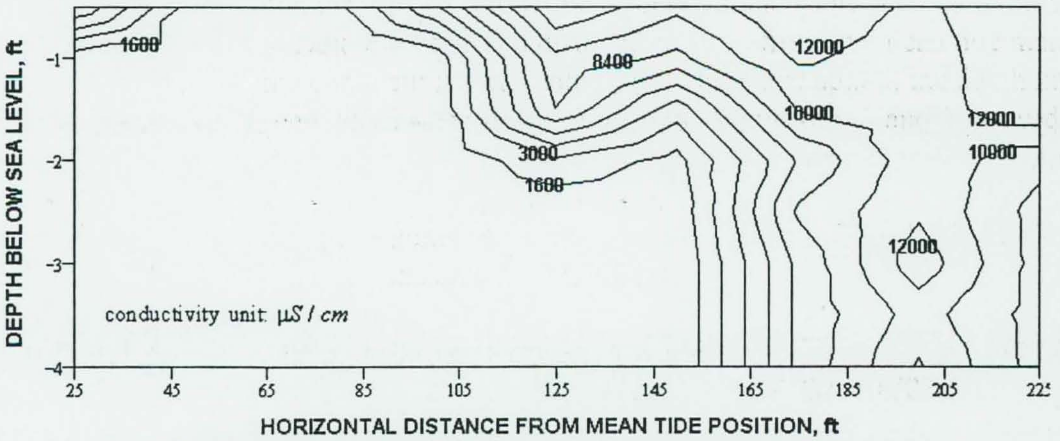

Figure6b. Conductivity profile at site #1. Data were logged at horizontal intervals of 30 ft.

The maximum conductivity values at sites 1 and 2 were in the range of 10,000-12,000 µS/cm, corresponding to a minimum formation factor of $F = 2.8\text{-}3.3$. According to Archie's law, the maximum porosity of the sediments falls in the range of 45-51%, if an intermediate value of $n = 1.5$ is assumed. Taking a conductivity value of 1,000 µS/cm as the maximum for fresh water, the shallowest data (measured at depth of 6 inches below sea level) indicate that seepage extends horizontally to ~40 ft at site 2 (Figure 6a). The freshening due to underflow extends down to > 2 feet. There is an overall trend for the conductivity to decrease with depth at horizontal distances out to 120 feet, that may be attributed to freshening from underflow and dispersion as well as to decrease of porosity with depth.

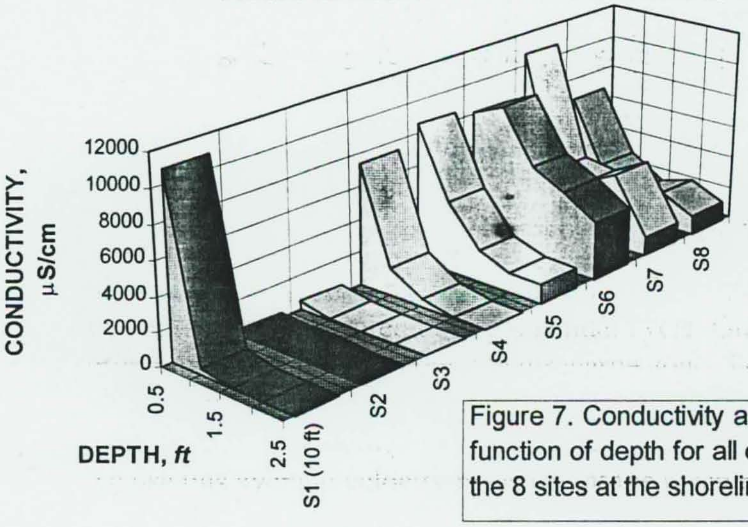

Figure 7. Conductivity as a function of depth for all of the 8 sites at the shoreline.

The spatial distribution of electrical conductivity is more heterogeneous at site 1 (Figure 6b). While the data suggest the existence of a freshening zone extending horizontally to ~ 100 ft, a small wedge of saline water was also delineated right next to the shoreline. The vertical extents of underflow and diffusion zones were > 4 ft.

The seepage activity varies significantly from site to site. Figure 7 plots the conductivity as a function of depth at the shoreline (*i.e.* at the mean tide mark) for sites 2-8. Data for site 1 at a distance of 10 ft. from the mean tide mark are also shown. At site 6, the conductivity was consistently high throughout the depth interval, implying that seepage was negligible at this site. While sites 2 and 3 showed significant reduction of conductivity and seepage throughout the depth interval investigated, the other sites all seemed to have "perched" saline wedges near the surface. Horizontal extent of the active discharge zone was estimated to range from 75 to 10 feet offshore, corresponding to a total seepage area of ~ 4,700 m^2.

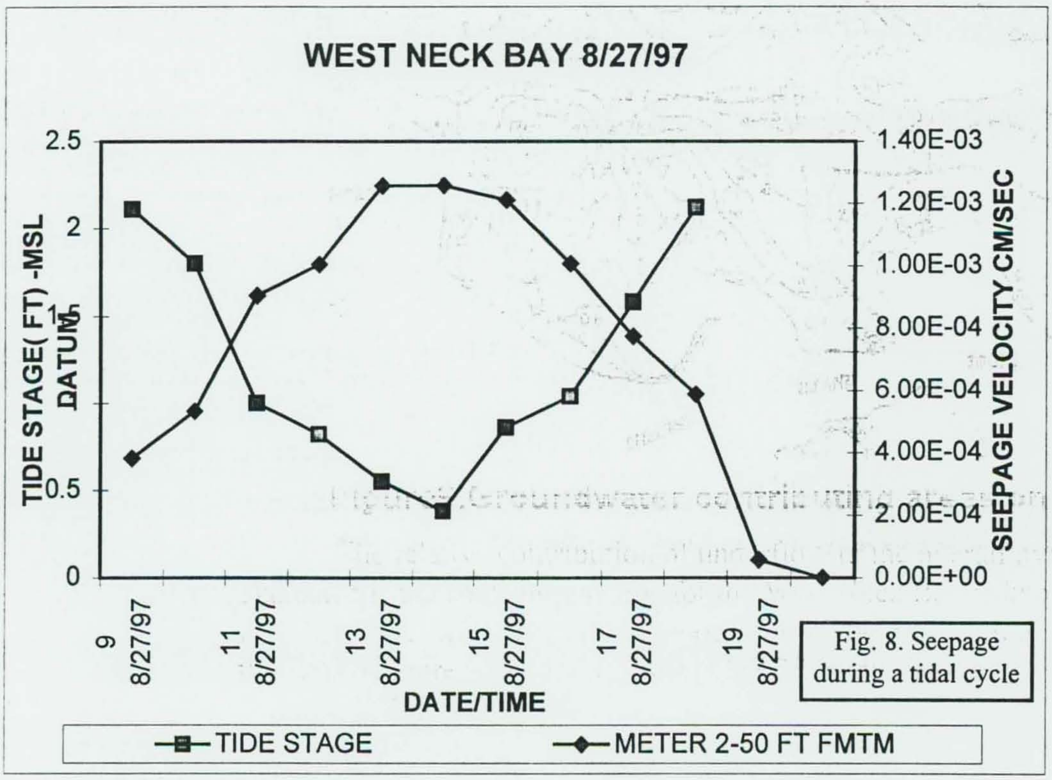

Fig. 8. Seepage during a tidal cycle

Seepage measurements were made at several locations along the transects. The ultrasonic meters were placed within the defined groundwater outcrop area and seepage velocities were measured during one tidal cycle. One seepage meter was placed in the mid-point of transect through the discharge zone. The specific discharge due to seepage was negatively correlated with the tidal stage, with values ranging from 1.27×10^{-3} to 3.94×10^{-5} cm/sec during one tidal cycle (Figure 8), with a mean of 5.83×10^{-4} cm/sec. If we use this average velocity measured at the mean position of the seepage zone to estimate the mean discharge rate in the seepage area, a value of 16 ℓ/m^2/hr = 384 ℓ/m^2/day is obtained.

On multiplying this estimated discharge by the seepage area of 4700 m^2, the total daily discharge was estimated to be 1.72×10^6 ℓ. It should be noted that the seepage rates at West Neck Bay are significantly higher than what were measured elsewhere on Long Island (Bokuniewicz, 1992, Shaw and Prepas, 1989 & 1990, and Cable, 1995). The rates measured at Coecles Harbor on Shelter Island in 1996 (Paulsen et al, 1996) were also much lower than the current measurements. Average seepage velocities measured in other parts of Shelter Island ranged from 5.50×10^{-5} cm/sec in Coecles Harbor to 2.54×10^{-4} cm/sec at Menhaden Beach. These other sites are located on the east side of the island where the hydraulic gradient is not as steep and the groundwater contributing areas are smaller.

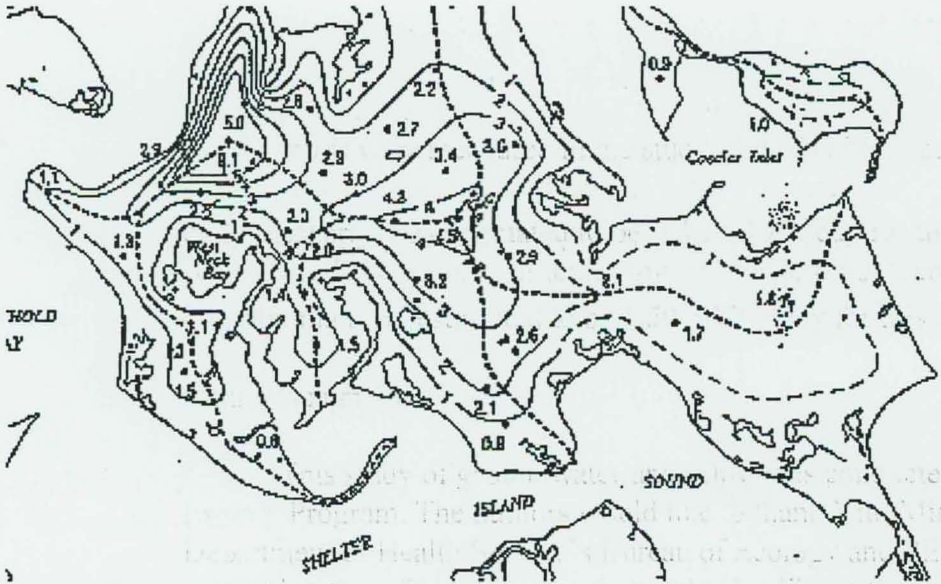

Figure9.Groundwater contributing areas on Shelter Island.

The relative contribution of underflow to the overall hydrologic budget can be evaluated if the contributing area for the West Neck Bay is known. The contributing areas for Shelter Island was recently mapped out on the basis of the USGS water table map of this area (Figure 9). From this recent USGS study (Schubert, 1997), we estimate the contributing area for the northeast portion of the bay to be $\sim 9.95 \times 10^5\, m^2$. An upper bound on the recharge rate is given by the precipitation (22.6 inches per year), which provides a total recharge of the contributing area of up to $1.50 \times 10^6\ \ell$/day, that is comparable to our estimated total discharge of $1.72 \times 10^6\ \ell$/day from seepage measurement. While the agreement is very encouraging, this hydrologic budget analysis also underscores several key hydrogeological questions that demand more comprehensive investigations. More dense arrays for geophysical logging should be deployed to delineate the seepage area in more detail, and more frequent seepage measurement should be conducted to elucidate the seasonal variation.

Conclusion

This study has demonstrated the feasibility of using a methodology that integrates geophysical logging and transient seepage measurement to map out the spatial distribution of seepage and measure the underflow discharge in real time. Conductivity values for the saturated sediments were observed to range from 280 μS/cm in freshwater zones to 12,800 μS/cm in zones with high salinity. The discharge zone at West Neck Bay, Shelter Island was observed to extend to 10-75 feet offshore. Electrical conductivity profiles of the coastal system obtained by direct-contact resistivity logging delineates in cross-section the subset of pore water that has been subjected to significant freshening, and in turn they provide important constraints on the geometry of the fresh/salt water interface and the mechanisms of mixing.

While the resistivity logging is very effective in identifying key areas with pronounced seepage, continuous measurements using the ultrasonic seepage meter provide high-resolution data on the discharge in real time. Relatively high seepage velocities ranging from 1.27×10^{-3} cm/s to 3.94×10^{-5} cm/s (with a mean value equivalent to 16 $\ell/m^2/d$) were measured in the study area. The input of underflow to the hydrological budget was evaluated. Integrating over the projected area of the seepage zone, the total daily discharge was estimated to be 1.72×10^6 ℓ/day for the northeast section of West Neck Bay. This estimate of underflow discharge is comparable to the recharge in the contributing area, estimated to be 1.50×10^6 ℓ/day for this section of the bay.

Acknowledgments

This study of groundwater underflow was conducted as part of the Peconic Estuary Program. The authors would like to thank Vito Minea, Suffolk County Department of Health Service's Bureau of Ecology and PEP program manager for supporting this effort. The authors would also like to thank members of Suffolk County's Health Services Bureau of Water Resources especially Supervisor Martin Trent and Geralynn Fitzpatrick, the field staff from Cornell Cooperative Extension Marine Program especially Sondra Dumais and Andrea Soo from Stony Brook University for their support and assistance in data collection.

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