Characteristics of the Ground-Water Seepage into Great South Bay

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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ABSTRACT

The water quality and salinity in Great South Bay represent a balance between the amount of seawater that enters the bay through its inlets and the amount of freshwater that is supplied from Long Island. Streamflow accounts for most of the freshwater supplied to the bay. This source is routinely gaged by the U.S. Geological Survey. The second largest contribution is the submarine outflow of ground water across the bay floor. Direct measurements of this source are reported here. This is the first such study of the submarine outflow into Great South Bay or, indeed, into any coastal body of water.

Measurements of the ground-water flow across the floor of the bay were made by enclosing a small area of the bottom in a cylinder that was vented to a plastic collection bag. Ground water flowing up across the sediment-water interface into the cylinder accumulated in the bag and the volume accumulated in a predetermined time was measured. These devices would collect up to 2 liters/hour near the bay shore.

Preliminary work showed that much of the seepage occurred within 100 meters of the shore. In this study, the flow was measured at six sites (five on the north shore of the bay and one on the south shore) along transects extending to a distance of 100 meters offshore. Over 300 measurements were made.

Submarine outflow rates were as high as 150 liters/day/square meter. The outflow near the shore was typically 50 liters/day/square meter and decreased to about 30 liters/day/square meter at a distance of 100 meters offshore. Measurements that were made simultaneously and as close together as possible differed by 4 liters/day/square meter (median) although the maximum difference was 49 liters/day/square meter. Measurements taken at the same location within a few hours of each other differed by 4 liters/day/square meter while the maximum difference was 29 liters/day/square meter. Differences greater than 10 liters/day/square meter were ascribed to local (or rapid), but as yet unspecified, changes in the hydrogeologic condition.

Variations in the outflow rate due to tidal changes in the water level could not be detected. The flow rate did appear to be sensitive to coastal flooding and rainfall, however. The day after tropical storm David passed Long Island the flow values were measured at one site and found to be nearly double the typical values at that site. They returned to normal within 10 days. Throughout the summer there was a general decrease in the outflow; there was a concurrent decrease in the monthly rainfall.

In order to calculate the total submarine outflow, the data were described as decreasing exponentially with distance from shore. The typical value of the submarine outflow was calculated to be 4.1×10^8 liters/day. This calculation excluded measurements made near Fire Island, but they suggest that significant amounts of ground water may enter the bay far from shore due to sustained, upward leakage from deep aquifers. As a result, the calculated value is an underestimate. The

outflow rates are relatively large and should significantly affect the pore water chemistry.

INTRODUCTION

The submarine outflow of ground water across the sea floor is an integral part of the coastal hydrography. It is usually the most poorly documented component of the freshwater supply and rarely measured directly. In areas where streamflow is small, ground-water seepage may dominate the freshwater discharge controlling the distribution of salinity in the coastal zone. The magnitude and distribution of the ground-water flux are necessary parameters for modelling the salinity distribution and for estimating the rates at which dissolved chemicals are transported across the sediment-water interface. These are important elements of water-quality models. The submarine outflow is also that fraction of the ground-water discharge that maintains the position of the freshwater/saltwater interface in coastal aquifers. Great South Bay, Long Island, New York is one place where the flow of ground water across the sea floor is especially important. There are two reasons for this. The first reason is that the Island's water supply is drawn entirely from wells and a decrease in the ground-water flow may permit saltwater contamination. The second reason is that the quality of the bay water helps to maintain a productive hard clam industry. Because there are no large streams discharging into the bay, the flow of ground water across the bay floor plays an important role in freshening the bay. This report discusses some of the first *in situ* measurements of the ground-water flow across the floor of Great South Bay in order to document variations in the magnitude and distribution of the submarine outflow.

STUDY AREA

Great South Bay (Figure 1) is the largest of a series of interconnecting shallow lagoons along the south shore of Long Island, New York. The bay is approximately 34 km in length and has a maximum width of about 9 km. The study area for this project lies between Smith Point on the east and the Robert Moses Causeway on the west. Within these limits the bay covers an area of 2.09 × 10^8 m^2. The mean water depth is 1.3 m. The bay is sheltered behind a barrier island (Fire Island). The flow into the bay from the Atlantic Ocean is restricted to narrow tidal inlets. The largest of these is Fire Island Inlet. As a result, the tidal range in the bay is less than 0.25 m although the range in the ocean outside of the bay exceeds 1 m. In addition, the mean water level in the bay is higher than mean sea level in the ocean (Weyl, 1974). This is because the cross-section of Fire Island Inlet is larger during times of high tides than it is at low water; consequently, it is easier to fill the bay than it is to empty it. The difference in mean sea level inside and outside of the bay must be less than 0.85 m.

The bay lies in sandy glacial outwash (Perlmutter and Crandell, 1959). This permeable material has a thickness of about 30 m and it is underlain by an impermeable clay (the Gardiners Clay). The water-table aquifer (or the Upper Glacial Aquifer) is within this layer. Northward, away from the bay shore, the water-table gradient is about 0.002 (Suffolk County Department of Environmental Control, 1978); in other words, the elevation of the water table rises

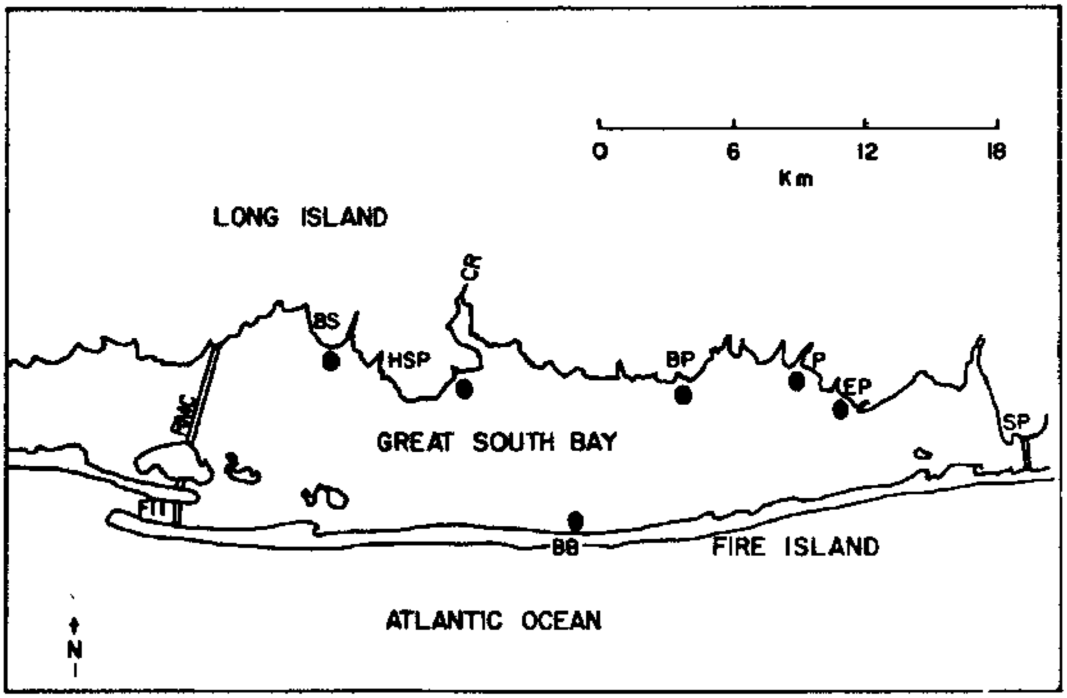

Fig. 1. Study area in Great South Bay on the south shore of Long Island, New York, between Smith Point (SP) and the Robert Moses Causeway (RMC). The study sites are at Bay Shore (BS), Heckscher State Park (HSP), Bayport (BP), Patchogue (P), East Patchogue (EP), and Barrett Beach (BB). FII is Fire Island Inlet and CR is the Connetquot River.

2 m over a distance of 1,000 m. The glacial aquifer is the most homogeneous and isotropic of Long Island's aquifers; this means that its composition is relatively uniform and that water may flow with almost equal ease either horizontally or vertically. The ease with which water can flow through an aquifer is measured by the aquifer's hydraulic conductivity. This property of the aquifer may be measured in units of meters per day. An aquifer with a hydraulic conductivity of 200 m/day is very permeable. Such an aquifer might be made of gravel, and water can flow through it easily. A soil or sediment with a hydraulic conductivity of, say, 0.1 m/day is very impermeable. Clay would make an impermeable layer and water can seep through such a material only with difficulty. At the south shore, the hydraulic conductivity of the glacial aquifer is about 60 m/day for ground-water flows in the horizontal directions. Flows in the vertical direction are slightly more impeded; the hydraulic conductivity in a direction normal to the layers of sand that make up this aquifer are calculated to be between 24 m/day and 6 m/day at the south shore (Getzen, 1977). The ratio of the hydraulic conductivity normal to the layering (essentially vertical) to the conductivity parallel to the bedding (essentially horizontal) is a measure of the anisotropy of the aquifer. The calculated anisotropy for the glacial aquifer is, therefore, between 1:10 and 1:2.5 although locally it may be as low as 1:1.8 (Getzen, 1977).

Below the Gardiners Clay are unconsolidated Cretaceous beds which form intermediate and deep artesian aquifers. The intermediate aquifer (the Magothy Aquifer) is about 270 m thick under the study area. Getzen (1977) has estimated that it has a horizontal hydraulic conductivity of about 16 m/day under the south shore and that it shows a vertical to horizontal anisotropy of between 1:30 and 1:60. The intermediate aquifer is separated from the deep aquifer (the Lloyd Aquifer) by a relatively impermeable clay layer (the Raritan Clay). The top of the clay lies at a depth of about 300 m under the south shore (Perlmutter and Crandell, 1959). Very little is known about the hydraulic characteristics of the deep aquifer, but it is thought that little water flows through it (Franke and Getzen, 1975). The three aquifers are underlain by bedrock at a depth of about 550 m (Perlmutter and Crandell, 1959).

PREVIOUS WORK

There have been few previous *in situ* measurements of the ground-water flow across the floor of Great South Bay. Indirect estimates of this fraction of the hydrological cycle have been made, however, by several investigators. In 1951, the hydrography of the bay was studied by a group from the Woods Hole Oceanographic Institution (Anonymous, 1951). The inflow of ground water to the bay was calculated as the difference between the measured loss by the tidal exchange and the supply by streamflow. The ground-water seepage was thus estimated to be 1.4×10^9 ℓ/day, accounting for 78% of the freshwater supplied to the bay. A later report (Guillard, Vaccaro, Corwin, and Conover, 1960) shows a good correlation between the salinity in the bay and an empirical ground-water index. Pluhowski and Kantrowitz (1964) did a study of the hydrology of that part of Long Island bordering the western half of Great South Bay. Using available records of precipitation and streamflow, they constructed a water budget to estimate that submarine outflow accounted for about 30% of the total average freshwater outflow past the north shore of Great South Bay. By using the shoreline length as a scale factor, their results may be extrapolated to the entire bay. For these calculations the length of the shoreline from the Robert Moses Causeway to Smith Point was measured from a map

(Suffolk County Department of Environmental Control, 1978) to be 47 km. This exercise gives a value of 3.6×10^8 ℓ/day as the rate of ground-water discharge into the tidewater of the bay. Following the estimate of Pluhowski and Kantrowitz, about 79% of this discharge, or 2.8×10^8 ℓ/day, is discharged into the tidal reaches of streams and the remaining 0.8×10^8 ℓ/day enters the bay across the bay floor.

The magnitude of the seaward flow of ground water in the aquifers under the south shore of Long Island can also be calculated from an empirical expression known as Darcys Law. Darcys Law governs the rate of flow of water in a permeable medium. Both Franke and McClymonds (1972) and Pluhowski and Kantrowitz (1964) have made these calculations. The area studied by Franke and McClymonds (1972) was larger than the area covered in the present report, and the area studied by Pluhowski and Kantrowitz was smaller. Their results, however, may be scaled to the present study area. The scale factor is the ratio of the shoreline length of our study area (47 km) to the shoreline length of the previous study area (118 km and 35 km respectively). In this way, the flow under the south shore of our study area is estimated to be 1.9×10^8 ℓ/day based on the work of Franke and McClymonds (1972) and 1.0×10^8 ℓ/day based on the results of Pluhowski and Kantrowitz (1964).

From the water balance of Pluhowski and Kantrowitz, Saville (1962) estimated that freshwater was supplied to the bay at a rate of 0.98×10^9 ℓ/day, excluding the submarine discharge. The quantity of freshwater discharged across the bay floor was omitted from Saville's calculation because "the amount is so small and uncertain"; including Saville's estimate of this quantity would raise the estimate of the total freshwater supply to 1.03×10^9 ℓ/day. The earlier study (Anonymous, 1951) had reported the total freshwater inflow rate to be 1.79×10^9 ℓ/day. Since all of these estimates were made from limited data collected at different times, there would seem to be no reason to prefer one estimate over another.

The first direct measurements of the seepage flow were made along four offshore transects in the bay (Bokuniewicz, 1980). Two of these transects began at the beach of the town of Bay Shore in the Islip township, one was made off the east shore of Heckscher State Park, and one at the Bayport beach. Along each transect the flow rate was usually measured at four locations. The flow of water across the bay floor was measured by enclosing an area of the bottom with a cylinder vented to a collection bag. This procedure was developed and tested by Lee (1977) and has been used in investigations of the hydrology of glacial lakes. (The same basic method was used in the present study although several improvements were added. These will be described in the Methods section and the Appendix of this report.) At each study site, undisturbed samples of the bay floor were also collected and the vertical, hydraulic conductivity of these samples was measured by standard methods (Klute, 1965).

The measurements show that the flow rate decreases rapidly offshore. Within 30 m of the shoreline, the submarine outflow rates were typically 40 ℓ/day-m^2 and decreased to less than 10 ℓ/day-m^2 at a distance of 100 m from shore. The maximum measured flow rate was 140 ℓ/day-m^2 and the minimum was 6 ℓ/day-m^2. The bay floor at the study locations was sand or silty sand of high permeability. The vertical hydraulic conductivities ranged from 12 to 68 m/day.

The magnitude and distribution of the submarine outflow are not unaffected by local conditions. At Heckscher State Park, for example, the beach was underlain by a clay layer with a hydraulic conductivity of only 0.05 m/day. This layer resulted from the burial of a salt marsh when the beach was artificially constructed in 1930. As expected, the submarine outflow was very low through this layer.

The flow rate across the bay floor may be described by an exponentially decreasing function. The correlation coefficient between the natural logarithms of the measured flow rates and the distance from shore for each transect was greater than 0.95. [A similar result has been obtained during studies of glacial lakes (McBride and Pfannkuch, 1976)]. The flow distribution may, therefore, be specified with two parameters--the flow value at the shoreline, A, and a "decay" constant, c, that governs the rate of decrease of the flow offshore. The total flow along a transect is then A/c. The calculated total flow along the four transects were 2,100; 1,100; 8,500; and 3,900 ℓ/day-m. The submarine freshwater inflow is confined to a narrow band along the shore. Between 40% and 98% of the total flow along a transect occurred within 100 m of the shoreline. From these measurements, the total flow of ground water across the bay floor was calculated to be about 2×10^8 ℓ/day, or 10 to 20% of the total freshwater inflow.

The flow of ground water in Long Island's aquifers has been studied theoretically with a three-dimensional analog model by Getzen (1977). The calculations in the model are done at discrete points, called "nodes," on a three-dimensional grid that represents Long Island's aquifers. The ground-water flow, pore water pressure, and other parameters are evaluated only at these points. The nodes are spaced at intervals of 1,829 m horizontally and 120 m vertically. While this spacing is adequate for studying the regional hydraulic characteristics, it is not suitable for examining the details of the submarine outflow through the bay floor. This is because significant changes in the seepage flow have been measured over distances of less than 100 m. The purpose of this report is to document these changes at the shore of Great South Bay.

METHODS

The flow of water across the bay floor was measured by enclosing an area of the bottom with a cylinder vented to a plastic collection bag. The cylinder was the end of a 55-gallon, steel drum which was cut off and imbedded in the sediment, open end down. The closed top of the cylinder was fitted with a nozzle and, after the cylinder was implanted, a plastic bag was attached to the vent. The bag initially contained a known, small quantity of bay water (about 10 mℓ). Ground water flowing up across the sediment-water interface into the cylinder accumulated in the collection bag. To protect the bag from disturbances by waves, it was enclosed in a rigid, but not watertight, chamber. After a predetermined length of time the bag was removed and the volume of water in the bag was measured. The basic design of this measuring device was developed by Lee (1977), although the addition of the chamber to reduce wave disturbances was a modification of Lee's design for this project. Eight of these devices were built. The details of their construction and use are given in the Appendix.

The devices were placed in the bay floor along a line perpendicular to the shoreline. Previous measurements showed the outflow rate to decrease exponentially with distance from shore and that most of the flow occurred within 100 m of the shoreline (Bokuniewicz, 1980). As a result, the devices were set at increasing distances from shore to a distance of about 100 m. Measurements were made simultaneously at every device in the transect. Duplicate measurements were made at two locations along the transect. At these locations two flow-measuring devices were imbedded in the bay floor as close together as possible and simultaneous measurements were made. The devices were usually left in place for one hour. As much as 2 ℓ of water could be collected in this time. After the collection bags were retrieved, the measurements were usually repeated with another set of bags without moving any of the devices. Occasionally, a third set of measurements was also taken.

Measurements were made along transects at five sites along the north shore of Great South Bay between Bay Shore and East Patchogue (Figure 1). The sites were offshore of South Bay Avenue in Bay Shore, at Beach No. 9 in Heckscher State Park, offshore of Gillette Avenue in Bayport, offshore of the beach at Roe Avenue in Patchogue, and offshore of Dunton Avenue in East Patchogue. These sites extend over 24 km of the shoreline and are spaced about 6 km apart. The outflow at the first three of these sites had also been measured during the summer of 1978 (Bokuniewicz, 1980). Two of these sites were offshore of sand beaches (Bayport and East Patchogue) and two were offshore of salt marshes (Bay Shore and Patchogue). The remaining site was offshore of a sand beach that had been artificially constructed over a marsh (Heckscher State Park). Sites were chosen where the water was at wading depth to a distance of 100 m from shore and where the bottom sediments were free of boulder or debris.

An additional site was studied on the south shore of the bay at Barrett Beach, Fire Island. This site was picked to investigate the possibility that there may be a net flow of water from the bay to the ocean under Fire Island. Such a flow might be expected because the mean sea level in the bay should be higher than mean sea level in the ocean (Weyl, 1974). The measurements made at Barrett Beach were an attempt to document this outflow. Barrett Beach was selected because Fire Island is narrowest at this point. Furthermore, the measurements were made during periods of spring tides. These two choices were made in order to give the best chance of seeing the hypothesized, subsurface outflow. (As we will discuss in the Results section, this outflow was not detected.)

At each site borings were made in the beach to examine the shallow subsurface structure. Samples were collected within 30 m of the shoreline and down to the depth of the water table which was within 1.2 m of the beach surface. Deeper samples could not be retrieved with the equipment we used because the sides of the test hole would collapse when the sand became saturated.

RESULTS

Two hundred and forty-eight measurements were made at the 5 sites along the north shore of Great South Bay and 83 measurements were made at Barrett Beach on the south shore of the bay. All these measurements were made between 6 June and 13 September 1979. Figure 2 is a plot of all the flow observations made along the north side of the bay. These represent varying conditions at five different sites and many different time periods. Within 100 m of the shore, the submarine outflow was typically 40 ℓ/day-m^2. There was a tendency for higher values to be found closer to shore; between 70 and 100 m the flow rates were typically 30 ℓ/day-m^2 and within 20 m of shore they were near 50 ℓ/day-m^2. This collection of measurements may be biased toward higher values because on several occasions we made a conscious effort to sample after rainstorms when the outflow rates were expected to be higher than normal. At any particular distance from shore all the flow measurements fell within 70 ℓ/day-m^2 of each other except for two unusually high values. The differences in the flow rates include differences between sites and differences between different times at the same site as well as uncertainties in the measuring technique. The range of outflow values was higher near shore than it was far from shore. The magnitude of the outflow and the range of measured values are similar to the results of a study of seepage into a lake (Lake Sallie, Minnesota; Lee, 1977, McBride and Pfannkuch, 1975). This similarity is not unexpected because the hydrogeologic conditions of the lake and the bay are similar (Bokuniewicz, 1980).

The devices were tested in the laboratory by Lee (1977); he found that they are able to measure flows as low as 0.09 ℓ/day-m^2. In the present study, the sensitivity of the devices was also estimated by comparing duplicate and replicate measurements. Duplicate measurements were two measurements that were made simultaneously and as close together as possible. Replicate measurements were two measurements that were made within a few hours of each other at the same location. Seventy duplicate pairs and 110 replicate pairs of measurements were made.

As mentioned earlier in this report the reliability of the outflow measurements was considerably improved by enclosing the collection bag in a leaky, rigid chamber in order to protect the bags from wave disturbances. The effects of waves on the unprotected collection bag can be seen in a set of three replicate measurements that were made along a transect at Patchogue on 6 June 1979. These outflow measurements are shown in Figure 3. The highest rate of flow was 65 ℓ/day-m^2 at a distance of 5 m from shore and the rate decreased to 45 ℓ/day-m^2 at 92 m. Between the first two replicate samples, the measured values differed by less than 2 ℓ/day-m^2 except at a distance of 70 m from shore where the difference was 11 ℓ/day-m^2. The third replicate set of measurements was considerably lower than the first two sets. At the time these sets of measurements were made the chambers that were later added to dampen wave disturbances were not in place. The first two sets of data were collected during calm seas and they were very similar. The third set, however, was taken after waves about 0.3 m high had developed. In shallow water, these waves violently disturbed the collection bags and we attribute the lower flow values to this disturbance. The problem was eliminated by the modifications that we made to the devices for this study. (The third replicate set of measurements that were made on 6 June at Patchogue was excluded from the subsequent analyses.)

The differences between replicate measurements due to tidal changes in the water level could not be detected. These measurements reaffirm the same result found by Bokuniewicz (1980). In principle, a systematic change in the submarine outflow rates should occur over a tidal cycle. At low tide the water-table gradient in the beach should be sharper and the hydraulic gradient offshore should be higher than at times of high tide. As a result, the ground-water outflow rates should be higher near the time of low tide and decrease to a minimum near the time of high tide. There also should be some difference between the time of high (or low) water and the time of minimum (or maximum) outflow rates because the changes in the water-table elevation will lag behind the tides somewhat. The tidal effect has been documented off the coast of South Carolina where the tidal range is 0.82 m (Lee, 1977). In Great South Bay, however, there were no systematic changes in the outflow values with changing tide level. Apparently, the tidal range in the bay was not large enough to have had a measurable effect on the ground-water outflow. Although tidally induced changes in the submarine outflow could not be measured directly, the magnitude of this effect was investigated by monitoring the tidal changes in the water table within the beach at Patchogue. Screen wells were installed 7.2, 10.9, and 27.1 m landward from the shoreline. The wells extended

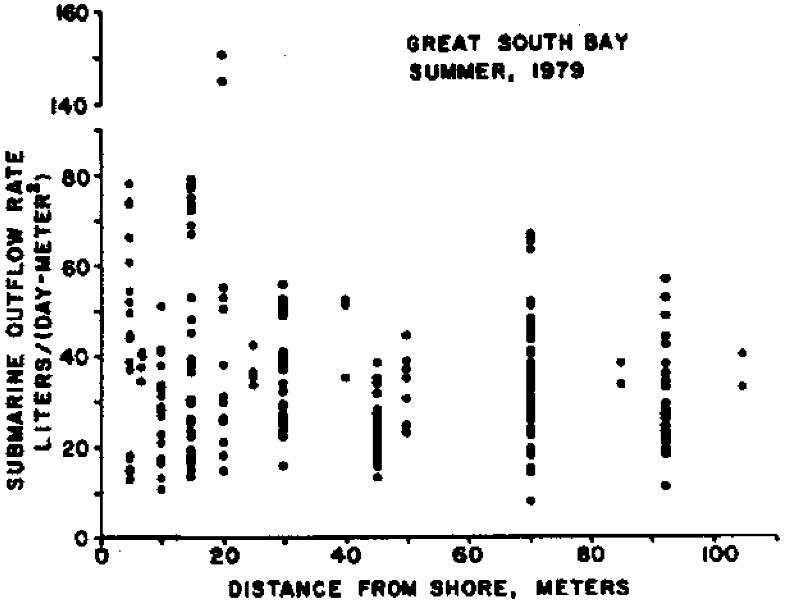

Fig. 2. Distribution of flow rates as a function of the distance from shore for all sites at the north shore of the bay.

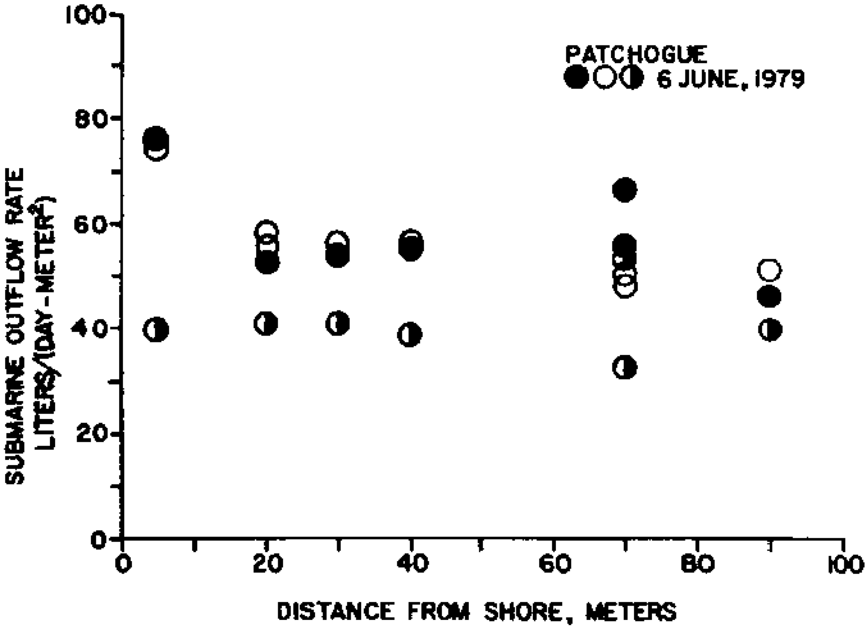

Fig. 3. Outflow rates at Patchogue 6 June 1979. The solid ornament shows the first set of measurements made that day; the open ornament, the second set; and the half-filled ornament, the third set. This convention will be followed in all the subsequent figures.

about 0.2 m below the water table at low tide and measurements of the water level in the wells were made periodically to watch the change in the water-table elevation over a tidal cycle. The water in these wells had salinities between 0 and 4 ‰. At this site, the changing tide affected the water table within about 10 m of the shore. Further inland, no change in the water-table elevation was seen over a tidal cycle. It is unlikely that such a limited change in the water table would significantly affect the outflow further than a few meters from shore. On a rising tide, the water table near the shore also rises. From low to high tide about 700 ℓ of water enter each meter-width of the beach. Likewise, during the falling tide, 700 ℓ/m must escape to the bay and the ground-water seepage should be augmented by this amount. It is likely that almost all of this water crosses the bay floor through the intertidal zone. The tidal variations in the submarine outflow due to these changes would be restricted to within a few meters of the shore. The seepage-measuring devices, however, were rarely placed closer than 10 m from the shore because they must be completely submerged in order to work properly. As a result, no tidal variations in the outflow were observed and tidal corrections were not applied to the data in the subsequent analysis.

More than half of the duplicate measurements were with 4 ℓ/day-m^2 or 20% of each other. The maximum difference, however, was 49 ℓ/day-m^2 or 98%. More than half of the replicate measurements were within 4 ℓ/day-m^2 or about 11% of each other, while the maximum difference was 29 ℓ/day-m^2 or about 97%. The histograms in Figure 4 show the distribution of outflow differences between both replicate and duplicate measurements. These differences are expressed both as absolute flow rates and also as a percentage of the average flow value for each pair of measurements. In general, the differences were less than 10 ℓ/day-m^2 or about 20%. By inspecting these comparisons, the accuracy of the measurements appears to be ±5 ℓ/day-m^2 or ±10%. Differences between duplicate or replicate measurements that were greater than 10 ℓ/day-m^2 were ascribed to local (or rapid), but as yet unspecified, changes in the hydrogeologic conditions.

We will now examine the measurements made at each site separately in order to study the temporal changes at each location, local anomalies, and the difference between sites.

Patchogue

The most extensive set of observations was made at Patchogue. This site was offshore of the beach at the end of Roe Avenue. There is a large marsh here separated from the bay by a beach 30 m wide. The bay floor is sandy with extensive but sparse eelgrass beds. The water was 0.8 m deep at a distance of 100 m from shore. Borings showed the beach to be sand at least down to the depth of the water table.

At this site, a transect of ground-water flow measurements was repeated six times over the summer. Measurements were made on 6 June, 26 June, 24 July, 7 August, 7 September, and 13 September. Two sets of measurements were made on each day. Flow rates were the highest on 6 June (Figure 3). As mentioned earlier, on this day the maximum flow rate was 65 ℓ/day-m^2 at a distance of 5 m from shore and decreased to 45 ℓ/day-m^2 at 92 m. Flow values on 26 June (Figure 5) were substantially lower than those seen on 6 June except very near the shore. Replicate measurements made at a distance of 5 m from shore gave flow values of 79 ℓ/day-m^2 and 53 ℓ/day-m^2. The difference between these measurements, 26 ℓ/day-m^2, is more than twice as large as the differences between any of the other replicate measurements made that day. At this

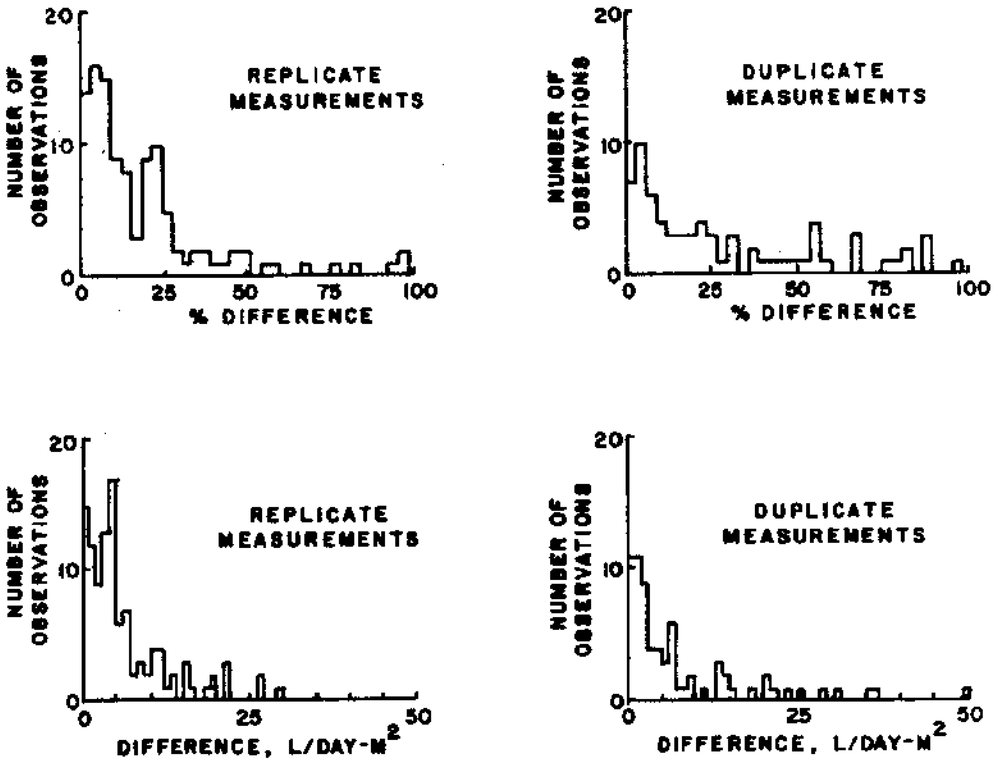

Fig. 4. Differences between duplicate and replicate measurements (see text for an explanation of these terms) expressed both as absoluted differences and percentage differences.

distance, the flow values might be expected to respond to the tides; however, the flow values increased while the tide was rising. This change was opposite the expected response and, other than to note that there is generally greater differences between flow measurements made near shore than between those made offshore, these changes in the flow remain unexplained. The differences between replicate measurements at the other locations along the transect on 26 June are within the expected accuracy of the devices. On 24 July the nearshore values (i.e. those made within 10 m of the shore) were unexpectedly low, while on 7 August unexpectedly high values were found at distances of 16 and 70 m from shore (Figure 5). A possible cause of these unusual flows will be discussed later. Within the uncertainty of the measurements, the other offshore values were identical to the measurements made on 26 June. The typical pattern of the outflow between 30 and 100 m is well defined. The nearshore measurements, while repeatable, were erratic.

The next measurements along the Patchogue transect were made the day after tropical storm David passed Long Island. High flow rates persisted unusually far offshore (Figure 6). Outflow values between 45 ℓ/day-m^2 and 70 ℓ/day-m^2 were measured at a distance of 70 m offshore. These rates were as high as those measured on 6 June and we believe that on both of these dates the high outflow rates were in response to storms. The observations that were made on 6 June followed four days of intermittent rainfall: 24 mm of rain fell at Patchogue on 3 June, 22 mm fell on 4 June, 3 mm on 5 June, and 5 mm on 6 June (National Weather Service, 1980). This rainfall was sufficient to increase the discharge of the Connetquot River by about 50% (T. Spinello, U.S. Geological Survey, Syosset, N.Y., personal communication, 1979); for the first three days of June the discharge was about 430 ℓ/sec while on 4 June it peaked at a value of 650 ℓ/sec. It is reasonable to expect that the submarine outflow was similarly increased.

The high outflow values measured on 7 September may be due to coastal flooding rather than heavy rainfall. In the Patchogue area, tropical storm David did not bring much rain (22 mm), and stream discharge was not substantially increased. Tides, however, ran 0.6 to 1.0 m above normal and extensive coastal flooding resulted. The flood water would percolate downward to temporarily raise the level of the water table near the shore. As the tides dropped, this would increase the submarine outflow rates. An alternative explanation for the high flow rates observed on 7 September has been proposed by H. Buxton of the U.S. Geological Survey (personal communication, 1980). He has suggested that the storm may have significantly disturbed the bottom sediments and thus increased their permeability. In this situation the flow rates would have increased even if the hydraulic gradient did not. Within 10 days (17 September) the outflow rates had returned to the values that were typical of those measured on 26 June, 24 July, and 7 August. The discharge of the Connetquot River shows a similar response to heavy rainfall; after a heavy rainfall the river discharge increases and then gradually returns to normal over the period of several days. This similarity is not unexpected because both the submarine outflows and the streamflow are responding to changes in the water table elevation. More research needs to be done, however, to examine the relationship between streamflow and submarine outflow.

East Patchogue

The easternmost site was in East Patchogue at the end of Dunton Avenue. This site was close to the Patchogue location and the beach here was similar except that it was not backed by a marsh.

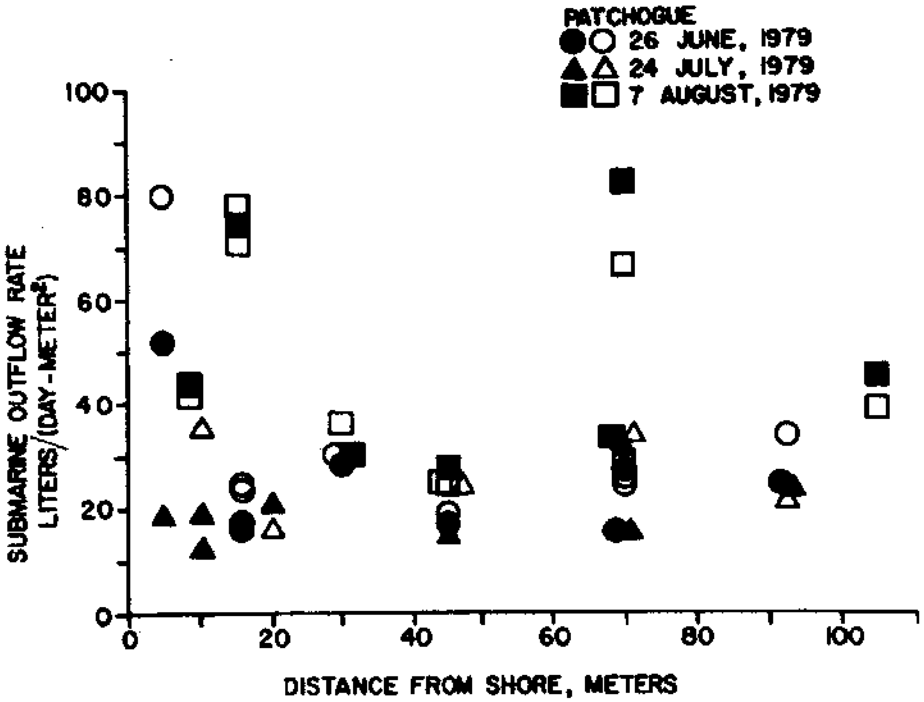

Fig. 5. Outflow rates at Patchogue, 26 June (circles), 24 July (triangles), and 7 August 1979 (squares). In some cases where the outflow rates measured at one location were nearly identical, the ornaments representing them were displaced slightly to the right and left so that they could be seen. This convention will be followed in all subsequent figures. See the caption to Fig. 3 for a further explanation of the ornaments.

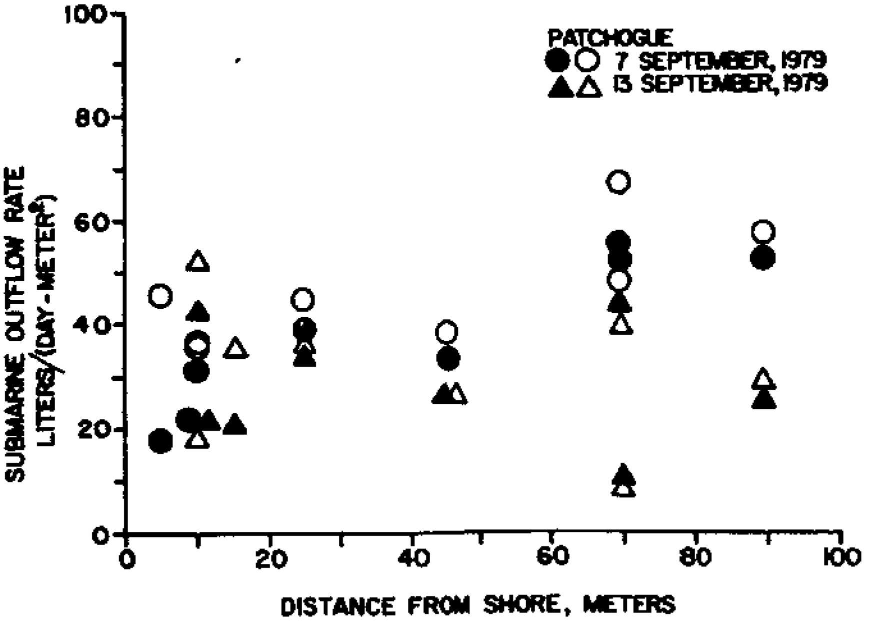

Fig. 6. Outflow rates at Patchogue, 7 September (circles) and 13 September 1979 (triangles). See the captions of Figs. 3 and 5 for further explanation of the ornaments.

Borings through the beach showed occasional thin layers of peat and gravel in the beach sand. The bay floor here was sandy and eelgrass beds were found farther offshore. At a distance of 100 m offshore the water was 0.9 m deep.

A transect of ground-water flow measurements was repeated here on three dates--16 June, 27 June, and 19 July 1979. Three sets of observations were made on the first date and two on each of the subsequent days. The results are shown in Figure 7; they are very similar to those taken at Patchogue. On 16 June the flow rate was found to decrease steadily from 80 ℓ/day-m^2 at a distance of 15 m from shore to 28 ℓ/day-m^2 at 92 m. Duplicate measurements were within 1 ℓ/day-m^2 of each other, but the repeated measurements at a distance of 70 m differed by 20 ℓ/day-m^2. We have no explanation for this particular difference. The flow rates measured on 27 June and 19 July were very similar and generally lower than those measured on 16 June. The highest flow rate near shore was 56 ℓ/day-m^2 measured on 19 July whereas flows as high as 80 ℓ/day-m^2 were seen on 16 June. Values 30 m offshore were now less than 35 ℓ/day-m^2 where they had been about 45 ℓ/day-m^2 eleven days earlier. Far offshore (at 70 and 92 m) the flow rates measured on all three dates were identical within the accuracy of the devices. Once again the differences between duplicate and replicate measurements and between measurements made on different dates were larger near shore than offshore.

The results at East Patchogue were so similar to those found at Patchogue that we could attribute no differences in the outflow magnitude or distribution due to the different settings at these two sites. None of the measurements at East Patchogue were made after rainstorms, but the lower flow rates on 27 June and 19 July may reflect decreasing rainfall during this period. Streamflow measurements at the Connetquot River support this hypothesis. The stream discharge decreased steadily from a value of 650 ℓ/sec on 4 June to 180 ℓ/sec on 3 August 1979 (T. Spinello, *loc. cit.*).

Heckscher State Park

The outflows along the transect at Heckscher State Park, as well as the next two transects at Bayport and Bay Shore, had been measured during the summer of 1978 (Bokuniewicz, 1980). The transect is offshore of Beach Number 9 on the east shore of the park. As discussed earlier, this beach was constructed artificially in 1930 over a salt marsh which now flanks the beach on either side. Beach sand was found down to the depth of the water table but a buried clay layer underlies the beach and outcrops at the bay floor 7 m offshore (Bokuniewicz, 1980). Except for this band of clay, the bay floor is sand. The water depth was 1.4 m at a distance of 100 m from shore.

Ground-water flow measurements were made along the transect on two days--3 July and 31 July 1979. Two sets of observations were made on each day (Figure 8). On 3 July the flow rates were near 60 ℓ/day-m^2 at a distance of 15 m from shore and they decreased to about 35 ℓ/day-m^2 at 85 m. A single flow rate was measured over the clay layer 5 m from shore. As expected, this value was low (10 ℓ/day-m^2); similarly, low flow rates had been found here the year before. The flow rates measured farther offshore during the summer of 1978 were the same as those seen on 3 July 1979 within the accuracy of the measurements.

On 31 July 1979 the measured outflow rates were similar beyond a distance of 30 m from shore, but significantly lower near shore. The depressed values near shore may reflect generally drying conditions during July; between 3 July and 31 July the discharge of the Connetquot River decreased steadily from 310 ℓ/sec to 245 ℓ/sec (T. Spinello, *loc. cit.*).

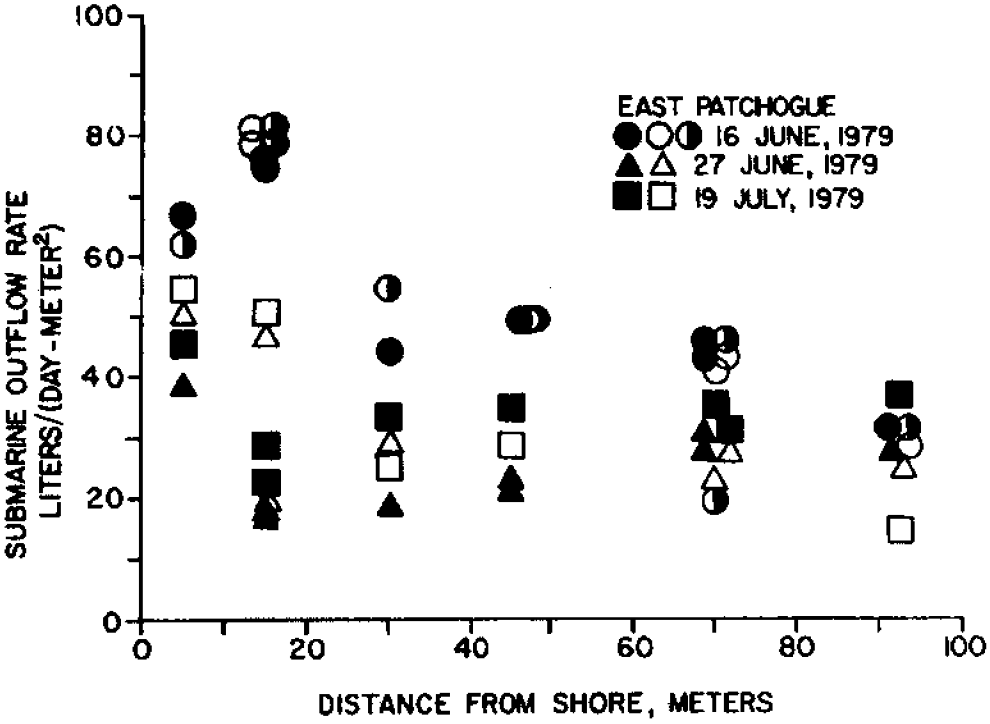

Fig. 7. Outflow rates at East Patchogue, 16 June (circles), 27 June (triangles), and 19 July 1979 (squares). See the captions to Figs. 3 and 5 for further explanation.

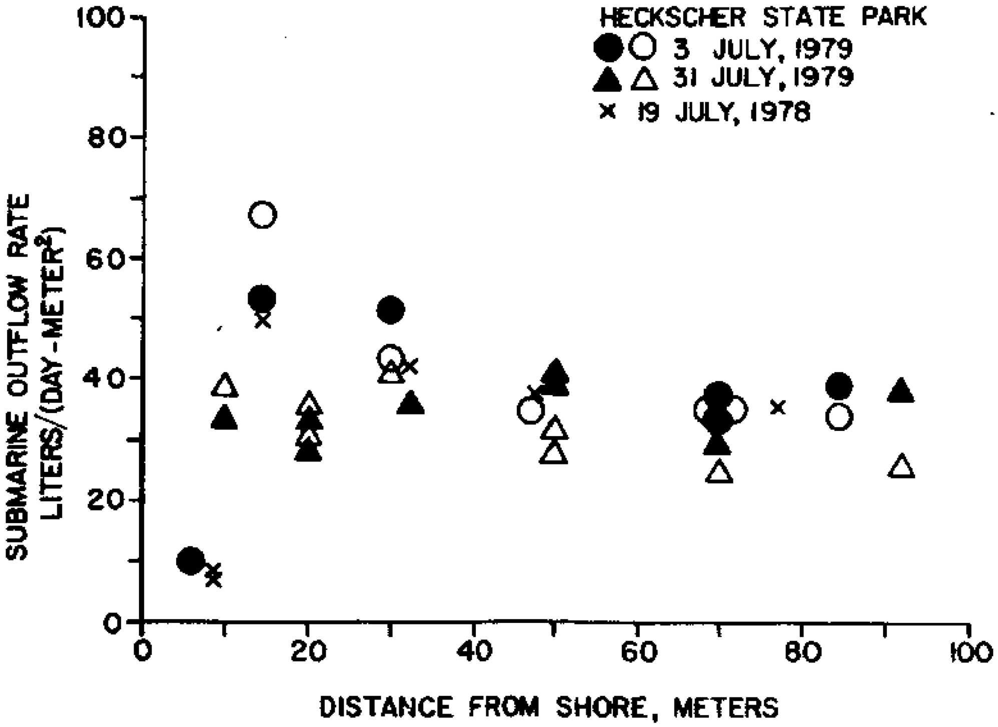

Fig. 8. Outflow rates at Heckscher State Park, 3 July (circles) and 31 July 1979 (triangles), and 19 July 1978 (crosses). See the captions to Figs. 3 and 5 for further explanation of the ornaments.

Bayport

The transect at Bayport was offshore of a narrow beach along a paved street (Gillette Avenue). This beach has apparently been filled with a variety of construction debris and we were not able to bore into the beach with hand tools. The bay floor at this location is sandy except very close to shore where pieces of concrete, bricks, and other large pieces of construction material are found. The water depth at a distance of 100 m was 1.0 m. Measurements of the ground-water flow were made along a transect on 26 July and 30 August 1979. Only one set of measurements was made on 26 July while two sets were collected on 30 August. A set of outflow measurements had also been made along this transect during the summer of 1978 (Bokuniewicz, 1980).

Flow values on 26 July decreased offshore from 47 ℓ/day-m^2 at 7 m (Figure 9). The outflow rates measured on 30 August were slightly lower but similar with one important exception. At a distance of 20 m from shore very high flow rates were measured. Replicate measurements at this location gave values of 150 ℓ/day-m^2 and 145 ℓ/day-m^2. These were the highest flow rates recorded during this study. No measurements had been made at this location on 26 July; however, the same unusual flow distribution was found during the summer of 1978 (Bokuniewicz, 1980). On 9 August 1978, an outflow rate of 140 ℓ/day-m^2 was measured at a distance of 18 m from shore along this transect, while further offshore the measured values were very similar to those measured in August and July 1979 (Figure 9). Bokuniewicz (1980) suggested that this anomalously high value might be due to the geometry of the shoreline but it appears now that this is a small area of extremely high flows superimposed on a normal distribution of offshore outflow rates. The anomalous region can not be more than 15 m wide although we do not know whether or not it exists as a narrow band parallel to the shore. It has apparently persisted for at least one year and, therefore, it is probably due to the local geologic structure, although it could be man-made, a buried drainpipe for example. It is interesting to note that people who often swim in the bay say that they occasionally find small areas of very cold water near the bottom. It seems likely that small patches of exceedingly rapid submarine discharges are not uncommon.

Bay Shore

The westernmost site was in Bay Shore at the end of South Bay Avenue. A narrow sand beach forms the shore here and the beach borders an extensive marsh. Borings showed that the beach was only 0.35 m thick. The beach sand overlies a muddy layer at the water table. The bay floor here is sandy mud and the water depth was 1.2 m at a distance of 95 m from shore. The outflow rates along a transect at this site had been measured previously during the summer of 1978 (Bokuniewicz, 1980). For the present study, the ground-water flow was measured along an offshore transect on two days--28 June and 2 August 1979. Two sets of measurements were made on each day (Figure 10).

Outflow rates at this site were relatively low compared to the other sites. This may be because the hydraulic gradient is lower than normal in the marsh and/or because the hydraulic conductivities of the bay floor sediments are lower than they are at the other sites. At this location the vertical hydraulic conductivity of the surficial sediment was about 12 m/day whereas a more typical value is near 50 m/day in the study area (Bokuniewicz, 1980). The outflow rates measured here during 1978 were substantially lower than the measurements reported here. Between 28 June 1979 and 2 August 1979 there was very little change in the submarine outflow at this site even

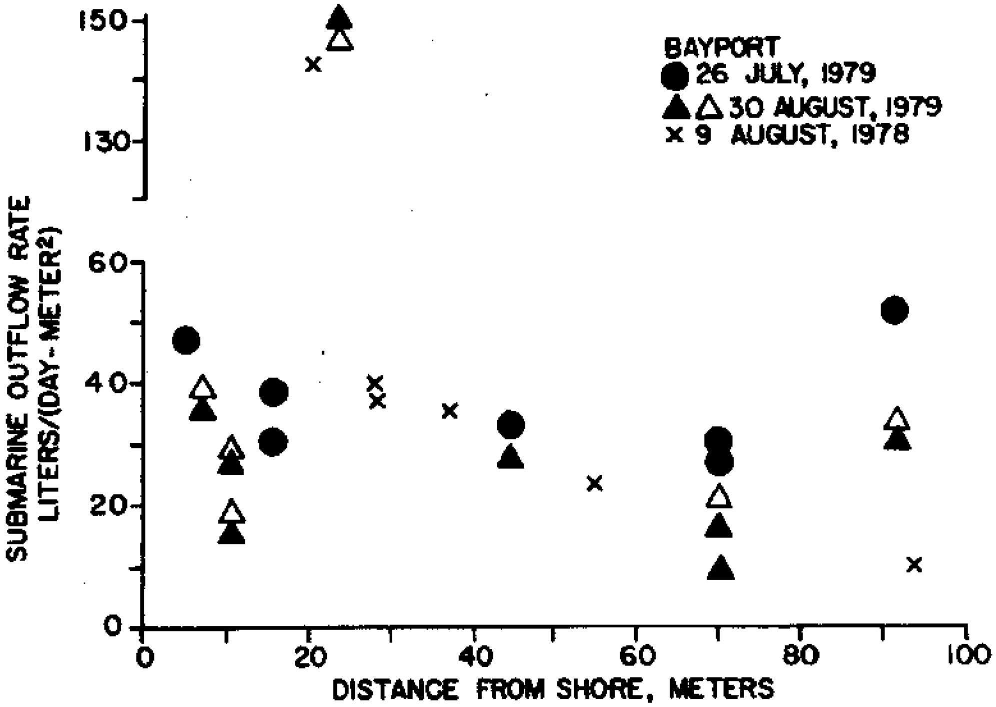

Fig. 9. Outflow rates at Bayport, 26 July (circles) and 30 August 1979 (triangles) and 9 August 1978 (crosses). See the captions to Figs. 3 and 5 for further explanation of the ornaments.

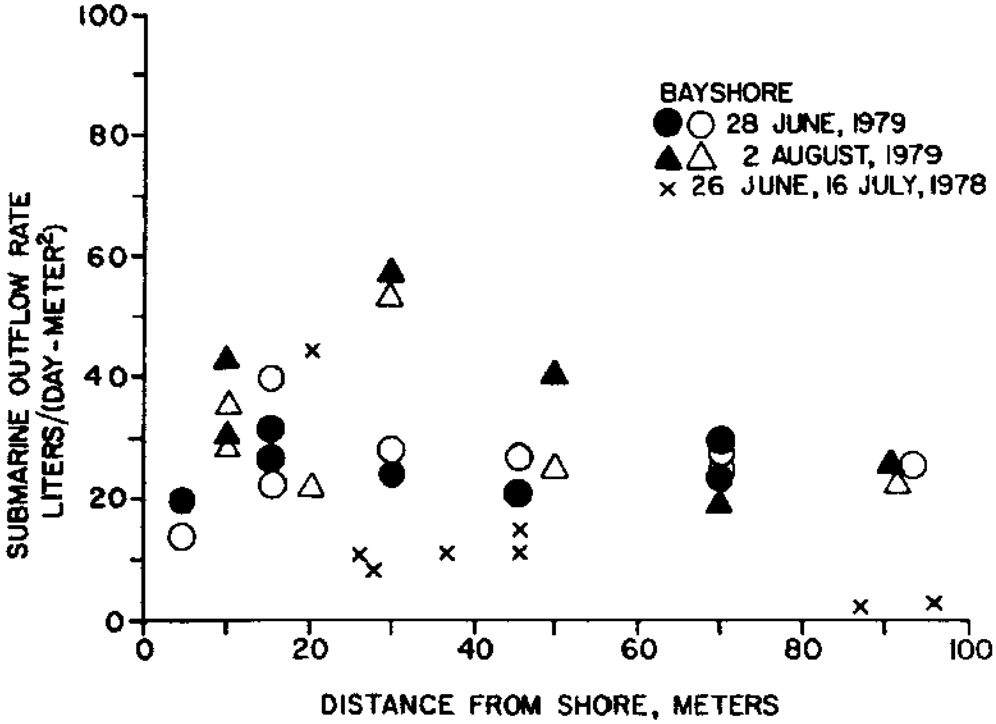

Fig. 10. Outflow rates at Bay Shore, 28 June (circles) and 2 August 1979 (triangles), and 26 June and 16 July 1978 (crosses). See the captions to Figs. 3 and 5 for further explanation of the ornaments.

though, as we have discussed earlier, conditions became progressively more dry during the summer. The lack of changes in the outflow at this site may be due to the effects of the marsh. One notable feature along the bay shore transect is the difference in outflow rates at a distance of 30 m from shore between 28 June and 2 August. On 28 June the flow rates here were between 20 and 25 ℓ/day-m^2 while on 2 August they were between 50 and 60 ℓ/day-m^2. Perhaps this is evidence of another localized area of high outflow rates like that seen at Bayport where small differences in the location of the measuring device cause large differences in the measured outflow.

Barrett Beach

One site was chosen on the south shore of the bay at Barrett Beach on Fire Island. This is the narrowest point on Fire Island; the island is only 225 m across here. The beaches are backed by dunes that are about 4.5 m high. The bay floor is sand and the water is shallow. The water depth is only 0.7 m at a distance of 184 m from shore. Ground-water flow measurements were made on each of three dates--10-11 June, 10 July, and 9-10 August 1979. These days were chosen to correspond as closely as possible to times of maximum spring tides. On each day the periods over which flows were measured were predetermined from predictions of the tide level in the ocean and in the bay. We assumed that the elevation of high tide in the bay and in the ocean would be the same and then from the tide tables we calculated the difference in water levels on either side of the barrier island at Barrett Beach. The flow measurements were made over periods when the ocean level was expected to be higher than the bay level and vice versa. On 10-11 June and 9-10 August 1979 measurement along the transect was also made over a complete tidal period (12.4 hours).

On 10-11 June, four sets of measurements were made (Figure 11) along a transect into the bay. The first set of measurements was made over an entire tidal period. They showed the flow to be less than 5 ℓ/day-m^2 out to a distance of at least 98 m. The second set of measurements was made over a three-hour period centered on the time when we expected the difference between the bay water level and the ocean level to be greatest with the ocean being higher than the bay. The flow rates measured at this time were slightly higher. The highest was about 22 ℓ/day-m^2 at a distance of 75 m. The next two sets were taken at times when the bay level was expected to be higher than the ocean level. If the difference in water level was causing a flow of ground water from the bay to the ocean, we should have seen negative outflow values during the third and fourth sets; that is, if we put a known amount of bay water into the bags before we started the measurements, we should expect this amount to decrease as water moved into the sediment. This was not observed. The outflow values of the third and fourth set of measurements were comparable in magnitude to the second set and higher than the first.

The same results were found on 10 July 1979. Four sets of measurements were made (Figure 12). The first set was taken during a period when the ocean level was expected to be higher than the bay level and the next three sets were made while the bay level was expected to be higher than the ocean level. No unequivocal, systematic changes in the outflows were detected, although the highest flow rate (68 ℓ/day-m^2 at 10 m) was measured when the ocean level was higher than the bay and relatively higher flows might be expected.

On 9-10 August, two sets of measurements were done and a special effort was made to measure flows very near the shore (Figure 13). The results of the first set represent the flow rates over an entire

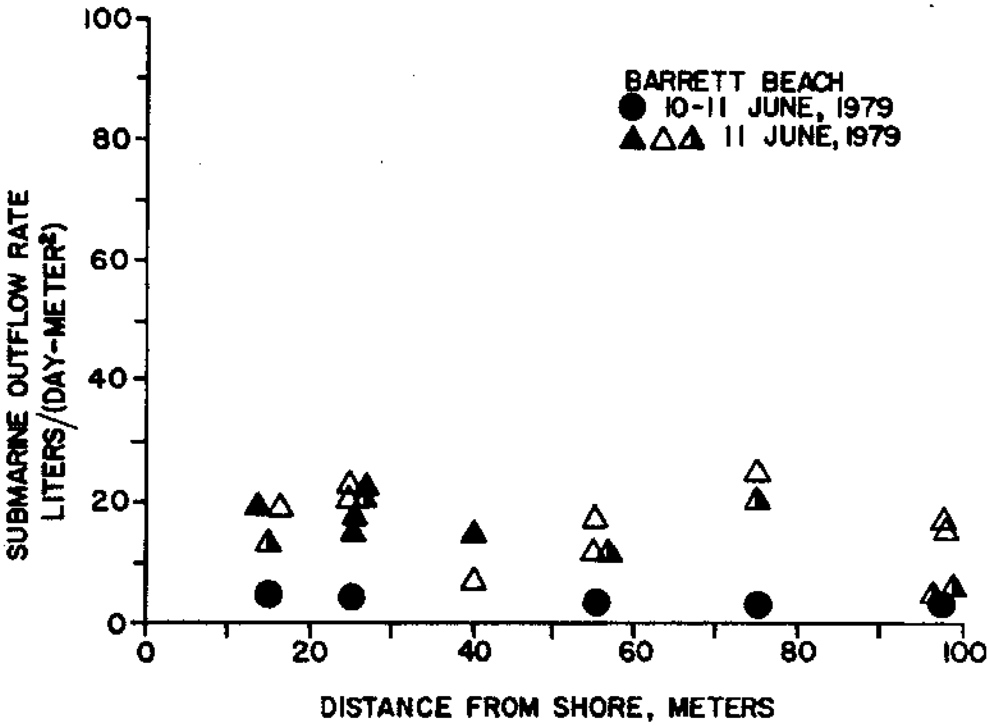

Fig. 11. Outflow rates at Barrett Beach, 10-11 June (circles) and 11 June 1979 (triangles). See the captions to Figs. 3 and 5 for further explanation of the ornaments.

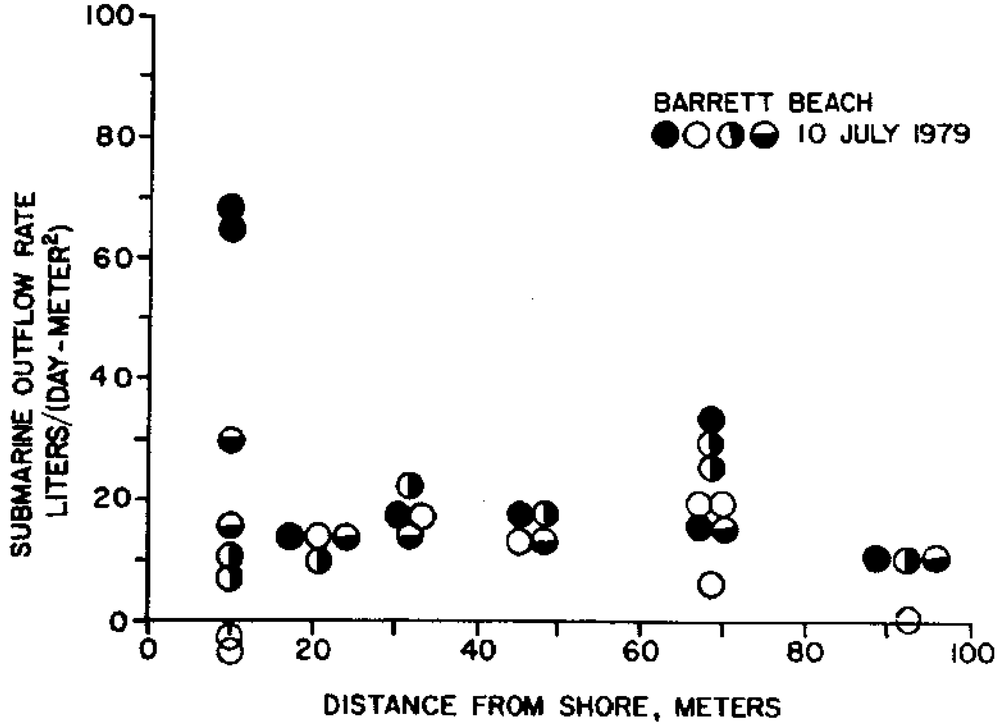

Fig. 12. Outflow rates at Barrett Beach, 10 July 1979. See the captions to Figs. 3 and 5 for further explanation of the ornaments.

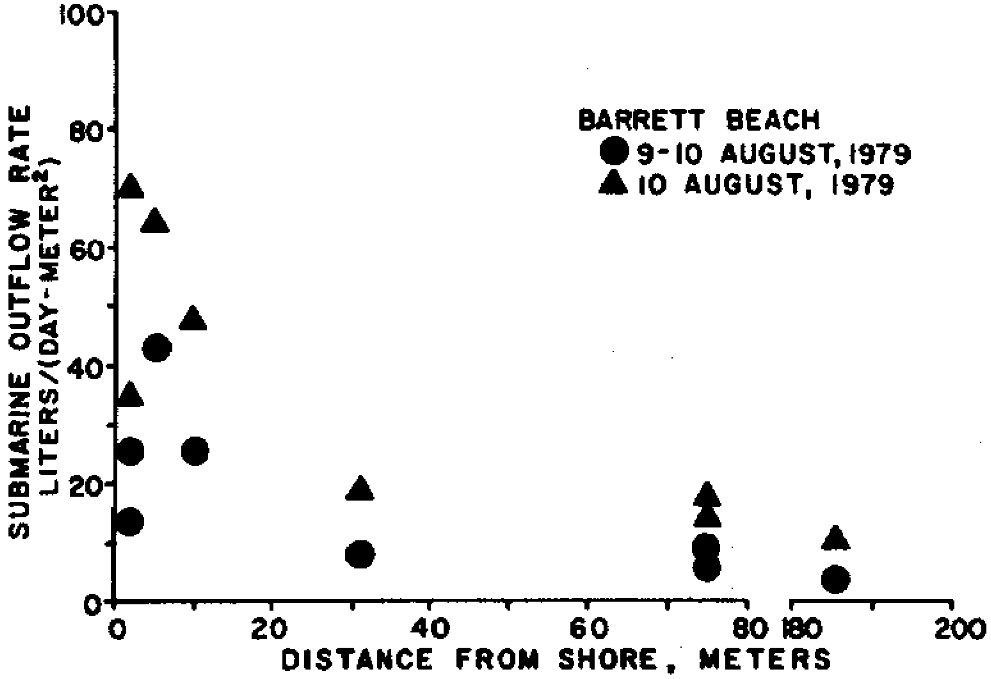

Fig. 13. Outflow rates at Barrett Beach, 9-10 August (circles) and 10 August 1979 (triangles). See the captions to Figs. 3 and 5 for further explanation of the ornaments.

tidal period while the second set was collected over the time when the ocean level was expected to be higher than the bay level. The average outflow over the tidal period was consistently lower than that measured while the ocean level was higher than the bay, but the results are not conclusive. The distribution of outflows on this day was similar to that seen on the north shore of the bay. Flow values were high near shore and the differences between duplicate and replicate measurements were larger near shore. We believe that the high flow values very near the shoreline are evidence of a discharge of ground-water from the freshwater lens under Fire Island. We do not know, however, if this source is sufficient to explain the offshore flow rates; some water may be due to upward leakage from the Magothy or the Lloyd aquifers. If this is the case, then measurable submarine outflows should be found in the bay far from shore. Some preliminary measurements seem to support this hypothesis.

DISCUSSION

Water Quality

All measurements were made within several hours after the time when the devices were implanted. The salinity and, presumably, other characters of the water that was collected in the bags were the same as the ambient bay water. On several occasions we noticed, however, that when the devices were removed the water that they contained was significantly colder than the bay water.

Lee (1977) points out that if you wish to collect samples of the pore water, you must allow the devices to rest in place for a sufficient time to drive out any water that is trapped in the devices when they are implanted. These sorts of measurement have been made in lakes

(Lee, 1977; Downing and Peterka, 1978). For the outflows in Great South Bay, the time required to purge the devices may be calculated and such a calculation is instructive.

A flow rate of 10 ℓ/day-m^2 corresponds to a flow velocity of 0.01 m/day across the sediment-water interface or a velocity of about 0.016 m/day within the sediments if we assume a porosity of 50%. When the devices are implanted, a layer of bay water 0.03 to 0.05 m thick is trapped under them. For a reasonably high flow rate of, say, 50 ℓ/day-m^2, one full day would be needed to displace a volume of water equal to that trapped under the device initially. Because of mixing between bay water within the device and the upward-flowing ground water about three days would be needed to insure a complete purge. To test the pore water it would be easier to collect a core and to sample the pore water at various depths directly.

There are two reasons why salinity of the water crossing the sediment-water interface is not expected to be zero. The first is that salt from the bay can diffuse down into the sediment pore water against the submarine outflow. Against a flow of 10 ℓ/day-m^2, salinities would decrease to a few parts per thousand from normal bay salinities at a depth of only 0.02 m. The second reason involves the flow of salty water from the bay through the aquifer and shoreward across the freshwater/saltwater interface. The upward flow of fresh ground water then returns this salt to the bay. This circulation of salt water within the aquifer is discussed by Cooper, et al. (1964). From field studies in Florida, they have estimated that 10 to 13% of the water flowing upward across the sediment-water interface at the shoreline is recirculated salt water.

Where the submarine outflow rates are liters per day per square meter, the salinity of the pore water could be very low just a few centimeters below the sediment-water interface. This abrupt salinity gradient could explain the formation of ice in the top layers of the bottom of the bay during the winter. Such ice is well known among baymen as "anchor frost," "anchor ice," or "frozen bottom." Mr. Arthur Cooley (Bellport Senior High School, personal communication, 1980) has been studying the occurrence of anchor ice. It was he who brought this phenomenon to our attention and suggested that it is due to the outflow of nearby freshwater from the sediment into the bay water. During the coldest part of the winter, saline bay water can dip below 0°C perhaps as cold as -1.5°C without freezing. The temperature of the pore water could drop below 0°C to a depth of almost 0.2 m. As a result there should be a considerable thickness of the bay floor sediment which could freeze even though the bay water itself is not.

If this explanation of anchor ice is correct, its distribution may assist in understanding the location and extent of freshwater flow into the bay through the bottom. Baymen report that anchor ice can be up to 0.1 m thick; that it is patchy, sometimes as big as a boat, sometimes as large as a football field; and that it occurs more frequently in muddy rather than sandy bottom. Anchor ice can even be found as much as several kilometers from the shoreline. The measurement of the salinity of pore water should help to determine if this explanation of anchor ice is correct and thereby add to our knowledge of the water budget of the bay.

Total Submarine Discharge

The distribution of flow rates offshore may be described by an exponentially decreasing function of the form Ae^{-cx} where A is the flow rate at the shoreline, c is an empirical "decay" constant that governs the rate of decrease of the flux offshore and x is the distance from the shoreline. These types of mathematical description were investigated numerically by McBride and Pfannkuch (1975) for a wide range of hydrogeologic conditions, including situations similar to that at Great South Bay. They have concluded that a simple exponential function is an adequate approximation to the more complicated, exact solutions to the equations that govern the flow of ground water. This was shown to be the case for the ground-water flow into Lake Sallie (McBride and Pfannkuch, 1975) and also for the outflow into Great South Bay (Bokuniewicz, 1980).

This simple mathematical description could be useful because it provides us with a consistent and reasonable method of handling the data. The mathematical formula can be used to extrapolate the flow measurements and to calculate the total outflow magnitudes. The values of A and c were determined for each transect by fitting a least-squares regression line to a plot of the logarithm of the flow rate versus distance. These two parameters are given in Table I. The measured correlation coefficient ranged from +0.91 to -0.97. Values of the correlation coefficient near -1 indicate that the mathematical formula describes the measurements well, while positive values or values near zero mean that the mathematical formula is not an adequate description of the data. The measured values might be expected to deviate from the predicted values for several reasons. One reason is that the equation used to calculate the predicted values is only an approximation of a more complicated, exact solution. The more exact mathematical description of the ground-water flow would require that measurements be made of the hydraulic gradient and the distribution of permeabilities and such solutions must often be evaluated numerically. For the examples considered by McBride and Pfannkuch (1975) the approximate evaluation differed from the exact solution by as much as 30% at some places. Differences between the predicted and measured values of the flow rate are also due to local irregularities in the actual hydraulic conditions. The unusually large outflow rates observed at Bayport, for example, can not be accounted for with the formula. Along other transects the flow values very near the shore were found to vary widely. These unexplained nearshore irregularities can significantly affect the quality of the mathematical description. If they are random, as they appear to be, then the formula should describe the statistical mean flow distribution near the shore. We have not made enough nearshore measurements to test whether or not this is the case. As a result, the formula is not as good a description of the individual flow values as previously supposed. Nevertheless, it does give us a reasonable and consistent way of estimating the total outflow from the available data.

With this mathematical description, the total flow rate through the bay floor per unit length of shoreline is A/c whenever c is greater than zero. These values are given in Table I. In order to estimate the total submarine outflow we chose a value for the flow rate per unit length of shoreline that is representative of the conditions on the north shore of the bay during the summer of 1979 and then multiplied that value by the length of the shoreline (47 km) to calculate the total outflow into the study area. The representative value of A/c was calculated to be 8,676 ℓ/day-m. This was done by calculating a weighted average of the values tabulated (Table I), that is to say, an average value was calculated which takes into account the fact that the formula describes some of the measurements better than others. The values of A/c for each day were multiplied by the square of the corresponding correlation coefficient (r^2). The square of the correlation coefficient is the weighting factor. In this way, values of A/c that were calculated from mathematical descriptions with a better degree of correlation to the measurements were assigned more importance than those

Table I

Mathematical Description of the Submarine Outflow Rates

Site	Date 1979	A ℓ/day-m^2	c 1/m	r*	A/c ℓ/day-m
Patchogue	06 June	62.5	0.0025	-0.45	24,984
		63.2	0.0039	-0.78	16,215
East Patchogue	16 June	74.9	0.0095	-0.90	7,888
		90.8	0.0128	-0.97	7,091
		80.3	0.1190	-0.88	6,747
Patchogue	26 June	27.7	0.0036	-0.31	7,681
		34.6	0.0039	-0.28	8,864
East Patchogue	27 June	18.9	-0.0044	+0.39	-
		34.3	0.0043	-0.38	7,970
Bay Shore	28 June	23.9	-0.0011	+0.16	-
		22.7	-0.0024	+0.26	-
Heckscher State Park	03 July	58.1	0.0055	-0.94	10,558
		58.7	0.0071	-0.72	8,270
East Patchogue	19 July	29.8	-0.0010	+0.14	-
		54.8	0.0172	-0.95	3,187
Patchogue	24 July	14.5	0.0055	+0.65	-
		20.5	0.0020	+0.21	-
Bayport	26 July	36.7	0.0016	-0.25	22,956
Heckscher State Park	31 July	29.8	-0.0027	+0.64	-
		36.2	0.0040	-0.65	9,048
Bay Shore	02 August	44.9	0.0068	-0.58	6,606
		33.1	0.0037	-0.35	8,946
Patchogue	07 August	50.2	0.0025	-0.18	20,060
		52.7	0.0050	-0.38	10,548
Bayport	30 August	40.2	0.0120	-0.47	3,351
		42.7	0.0080	-0.40	5,353
Patchogue	07 September	23.3	-0.0103	+0.91	-
		36.3	-0.0051	+0.72	-
	13 September	28.5	0.0009	-0.08	31,678
		36.4	0.0042	-0.36	8,660
Barrett Beach	10 June	05.5	0.0110	-0.93	495
		18.3	0.0119	-0.91	1,551
		15.4	0.0023	-0.18	6,685
		20.2	0.0126	-0.75	1,603
	10 July	42.5	0.0178	-0.67	2,385
			-		-
			-	+0.45	-
		18.8	0.0083	-0.68	2,269
	10 August	21.3	0.0119	-0.84	1,789
		43.9	0.0095	-0.83	4,624

* This is the linear correlation coefficient between the natural logarithm of the measured flow rates and the distance from shore at which those rates were measured.

with a poorer degree of correlation. For each day the values of r^2A/c were added and their sum then divided by the sum of the r^2 values for that day. This is the weighted average outflow for any particular day. The weighted mean for the entire summer was then found by repeating the operation using the weighted average outflows for each day and the sum of the r^2 values for each day as a new weighting factor.

If an outflow rate of 8,676 ℓ/day-m is assumed to be representative of the entire shoreline during the summer of 1979, then the total flow of ground water into the study area along the north shore was 4.1×10^8 ℓ/day. This value does not include the discharge into the tidal reaches of streams and it is larger by a factor of two than the estimate made from measurements taken a year earlier (Bokuniewicz, 1980).

The total submarine discharge includes not only the fresh ground-water discharge but also some recirculated seawater (Cooper, et al., 1964). In the aquifers near Miami, Florida about seven-eighths of the total discharge at the shoreline was found to originate as freshwater in the inland parts of the aquifer; the remaining one-eighth represented a return of seawater entering the aquifer across the sea floor (Cooper, et al., 1964). If we assume that the ratio of freshwater to seawater in the submarine discharge is the same in Great South Bay, then the total discharge of freshwater across the bay floor in the study area is calculated to be 3.6×10^8 ℓ/day. This value is about 20 to 35% of the total freshwater supply.

Although we have made only a few measurements on the south shore of the bay, it is instructive to estimate the magnitude of the total outflow into the bay along the Fire Island shore. For the tabulated values of A/c at Barrett Beach, a weighted average was calculated as before. This value is 2,320 ℓ/day-m. If we assume that this value is representative of conditions along the entire south shore of the bay during the summer of 1979, then the total outflow was about 1.0×10^8 ℓ/day-m, or about one-quarter as large as the total submarine outflow along the north shore.

Theoretical Descriptions of the Submarine Discharge

The simple mathematical description of the flow is useful for extrapolating the results and calculating total or average flows. It is, nonetheless, empirical and does not show the importance of the various hydrogeological parameters that, in principle, must control the seepage flux. These parameters include:

a. the vertical conductivity, K_v
b. the ratio of the vertical to the horizontal conductivity, K_v:K_h
c. the hydraulic gradient, G

In order to study the importance of these parameters, you must find theoretical solutions to the equations governing the flow of water in aquifers. These equations are called Darcys Law and the Richards equation (1931).

Theoretical studies are usually done by numerical methods (McBride and Pfannkuch, 1975; Freeze and Witherspoon, 1966). There are several advantages to using numerical methods. More complicated situations can be handled numerically than can be studied with analytical solutions. If adequate data on the conductivity and geometry of the aquifers exist, the numerical solutions are best for investigating a particular region. Numerical solutions must be done on a computer, however, and they may be costly. They are also essentially "black boxes"; they transform the data into the solution but they offer no insights into the relationships between the critical parameters that control the form and magnitude of the answer. For this an analytical solution is useful, even though some simplifying assumptions are needed to solve the governing equations analytically.

The theory of the flow of ground water near the shore is discussed as part of a classic paper on ground-water flow in general written by M. K. Hubbert (1940) and more of the details of ground-water movement in coastal aquifers are developed by Cooper, et al. (1964). This previous work has been directed toward predicting the position of the saltwater/freshwater interface within the aquifer but the theories also predict that freshwater flows across the sea floor through a narrow gap between the beach and the freshwater/saltwater interface offshore. According to formulae that describe these conditions the width of the gap through which freshwater escapes to the sea is:

$$X_o = Q/2\gamma K \qquad (1)$$

where Q is the freshwater flow per unit length of shoreline, K is the hydraulic conductivity of the aquifer and γ is the excess specific gravity of seawater over that of freshwater. For the situation in Great South Bay, Q would be the total submarine discharge per unit length of the shoreline (A/c) less the fraction of that discharge due to recirculating seawater (which we have assumed to be 1/8). In deriving this formula, the aquifer is assumed to be homogeneous and isotropic; in other words, the hydraulic conductivity is the same everywhere and the vertical hydraulic conductivity is the same as the horizontal hydraulic conductivity. Mathematically, $K = K_h = K_v$. The density difference between seawater and freshwater is only about one-fortieth the density of freshwater, so that $\gamma = 1/40$.

By using 1 we can calculate X_o. For the bay a reasonable value for Q would be about 7,600 ℓ/day-m. "K" should be between 6 m/day and 60 m/day; let us choose $K = \sqrt{360}$ m/day = 19 m/day for this example. With these values, the value for X_o is 8 m. Clearly this is too small. One reason for this may be that the vertical and horizontal are not, in fact, the same. A correction due to the anisotropy can be estimated, however, (Freeze and Cherry, 1979); this is done by multiplying X_o by the square root of K_h/K_v. The square root of K_h/K_v is 3.15 so that the corrected value of X_o is about 25 m. This is still smaller than observed. The reason for the poor agreement between the theory and the observations may be due to the fact that the theory assumes that the salt water in the aquifer is stationary and that flows occur only above a sharp saltwater/freshwater interface. In nature, of course, the interface between the salt water and the freshwater in the aquifer is not sharp but rather gradual, and brackish or salty water is certainly in motion at least near the "interface."

To study this situation we have developed another analytical solution to the equations that govern the magnitude and distribution of ground-water flows. For our new solution we have ignored the fact that the salt water is more dense than the freshwater; in other words, we are assuming that there is no recirculation of salt water in the aquifer and that the ground-water flows are seaward everywhere. These assumptions may not be too unreasonable because in Florida where the situation has been studied in the field, it was found that the recirculation seawater flows were most likely, only about 13% of the total discharge, and that the ground-water flows were seaward not only in the freshwater lens but also in the saline ground water under the sea floor at least during periods of high hydraulic gradients. Our solution was done in two dimensions (horizontal and vertical). We assumed that the hydraulic gradient was constant away from the shore, that the aquifers sit on an impermeable stratum, that the thickness of the aquifer was uniform, and that the aquifer was homogeneous although not necessarily isotropic. The submarine outflow rate is then given by

$$(2) \quad Q = K_v \, G\left[\ln(\coth \pi x k/4\ell)\right]/k\pi$$

where x is the distance from the shoreline, ℓ is the thickness of the aquifer, and $k = \sqrt{K_v/K_h}$. The solution is only approximate but it is accurate when $\pi s k/4\ell \geq 3$ where s is the distance between the shoreline and the water-table divide; this condition is met in the study area.

The flow rate at any location can be seen to be directly proportional to the hydraulic gradient and the vertical intrinsic permeability. Any percentage changes in either of these quantities will produce the same percentage change in the submarine outflow rate. The rate at which the seepage flux decreases offshore is determined primarily by the thickness of the aquifer. The rate of decrease, as well as the magnitude of the submarine outflow, is less sensitive to the anisotropy in the aquifer because only the square root of the anisotropy ratio enters the solution. Because of the nature of the hyperbolic cotangent function (coth), the flow rates will go to zero at a distance from shore of about $4\ell/k$.

As a result of the simplifying assumptions that were made in obtaining the analytical solution, it is difficult to choose appropriate values of the hydrogeological parameters unequivocally. The aquifer thickness, ℓ, for example, was assumed to be constant whereas the aquifers actually increase in thickness seawardly. Nevertheless, an attempt at evaluating the solution may be illustrative. Let us assume that the ground-water flow is confined to the glacial aquifer. The value for ℓ is then 30 m. "k" is between 0.3 and 0.6; let us choose $k = 0.6$ in order to confine the outflow to a zone that is as narrow as possible. To make the outflows as large as possible, K_v will be picked to be as large as possible; $K_v = 68$ m/day. The hydraulic gradient, G, is 0.002, and $\pi = 3.14$. With these choices, we find that the flow is confined to a zone within 191 m from shore. Of course, the values farthest from shore would be very low. The predicted flow values are given in Table II. The agreement between these predicted values and the measured values is encouraging, and we expect that this analytical solution will be useful in future work. It is notable, for example, that if we assume that the outflows are controlled by the Magothy aquifer ($\ell = 335$ m, $k = 0.18$) then the submarine outflow should extend more than 7 km from shore.

Table II

Predicted Submarine Outflow

$K_v = 68$ m/day, $G = 0.002$, $k = 0.6$, $\ell = 30$ m

Distance from shore m	Submarine Outflow rate ℓ/day-m^2
5	180
10	132
25	70
50	30
75	14
100	6

CONCLUSIONS

1. The flow of ground water across the floor of Great South Bay can be measured near the shore with devices that were developed by Lee (1977) and modified for this study. Ground-water flow rates can be measured to within ±5 ℓ/day-m^2 if the instruments are properly placed, if a screen is attached on the interior of the device over the vent to prevent clogging, and if rigid, vented chambers are placed over the collection bags to dampen wave disturbance.

2. Submarine outflow rates of about 50 ℓ/day-m^2 should be expected within 20 m from shore. Between 70 and 100 m the flow rates are typically about 30 ℓ/day-m^2.

3. The tidal range in the bay is not sufficient to produce measurable changes in the submarine outflow over a tidal cycle.

4. The passage of storms can affect the submarine outflow either by disturbing the bay-floor sediments and thus increasing their hydraulic conductivity or by raising the hydraulic gradient with rainfall or coastal flooding. Increases in the outflow appear to be proportionally greater offshore and to persist for less than 10 days.

5. Simultaneous measurements made as close together as possible sometimes showed large differences (> 10 ℓ/day-m^2). The same was true of some measurements made at the same location a few hours apart. Differences between duplicate and replicate measurements are relatively greater within, say, 10 m offshore than they are beyond 30 m from shore. The magnitude of these differences seems to be too large to be due to failure of the technique. As a result, we believe that these are indications of local or rapid variations in the pore water pressure and/or the hydraulic conductivity.

6. There are small areas of unusually high outflows across the bay floor. Flow rates as high as 150 ℓ/day-m^2 were measured at one such spot. This rapid outflow was confined to a zone no more than 15 m wide and it seems to have persisted for at least one year, but probably much longer.

7. Significant volumes of freshwater may be entering the bay across the bay floor from the freshwater lens under Fire Island or from leakage of water out of the intermediate and deep artesian aquifers. Along the Fire Island shore this outflow may be as much as 25% of the magnitude of the seepage flow along the north shore of the bay.

8. The submarine outflow rates that were measured within 100 m from shore are sufficiently high to imply that brackish water or freshwater should be found at depths of a few centimeters within the bay sediments.

9. The total submarine discharge of ground water at the north shore of the bay is estimated to be about 4.1 × 10^8 ℓ/day. This value excludes that ground water which is discharged into the tidal reaches of streams. If we assume that one-eighth of this discharge is recirculated seawater, then freshwater is supplied at a rate of 3.6 × 10^8 ℓ/day across the bay floor.

RECOMMENDATIONS FOR FUTURE RESEARCH

This study had two unique aspects. It represents the first extensive set of ground-water seepage flow measurements made in the coastal zone and the only measurement available in Great South Bay. In addition, analytical solutions to the Richards equation are rarely studied, and this was the first time a solution was examined for shoreline conditions.

As a result of these elements of our work, the research raises many questions that could not be adequately addressed during the period of this study. Future research should be directed to the following questions:

1. What is the distribution of vertical intrinsic permeabilities of the bay floor?

2. Can the submarine ground-water outflow be predicted from measurements of rainfall, streamflow, or the level of the water table?

3. How does the submarine outflow affect the distribution of dissolved chemicals, salt in particular, in the pore water of the bay sediments, and the flux of these chemicals across the sediment-water interface?

4. Is there persistent upward leakage of ground water from deep artesian aquifers producing significant submarine outflows far from shore? If so, what is the magnitude and distribution of these flows?

5. What is the distribution of the submarine outflow *along* the shore, in

particular, what is the size, extent, and cause of local, rapid outflows?

6. What is the rate of supply of freshwater to the bay along the Fire Island shore?

7. When air is entrapped in the water, the water-table height will vary with atmospheric pressure (Peck, 1960). The maximum rate of change of the water-table height with air pressure occurs when the water table is at or near the surface of the soil as is the case near the tidal zone. Measurements of the ground-water flow near shore which show large unexplained fluctuations from sampling date to sampling date may, in fact, be manifestations of changes in atmospheric pressure changes. This phenomenon deserves further attention.

REFERENCES

Anonymous. 1951. Report on a survey of the hydrography of Great South Bay made during the summer of 1950 for the Town of Islip, N.Y. Woods Hole Oceanographic Institution. Ref. No. 50-48. 30 pp. Unpublished manuscript.

Bokuniewicz, H. J. 1980. Ground-water seepage into Great South Bay, N.Y. Est. Coast. Mar. Sci. 10. In press.

Cooper, H. H., F. A. Kohout, H. R. Henry, and R. E. Glover. 1964. Sea water in coastal aquifers. U.S. Geol. Survey Water-Supply Paper 1613-C. 84 pp.

Downing, J. A. and J. J. Peterka. 1978. Relationship of rainfall and lake ground-water seepage. Limnol. Oceanogr. 23: 821-824.

Franke, O. C. and R. T. Getzen. 1975. Evaluation of the hydrologic properties of the Long Island ground-water reservoir using cross-sectional electric analog models. U.S. Geol. Survey Open-file Rpt 75-679. 80 pp.

Franke, O. C. and N. E. McClymonds. 1972. Summary of the hydrologic situation on Long Island, N.Y., as a guide to water-management alternatives. U.S. Geol. Survey Professional Paper 627-F. 59 pp.

Freeze, R. A. and J. A. Cherry. 1979. Ground-water. Prentice-Hall, Inc. Englewood Cliffs, N.J. 604 pp.

Freeze, R. A. and P. A. Witherspoon. 1966. Theoretical analysis of regional groundwater (sic) flow: 1. Analytical and numerical solutions to the mathematical model. Water Resources Res. 2:641-656.

Getzen, R. T. 1977. Analog-model analysis of regional three dimensional flow in the ground-water reservoir of Long Island, N.Y. U.S. Geol. Survey Professional Paper 982:1-49.

Guillard, R. R. L., R. F. Vaccaro, N. Corwin, and S. A. M. Conover. 1960. Report on a survey of the chemistry, biology and hydrography of Great South Bay conducted during July and September 1959 for the townships of Islip and Brookhaven, N.Y. Woods Hole Oceanographic Institution. Ref. No. 60-15. 5 pp. Unpublished manuscript.

Hubbert, M. K. 1940. The theory of ground-water motion. J. Geology 48: 785-944.

Klute, A. 1965. Laboratory measurement of hydraulic conductivity of saturated soil. Pages 210-220 *in* C. A. Black et al., eds. Methods of soil analysis, Part 1. No. 9 in the series Agronomy. Amer. Soc. Agron.

Lee, D. R. 1977. A device for measuring seepage flux in lakes and estuaries. Limn. and Oceanogr. 22:140-147.

McBride, M. S. and H. O. Pfannkuch. 1975. The distribution of seepage within lakebeds. J. Res. U.S. Geol. Survey 3: 505-512.

National Weather Service. 1980. Climatological data. Asheville, North Carolina.

Peck, A. J. 1960. The water table as affected by atmospheric pressure. J. Geophys. Res. 65: 2383-2388.

Perlmutter, N. M. and H. C. Crandell. 1959. Geology and ground-water supplies of the south shore beaches of Long Island, N.Y. New York Acad. Sci. Annals 50: 1060-1076.

Pluhowski, E. J. and I. H. Kantrowitz. 1964. Hydrology of the Babylon-Islip area, Suffolk County, Long Island, N.Y. U.S. Geol. Survey Water-Supply Paper 1768. 119 pp.

Richards, L. A. 1931. Capillary conduction of liquids through porous mediums. Physics 1: 318-333.

Saville, T. 1962. Report on factors affecting the pollution of Great South Bay, Long Island, N.Y. with special reference to algal blooms. Report to Jones Beach State Parkway Authority, Babylon, N.Y. Unpublished manuscript.

Suffolk County Department of Environmental Control. 1978. Contour map of the water table and location of observation wells in Suffolk County, New York, 1978. Hauppauge, New York.

Weyl, P. K. 1974. The pollution susceptibility of the marine waters of Nassau and Suffolk Counties, New York. Marine Sciences Research Center Tech. Rpt. No. 20, State University of New York, Stony Brook, New York. 21 pp.

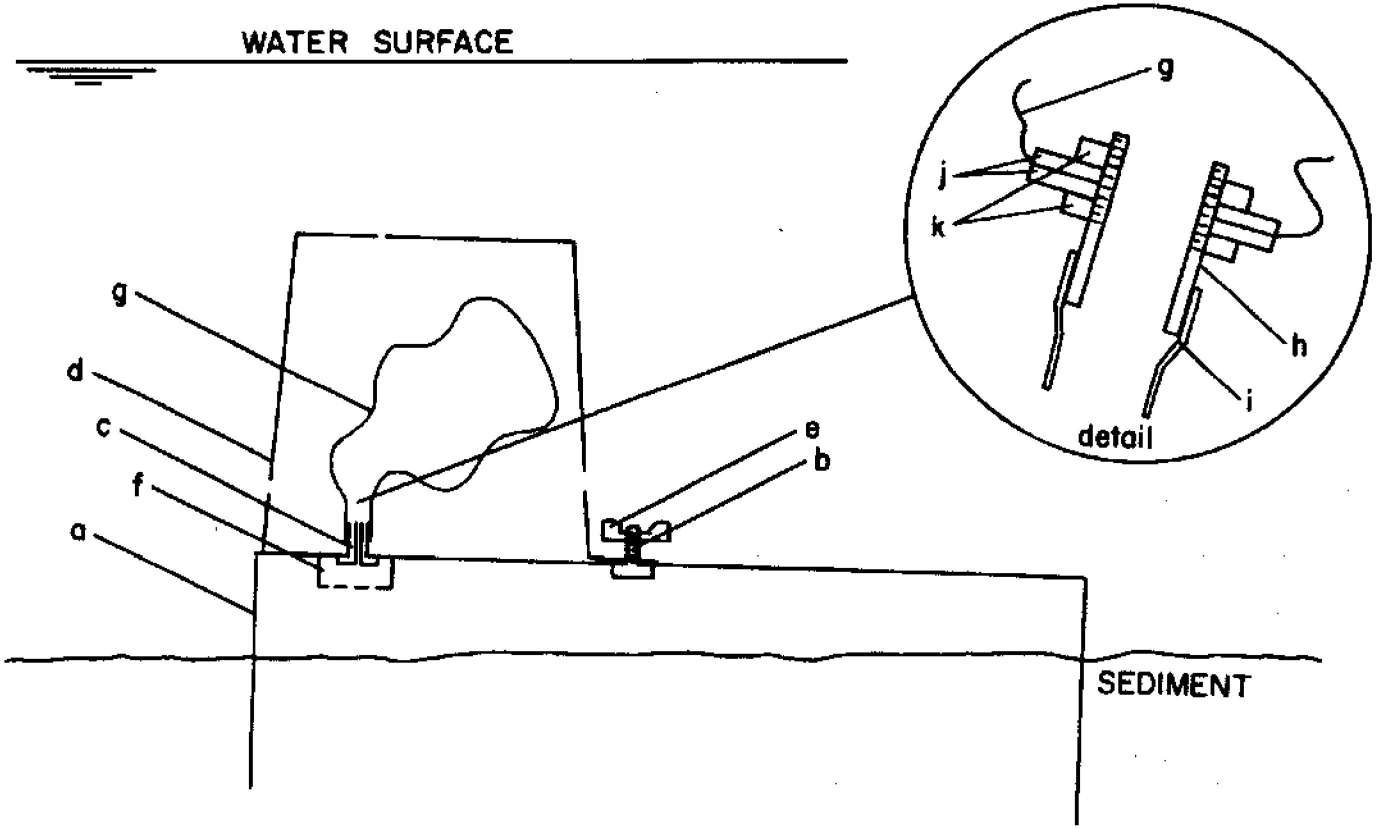

Fig. A1. Schematic of the ground-water, flow-measuring devices in place in the bay floor. *a* is the end of a 55-gallon drum, *b* is a brass bolt, *c* is a tapered nozzle, *d* is a galvanized bucket, *e* is a wing nut, *f* is a perforated plastic cover, *g* is a 4-liter plastic bag, *h* is a threaded PVC tube, *i* is a section of tygon tubing, *j*s are rubber washers, and *k*s are hex nuts.

APPENDIX

CONSTRUCTION AND USE OF THE GROUND-WATER FLOW-MEASURING DEVICES

Introduction

Submarine outflow across the floor of Great South Bay can be measured directly using seepage devices similar to those designed and tested by Lee (1977). A shallow cylinder is placed open-end down into the sediment. Ground water flowing upward into this cylinder is trapped and diverted into a plastic bag connected to the device (Figure A1). After a few hours, the bag is removed and the volume of water is measured. From the time duration of the experiment, the volume of water in the bag, and the area covered by the device, a volume rate of flow per unit area can be calculated. Multiplying the volume flow rate by the area determines the seepage velocity. Eight seepage devices were constructed for this study.

Construction of the Seepage Device

Seepage devices were constructed from the ends of 55-gallon oil drums. Three holes were drilled on the top of each device. Two of the holes were fitted with brass bolts to hold a steel chamber over the bag for protection. The third hole was fitted with a tapered nozzle to serve as vent for the flowing ground water. The nozzle hole was drilled near the edge of the drain so that by tilting the device during placement any entrapped gas could escape. After the nozzle hole was drilled, the two holes for the bolts were arranged to accommodate the best position of the chamber over the nozzle. We used galvanized pails for chambers. The chambers were rigidly held in place with wing nuts. To keep pressure equal inside and out, four small (5 mm) holes were drilled through the pail. In addition to the chambers, small perforated plastic covers were used to prevent clogging of the device during use. The holes in the cover were the same diameter as the nozzle bore. These covers were placed over the nozzle entrance on the underside of each device. An epoxy coating was given to the seepage device in order to seal the cover permanently in place and protect the rest of the device from rust. The tops of the devices were painted orange so they could be seen under water easily.

Construction of Collection Bag

Bags to be connected to the seepage device were 4-liter plastic alligator bags with a wall thickness of 0.017 mm. They were connected to PVC-adaptors which are threaded on one end and smooth on the other. The smooth end was fitted with a short section of tygon tubing so that the bag-adaptor assembly could be connected tightly to the nozzle of the seepage device. The bag was best connected to the threaded part of the adaptor by cutting a 2.5 cm hole into one side of the bag and securing it with rubber washers and hex nuts. The rubber washers prevented tearing of the bag as the hex nuts were tightened. Once the bag assemblies were complete, the open end of the bag was heat-sealed by using a 25-watt pencil soldering iron. The end to be sealed was placed between two pieces of newspaper and sealed by running the iron down the length of the newspaper.

Sampling

In use, eight seepage devices (minus the bag assemblies) were slowly pressed into the bottom sediment until the top was about 5 cm from the sediment. The vented side rested higher so that any entrapped air could freely escape. After the device was set, sediment was placed around the side of the device to insure a good seal between the seepage device and the sediment. After the device was in place, it would be given a gentle upward tug; if the seal was bad the device would pull out of the sediment easily. When this happened the seepage device was removed completely and reset in an undisturbed area. The nozzle was cleaned with pipe cleaners in case any sediment had become lodged in the nozzle during placement. Six seepage devices were usually placed 10, 15, 30, 50, 70, and 100 m from shore. Two additional devices were placed next to the devices at 15 and 70 m from shore. It took between one and two hours to install the eight seepage devices.

The bags were placed on the seepage devices after they were deflated and seeded with a known volume of bay water. Deflating was done by squeezing the bag into a tight ball around the adaptor. Water was then added to the adaptor until full. About 8 mℓ were necessary to displace the air. The exact amount was recorded for each bag. The bag was closed by spreading plastic wrap over the open end and fastening it with a rubber band. When a negative flow (i.e. flow from the bag into the device) was anticipated the bag was filled with 200 mℓ of bay water and sealed. After the bags were prepared, they were placed on the devices by pressing the tygon tube onto the nozzle. The plastic wrap was pierced by the nozzle and the bag was quickly and easily connected to the device. After the bags were connected, the rigid chambers were placed over the bags and secured by using wing nuts. Bag placement required less than 15 minutes. After a minimum of an hour, a second set of bags was prepared and placed on the devices one at a time after each bag from the first set was removed. To remove the bags the tygon tube was twisted off and the opening was immediately covered with a finger. The filled bags were brought back to the beach and the water removed. Between 0.5 and 1 ℓ were generally collected. Volumes were measured using volumetric flasks. The temperature of the samples was also measured. A sample of bay water was collected and brought back to the lab for salinity measurement.

<u>Postscript</u>: A recent measurement of the salinity of water within the devices suggests that the fraction of freshwater in the submarine discharge may be substantially less than seven-eighths as assumed on pages 21, 24, and 25. As much as about half of the submarine discharge may be recirculated bay water. Needless to say, if this is proven to be the case, it would substantially change our calculations (pp. 21, 24, and 25). Further measurements are needed in order to document the amount of recirculation.

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