Aspects of the Physical Oceanography of the Forge River

A report prepared for the
Town of Brookhaven
Long Island, New York

by

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Introduction

The Forge River (Figure 1) is the major tributary of Moriches Bay (Figure 2), a part of Long Island's south shore lagoonal system that is protected from the Atlantic Ocean by barrier islands. The river is a remnant streambed cut through the southerly sloping glacial outwash plain deposited during the Wisconsin glaciation that ended some 20,000 years ago. The stream valley flooded as sea level rose. It now functions as a small estuary. Circulation in the river is complex and is driven by a variety of forces including the tides, water column density structure, groundwater discharge, stream flow, and wind.

The river is shallow throughout and has been historically so. The mean depths in much of the center of the river, based on the soundings from the 1891 and 1933 hydrographic surveys, were about 1.2-1.4 m (4-4.5 ft) at mean low water. The centerline, mean depth, based on the School of Marine and Atmospheric Sciences (SoMAS) survey of 2007-2008, is 1.5-2 m (4.9- 6.6 ft). The depth now is slightly deeper in some locations than indicated on the previous surveys because a 70-m-wide (75-yd-wide) channel has been dredged to a design depth of 2.1 m (7 ft).

Tributaries (Figure 1) of the river including Wills Creek, Poospatuck Creek, Lons Creek, and Home Creek on the west side of the Forge have been dredged as well. The depths in these creeks can be as great as 2 m (6.6 ft). A sill has built up at the mouths of these tributaries so that each one acts as a small basin in which circulation is limited (Figure 3). The same is true for Old Neck Creek on the east side of the river.

Objectives

The objectives of this study of the physical oceanography of the Forge River are:

- to describe and quantify some of the important processes controlling summertime circulation, and
- to ascertain the significance of those processes in establishing hypoxic conditions in the river.

Methods

Quasi-synoptic (nearly simultaneous) water column properties such as temperature (T), salinity (S), dissolved oxygen concentration (DO) and depth at Suffolk County stations 2, 3, 4, 8, and 9 (Figure 1) were obtained at 0.30 m (1 ft) depth intervals by SoMAS using a hand-held YSI model # 85 Conductivity-Temperature-Depth (CTD) meter. Similar observations were made at additional stations 4A, 4B, 9A, and 9B to create cross-sections of time varying properties. Time series measurements of temperature, salinity, dissolved oxygen, and depth at station 2 (Brookhaven Town Pier) in 2006 and at the Waterways Condominiums in 2007 were determined using a YSI model # 85 CTD.

Continuous tidal heights in March and April 2008 were obtained at one-minute intervals using a Seabird SBE-26 pressure gauge corrected for atmospheric pressure. The gauge was mounted on the pier at the Waterways Condominiums. Tide measurements during the synoptic surveys were measured using a calibrated electronic tape measure at either the Brookhaven Town Pier or the pier at Osprey Park. Tide measurements were used to correct depth soundings to a mean low water nautical chart datum and to estimate the volume of the tidal prism entering the upper Forge.

Flows over the three-sided submerged box weirs at East and West Ponds were calculated from direct measurements of the head of water on each side at the spillway using the weir formula:

$$Q = cLH^{3/2}$$

where:

Q = discharge in ft^3/s,
L = width of spillway in ft,
H = head (height of water above crest of spillway) on spillway in ft,
c = coefficient determined by calibration under known conditions (Bretscheiner, 1966).

The value of c was chosen to be 3.5. Edge effects (reduced flow due to friction) were treated conservatively by double accounting for losses at the intersecting corners. The loss of each corner was assumed to be equal to 0.1 L. The total flow for each pond was the sum of the Q for each side.

These flows were checked during a 16 January 2007 survey using a Swoffer Flow Meter, Model 3000-1514 provided by Suffolk County Department of Health Services. West Pond discharge calculated using the head measurements was 7.9 ft^3/s and using the stream flow gauge was 12.0 ft^3/s. Flows calculated for East Pond from both head and gauge measurements were 3.2 ft^3/s. Based on these comparisons, no adjustments were made in the constant or other assumptions related to the discharge equation above.

On that same day, stream flow measurements were also made above tidal influence in Ely Creek, Swift Creek (north of Wills Creek on the west side of the Forge), Poospatuck Creek, and Old Neck Creek. Typically flows were determined in several segments of the stream cross-section and then summed over the entire stream geometry. Flows in the two small streams entering Wills Creek were estimated by collecting a known volume of water in a measured period of time because they were too shallow for the stream gauge.

Results

The Tide

The mean tidal range in the Atlantic Ocean just seaward of Moriches Inlet is about 1.1 m (3.6 ft) (Swanson, 1976). However, as the ocean tide enters Moriches Inlet, it is modified considerably. The mean and spring ranges are 0.88 m (2.9 ft) and 1.07 m (3.5 ft) respectively at the inlet (NOAA, 2008). High water occurs, on average, 57 minutes before Sandy Hook, NJ, the permanent tide station used by the National Oceanic and Atmospheric Administration (NOAA) as a reference station for Moriches Bay. Low water is 69 minutes earlier.

The tidal conditions in Moriches Bay are very much a function of the vagaries of the openings and closings of inlets through the barrier beach that isolates the bay from the open ocean. For example, Redfield (1952) reported that the mean range of tide at the U.S. Coast Guard Station (Figure 2) decreased from 0.21 m (0.7 ft) to 0.07 m (0.22 ft) from 1940 to 1951 as Moriches Inlet was gradually shoaling. After the inlet was reopened in 1953, the tide range increased some 0.06 m (0.2 ft). In 1958, when the inlet was widened and deepened, the range jumped to 0.18 m (0.6 ft) (Guillard et al., 1960).

Now NOAA's only tide predictions in the bay are at the Coast Guard Station and based on one year of observations from August 1989 to July 1990. Mean range there is 0.66 m (2.16 ft), spring range 0.76 m (2.51 ft). The time of high water is 18 minutes before that at Sandy Hook, NJ, low water 48 minutes after low water at Sandy Hook.

The severe 11 December 1992 nor'easter that struck Long Island created two breaches in the barrier island just to the east of Moriches Inlet -- Pike's Inlet and Little Pike's Inlet. Pike's Inlet was artificially closed very quickly but Little Pike's Inlet (4.5 km or 0.25 miles to the east of Moriches Inlet) was left unattended and grew substantially. Conley (1999) reported that the breach was 150 m (165 yards) wide by February 1993, growing to 520 m (570 yards) in late June of that year. Filling began in August 1993 and was completed by 25 September 1993 (Conley, 1999).

With Little Pike's Inlet open, the mean range at Speonk Point (Figure 2), based on about four months of record, was 0.81 m (2.7 ft). After the inlet was closed, the mean range decreased to 0.62 m (2.0 ft) (Conley, 1999).

The tides of Moriches Bay have undergone considerable change in the last 60 years or so; the range today is nearly three times greater than when the inlet was reopened in 1954. The times of arrival of high and low water relative to Sandy Hook have been reduced as much as two hours at the east and west extremities of the bay.

Recorded historical tidal measurements in the Forge River have not been found. However, several sets of tide observations were collected as part of this project. The primary data set was recorded at the Waterways Condominiums at the north end of the tidal river and covers 28 days in March and April 2008. Single tidal cycle observations were also collected on occasion at the Brookhaven Town Pier and at the pier in Osprey Park near the mouth of the Forge in 2006 and 2007.

Each record has been compared, using standard NOAA tidal reduction methods (Gill and Schultz, 2001), with the records of Sandy Hook. These comparisons result in estimates of the long-term mean ranges at each location. The variability of short records is thus reduced. For example, the 19-year value will be estimated within ± 0.04 m (± 0.13 ft) from one month of observations along the east coast of the U.S. (Swanson, 1974). The mean range (estimated 19-year value) at the Waterways Condominiums is 0.56 m (1.83 ft). The high waters, on average, arrived 63 minutes after high waters at Sandy Hook, low waters, on average, 77 minutes after those at Sandy Hook. Often, the high water stage and the low water stage persisted for a period of 30 minutes or so. There was considerable time variability around the mean values, however. The standard deviations for both high and low water time differences from Sandy Hook were ± 24 minutes. Based on a qualitative comparison with wind data from Islip Airport, the long stands at high and low waters and the large variability in the timing of high and low waters relative to Sandy Hook are most likely associated with local wind conditions (NOAA, 2008a, b).

The mean ranges at Osprey Park and the Brookhaven Town Pier are both estimated to be 0.59 m (1.9 ft). The times of arrival for high and low waters at the Brookhaven Town Pier are about 47 minutes and 76 minutes following the respective highs and lows at Sandy Hook. Tidal amplification does not occur along the river. The tidal range in the Forge is now reduced approximately 15 percent relative to the Coast Guard Station as the high tide travels in about 1.3 h from there up to the northern portion of the tidal river at the Waterways Condominiums.

Sea Level (mean of all 6 minute observations over the period of record) at the condominiums was 0.003 m (0.01 ft) higher than Tide Level (mean of all high waters and all low waters over the period of record). These parameters, for practical purposes being equal, mean that the period of the rising tide (time interval between low water and high water) was the same as the falling tide (time interval between high water and low water), suggesting that the tide was neither flood- (characterized by a rapid tidal rise with relatively strong flood current followed by a slow falling tide and weak ebb current) nor ebb-dominant in the upper Forge.

Water Column Properties

In fall 2005 and throughout 2006, Suffolk County Department of Health Services traversed the length of the river on several occasions collecting surface and bottom water property data. Temperature, salinity, and dissolved oxygen from the 6 June 2005 cruise are plotted in Figure 4. This figure illustrates a number of processes ongoing in the Forge in summer. The salt wedge is evident progressing from Moriches Bay (station 13) toward the north. A strong vertical gradient of salinity is present at the north (station 7) where fresh water enters primarily from East and West Ponds. The central reach (stations 9-12) is much more well mixed.

The accompanying dissolved oxygen longitudinal profile implies that DO is being transported at depth with the relatively oxygen rich bottom waters of Moriches Bay to the north. This particular profile was obtained at high tide in the mid-afternoon. Yet hypoxic and near anoxic conditions exist in surface waters north of the Brookhaven Town Pier where oxygen concentrations improve rapidly to the south. Hypoxic/anoxic conditions in bottom waters persist in the vicinity of station 11. One would expect that photosynthesis would have increased surface oxygen concentrations to supersaturated conditions that typically occur on a summer day. However, 5 June was a rainy, misty day as recorded at Islip Airport (NOAA, 2006a). During daylight hours, 62-88 percent of the sky was obscured. Thus photosynthetic processes were probably inhibited, and phytoplankton and macroalgal respiration continued throughout the day.

Summertime water column density structure, as determined by temperature and salinity, drives estuarine circulation in the river and tributaries, but also controls vertical mixing between surface and bottom waters.

A robust long-term record of the physical oceanographic water column parameters does not exist for the Forge River. However, from the diverse observations from several sources, including Suffolk County and SoMAS, it is possible to determine that the hydrographic properties are extremely variable in time and space. Some of the data from these sources, including temperature, salinity, and dissolved oxygen, are reviewed traversing northward along the river.

River Mouth and Osprey Park

The Suffolk County Department of Health Services has maintained a surface water quality monitoring station (80110) at the mouth of the Forge River since 1977. Sampling frequency (mostly in spring and summer) has increased with time so that the overall series is somewhat randomly sampled. The mean temperature for the series ending in 2001 was 14.5 °C with a range between 0.7 °C and 28.8 °C. The low temperature was in February 1993, the high in August 1995. The mean surface salinity was 26.5 psu (practical salinity units, the standard units for salinity now in use) with a range of 20.29 psu to 32.41 psu. The maximum salinity recorded occurred on 30 September 1981. According to the Local Climatological Data summarized for LaGuardia Airport, there had been only 2 mm (0.08 in.) of rain in the previous two weeks (NOAA, 1981). The minimum salinity occurred on 18 July 1984 following a two-week period when 97 mm (3.82 in.) of precipitation fell, including 12 mm (0.47 in.) on the day of sampling (NOAA, 1984).

This relatively long but unequally spaced time series shows that there was considerable interannual variability in temperature and salinity. However, there does not appear to be any trend in either parameter.

Observations made over a tidal cycle at Osprey Park on 3 April 2007 indicated that temperatures were relatively uniform over the depth of about 1.2 m but that there was diurnal heating. Temperatures beginning at 0800 EDT were about 7.5 °C; by 1400 EDT they were around 9.4 °C. Typically there was only about 0.2 °C decrease in the temperature from surface to bottom.

Salinity varied considerably over the tidal cycle at Osprey Park. Around high tide at 1000 EDT, the salinity peaked at about 29.9 psu with little differential between surface and bottom depths. Approaching low water, the surface salinity was 17 psu and the bottom salinity about 18 psu.

Brookhaven Town Pier and Waterways Condominium Pier

In 2006 (Brookhaven Town Pier) and 2007 (Waterways Condominiums Pier), temperature, salinity, and dissolved oxygen data were obtained every 15 min over a period of a month or so.

From 21-30 June 2006, at the Brookhaven Town Pier, the mean temperature about 0.6 m below the surface was 24.4 °C with a standard deviation of ± 0.8 °C. The maximum and minimum for the period were 27.0 °C and 22.1 °C. The mean and standard deviation for salinity were 20.36 psu ± 3.03 psu. The maximum salinity was 24.25 psu but the minimum was 8.23 psu. From 26-28 June, daily pulses of fresh water diluted the salinity signal. The maximum daily salinities were about 4 psu lower during this same period relative to the rest of the record. Over the period 23-28 June, some 5.38 cm (2.12 in) of rain fell at Islip Airport (NOAA, 2006a). Most of that precipitation (3.73 cm, 1.47 in) occurred on 24 June.

Over the period of 18 June to 6 August 2007, at the Waterways Condominiums, the maximum surface temperature was 31.6 °C and the minimum 20.0 °C. The mean and standard deviation for 18 June to 12 July was 25.1 °C ± 2.0 °C; 16 July-6 August 27.0 °C ± 2.1 °C. Diurnal fluctuations were on the order of 3 °-4 °C but were as much as 6 °C. Bottom temperatures ranged between 22.1 °C and 31.1 °C. The mean surface temperature was less than a degree warmer than the mean bottom temperature. There appeared to be a fortnightly temperature fluctuation of several degrees at both the surface and bottom. The warmer waters were associated with spring tides.

Surface salinities (18 June-6 August) ranged between 6.38 psu and 22.75 psu; bottom salinities 14.12-24.54 psu. Over the record, bottom salinities averaged about 4 psu greater than those at the surface. These data are summarized in Table 1.

The surface and bottom salinity records indicated a number of pulses of fresh water occurring on nearly a daily basis, particularly in the latter part of the time series. These fluctuations, which span up to 6 psu, were not coincident with rainfall events based on Islip, NY climatological records (NOAA, 2006a, b). There was also evidence of a semidiurnal period of salinity variations associated with the rise and fall of the tide. A fortnightly signal was apparent during which salinities, particularly at the bottom, were greater on spring tides and less on neaps.

On 8 August 2006, observations of temperature and salinity as a function of tide and depth were made at the Brookhaven Town Pier. The temperatures and salinities are plotted along with tidal height in Figures 5a and 5b. Note that there was considerable density stratification and that the conditions at the bottom depth (far right in the figure) changed little throughout the day.

Surface DO concentrations at station 2 (8 August 2006) varied from 0 mg O_2/L at sunrise to 13 mg O_2/L just after noon (Figure 6), a change from 0 percent saturation to 200 percent saturation. Bottom DO concentrations were essentially 0 mg O_2/L throughout the day.

The continuous sampler on the Brookhaven Town Pier (mounted at a fixed depth relative to the pier decking) indicated that the DO concentrations were extremely variable over the period of 20-30 June 2006. The sampler was relatively deep at high water compared to low water and thus some of the variability was likely the result of the sampler being well up in the water column (near the surface) on low tides.

North of the Long Island Rail Road

Salinities in the upper tidal Forge are probably influenced by a non-uniform discharge of fresh water temporarily impounded during the low stages of the tidal cycle behind the shallow, narrow sill that has built up in the channel cut through the Long Island Rail Road (LIRR) bridge and embankment. Suffolk County recorded conditions in this non-navigable water body (station 17) between Montauk Highway and the LIRR on four occasions over the period 2005 to 2006. The salinities varied between 7.8 psu and 19.8 psu. The low reading occurred near a low water on a weak neap, the high value near a high water as spring tidal conditions were waning. Rainfall did not appear to have been a factor in the salinity variations.

Water Column Structure as a Function of Tide

On 23 August 2006, the structure of water column properties temperature, salinity, dissolved oxygen, and percent oxygen saturation were obtained to create time-varying sections over a tidal cycle. One section (Figure 1) ran normal to the main channel of the Forge through stations 9, 9A, and 9B. This section was selected as it is away from the direct influence of a stream and so would be the most ideal to estimate the flux of salt and fresh water across the transect. A second section (stations 4, 3, 2, and 8) ran along Wills Creek, across the Forge to the center of Ely Creek. This one was picked in order to ascertain the influence of the sill (Figure 3) across Wills Creek on the flow of water into and out of the creek. A section, normal to Wills Creek through station 4, was also obtained about an hour past high tide.

Observations commenced around 0630 EDT on a rising tide (Figure 7) and persisted past high tide (around 0930-1000 EDT) and through low tide at about 1530 EDT. At the time, tidal conditions were well past neap and the range on the day of observations was very close to the mean.

Weather conditions on that day were quiescent. Air temperature at Islip Airport varied between 18 °C at night and 30 °C during the day (NOAA, 2006). Winds were generally calm in the morning and perhaps 3-5 m/s (6-10 knots) out of the southwest in the afternoon. The last rainfall had occurred on 20 August and, as recorded at Islip, was about 0.7 cm (0.3 in.). With the exception of another 0.2 cm (0.08 in.) of precipitation on 15 August, the month had been dry.

<u>Transect Across River Through Station 9</u>

Data from this section, including temperature, salinity, DO concentration, and DO percent saturation are displayed in Figures 8a-8d, representing four time periods (0715, 1015, 1325, and 1545 EDT) on 23 August 2006.

The water column was slightly thermally, vertically stratified during the early morning at about 0700 EDT. Surface waters were cooler than those at the bottom as a consequence of nighttime cooling of the atmosphere. Very rapidly, the western side of the transect became horizontally stratified as the air temperature warmed. In the morning, the water temperatures were somewhat cooler (nearly 0.5 °C) on the east side of the Forge compared to the west. This condition persisted and became stronger as high tide approached. In the center of the river and at its deepest part, cold Moriches Bay water appeared to move north as the tide rose. This continued until the tide fell. Toward 1300 EDT, the surface waters on the east began to warm and horizontal, thermal stratification developed around 1400 EDT while vertical stratification remained to the west. Horizontal stratification redeveloped around 1500 EDT.

Salinity was vertically stratified, particularly to the west from 0700 EDT through 1300 EDT. The greatest difference between surface and bottom salinities (≈ 3.5 psu) occurred near high tide (0930-1000 EDT). More typically, the difference was about 2 psu.

Beginning at 1400 EDT, the isohalines (contours of equal salinity) began to tilt down and to the east, indicating lower salinity water from the center to the east side of the river. This condition persisted through low tide. The maximum salinity difference between the surface water on the east and that on the bottom to the west was about 1.5 psu.

A weak salt wedge (fresh water overriding a salt front that moves with the tide) advanced and retreated with the tide through this section. The maximum observed bottom salinity of 24.1 psu occurred at high water, the minimum of 22.0 psu corresponded with low water. The relatively evenly spaced isohalines were vertically stratified and the varying distribution of isohalines over time suggests that some vertical mixing was taking place.

The general shapes of the iospycnols (contours of equal density) tracked those of salinity. The densest water was found in the deepest part of the channel through high tide when it began to dissipate.

Oxygen concentrations around 0700 EDT were greatest in the surface waters of the east side of the river and on the order of 5 mg O_2/L. The west side of the river was generally 1.5 mg O_2/L or so less throughout the water column. The bottom concentration on the west was definitely hypoxic (< 3 mg O_2/L). By 0900 EDT, the effects of photosynthesis were clearly observed as surface DO concentrations increased. Dissolved oxygen concentrations gradually increased through the water column as high tide (0930-1000 EDT) approached. They were slightly higher to the east compared to the west. The deepest part of the channel remained hypoxic.

About an hour past high water, the highest surface concentrations (> 9 mg O_2/L) developed to the west and the concentration at the bottom of the channel was no longer hypoxic.

Near surface concentrations of DO exceeded 10 mg O_2/L by 1300 EDT approaching 160 percent saturation. There was generally uniform vertical stratification for this property across the transect. The bottom value (6.58 mg O_2/L) in the dredged channel reached 88 percent saturation.

As low tide (≈ 1545 EDT) approached with little water near the east bank of the river, maximum observed values of DO exceeded 14 mg O_2/L and 200 percent saturation. Isolines of concentrations sloped down to the east. Lowest concentrations were near the west bank; they exceeded 8.5 mg O_2/L and 100 percent saturation.

<u>Transect Along Wills Creek and Across the Forge River</u>

Figure 9 depicts the depth relative to mean low water along this transect. Note the deep in Wills Creek, the sill across the creek and the shallows to the east. Figure 10 shows T, S, DO concentrations and percent saturation similar to those at section 9. They represent conditions at this transect at four different times, a-d.

Water temperatures along the transect were inversely stratified as they were cooler at the surface relative to the bottom until close to high tide between 0900 and 1000 EDT. As with transect 9, nighttime cooling of the water surface was apparent. Around 1000 EDT, a dramatic overturn in thermal structure took place with nearly uniformly cool water found to the east and into Ely Creek. Relatively warm water occurred to the west with the warmest being at depth. The temperature difference early in the morning was about 1.5 °C. As the surface water warmed, the difference was reduced to about 1 °C. As afternoon progressed, waters to the east warmed considerably but were isothermal with depth. The cooler waters were on the west and vertically stratified to station 2 (Brookhaven Town Pier). The greatest differences in temperatures were in late afternoon and in excess of 1.5 °C.

Salinity was vertically stratified past high tide. The differences between bottom and surface salinities over the morning were about 4-5 psu. Surface waters were about 1 psu fresher than those at transect 9 during the morning, indicating fresh water discharges into Wills Creek and Ely Creek.

Saline bottom water appeared to be flowing over the sill at Wills Creek and perhaps accumulating there to some extent, as measured salinities at stations 3 and 4 were equal to or slightly greater than salinities at station 2.

Just past high tide, when it was noted that the tidal current was strongly ebbing at the Brookhaven Town Pier, the greatest salinities were observed at station 3 along the transect. It would appear from the isohalines (0953-1058 EDT) that water at the 1.5 m depth and above was flowing out of the creek into the main channel of the Forge River. Near noon the salinities were greatest at stations 3 and 4. This remained the case throughout the afternoon.

The isopycnals generally have the same shape as the isohalines. The observed densities at station 3 were slightly greater ($\approx$ 0.2-0.3 sigma τ units or kg/m^3) than those at station 2, suggesting that there may not be a free exchange of bottom water in Wills Creek with that of the main channel of the river. Throughout the afternoon, the densest water was found at the bottom of Wills Creek. Over the tidal cycle, the changes in densities from stations 2, 3, and 4 were 1.45 psu, 1.20 psu, and 0.41 psu, respectively. This further suggests the sluggish nature of Wills Creek.

At about 0700 EDT, with the exception of the surface observation in Ely Creek, the entire transect was hypoxic. Most of Wills Creek, surface to bottom, was anoxic. Dissolved oxygen concentrations were uniform from surface to bottom over the entire transect but gradually increased from east to west.

Isolines of DO concentrations began to slope down to the east with time in the early morning. Station 4, which was tree-shaded and not subjected to direct sunlight, remained close to anoxic throughout the morning and was definitely anoxic at the bottom. Percent DO concentration generally remained lower in Wills Creek relative to the rest of the transect throughout the day.

Beginning around 0900 EDT, the DO concentrations began to increase on the east side of the river and in Ely Creek as photosynthesis commenced. At that time, the surface waters at stations 2 and 8 both experienced DO concentrations greater than 5 mg O_2/L and were at 60-70 percent saturation. Waters below 1 m remained hypoxic.

Just past high tide, surface waters at stations 3, 2 and 8 (Wills Creek, Brookhaven Town Pier, Ely Creek) varied between 5 and 7 mg O_2/L (90-100 percent saturation). Note in Figure 10c that the DO concentrations at stations 3 and 4 had an intermediate depth DO minimum < 0.4 mg O_2/L. At the bottom, DO concentrations were > 1 mg O_2/L.

Near noon, the entire water column in Wills Creek remained hypoxic and even approached anoxia. On the east side of the transect, DO concentrations were stratified and varied between about 9 mg O_2/L at the surface and 4 mg O_2/L at the bottom. Around 1400, DO concentrations exceeded 14 mg O_2/L (208 percent saturation) at station 8 (Ely Creek). The concentration gradient east of the Brookhaven Town Pier increased to the east and was more or less uniform top to bottom.

Dissolved oxygen concentrations remained vertically stratified to the west (Brookhaven Town Pier into Wills Creek). However, surface DO values did begin to exceed 100 percent saturation (≈ 7.5 mg O_2/L) after 1400 in Wills Creek. Bottom DO concentrations remained hypoxic, however.

Transect Across Wills Creek

A north-south transect in Wills Creek through station 4 (Figure 11) just after high tide indicated relatively fresh water at the surface with the freshest water occurring closest to the banks (18.3 psu to the north, 18.5 psu to the south). These were the lowest salinities measured during the survey. Salinity stratification was evident with the greatest salinity (22.9 psu) found at depth in the center of the creek.

Water temperatures varied from 24.0 °C-26.2 °C. Even late in the morning the warmest water (26.0 °C- 26.2 °C) was found at 0.9 m (3 ft) below the surface. The cooler water at the surface may have been due to groundwater seepage (≈ 13 °C) and shading from diurnal warming by the overhanging trees.

The entire section was well below hypoxic conditions with mid-depths on the south to the center of the transect nearly anoxic. At the deepest depth in the center, the DO concentration was slightly greater than 1 mg O_2/L.

Surface and Groundwater Flow

An objective of this investigation was to estimate the quantity of fresh water entering the upper Forge River. Specifically, we wanted to determine the volume of ground water entering the system relative to that of stream flow. To undertake this, we directly measured stream flow from East Pond, West Pond, Old Neck Creek, Wills Creek, Poospatuck Creek, Ely Creek, and Swift Creek.

Stream Flow

Flows from East Pond and West Pond to the tidal Forge were estimated on five occasions between July 2006 and January 2007 (Table 2). These ponds, which discharge close to each other on the south side of Montauk Highway, are the largest source of surface runoff to the upper Forge River. West Pond is consistently about 72 percent of the total flow of the two ponds. Flow can be quite variable and depends on rainfall in the drainage basin. The mean of our measurements was 22,350 m^3/d (790,000 ft^3/d). This compares well with the Redfield (1952) measurement of 21,600 m^3/d (763,000 ft^3/d) over the period December 1947-April 1948.

Applied Technologies (2007), working for the New York State Department of Environmental Conservation, measured the mean flow of from West Pond to be about 70,560 m^3/d (2.51 million ft^3/s) (49 m^3/min (29 ft^3/s)) over the period of 20-30 March 2007. The method of measurement was not cited nor would the company respond to phone calls. A three-fold difference in stream flows is not surprising, however, over the period of a year.

On 16 January 2007 stream flows above tidal influence were measured at Poospatuck Creek, Swift Creek, Wills Creek, Ely Creek, and Old Neck Creek (Table 3). These flows were quite small and are only about 20 percent of the combined flows from East and West Ponds.

Groundwater Flow

Salinity measurements were taken over nearly a complete tidal cycle on 23 August 2006 at a three-station cross section running through station 9. These measurements were used to calculate the mean salinity of the rising tide and that of the falling tide for the purpose of approximating the flow of ground water to the upper Forge. By knowing the salinity of the incoming tidal volume, the salinity of the outgoing tide, the volume of the water body between high and low water, and the measured stream flow, the volume of ground water entering over the tidal cycle can be estimated. This estimate was obtained using simple continuity concepts involving the tidal prism (the volume of water between mean high water and mean low water):

Let P represent the prism, then

$$P = V_f + V_Q$$
$$P = V_e - V_Q$$

and from salt conservation

$$S_f V_f = S_e V_e$$
$$V_f = R\, V_e$$

where

V_f = volume of water transported northward on a rising tide,
V_e = volume of water transported south on a falling tide,
S_f = average salinity of the rising tide,
S_e = average salinity of the falling tide,

V_Q = volume of fresh water entering the river on rising tide and also the falling tide,

$R = S_e/S_f$,

these relationships can be used to solve for V_Q in terms of P and R:

$$V_Q = P\ (1 - R)/(1 + R)$$

The mean salinity of the rising tide, integrated over time and space through section 9 was 23.1 psu, that of the falling tide, 21.3 psu (Table 4). The volume, V_f, of tidal water flowing into the upper Forge based on the mean area of the basin (mean of the low and high water surface areas, determined by planimeter) and the tidal range (0.59 m, 1.92 ft) is 295,000 m^3 (10.419 million ft^3). The volume of fresh water entering on the rising tide (V_Q) is 12,291 m^3 (434,120 ft^3). This equates to a flux or rate of flow (Q_T) over a tidal cycle of 6.2 hr of 0.55 m^3/s (19.4 ft^3/s).

Using the flux of fresh water measured directly from stream flow measurements, Q_F, the flux of ground water, Q_G, can be calculated by the difference:

$$Q_G = Q_T - Q_F.$$

Adjusting the January 2007 measured stream flow to that of flow from East and West Ponds on 23 August 2006 yields a stream flow to the upper Forge of 0.21 m^3/s (7.4 ft^3/s). Groundwater flow was thus 0.34 m^3/s (12.0 ft^3/s). At the source of the greatest input of fresh water to the Forge, groundwater discharge was 62 percent of the total of fresh water input.

Discussion

The Forge River functions in terms of its physical oceanography as an estuary driven by fresh water entering at its head and along its length and by a tidally-driven influx of saltwater from Moriches Bay.

The tide range throughout the river is essentially uniform, the mean range being 0.59 m (1.9 ft) at both Osprey Park and the Brookhaven Town Pier. It is 0.56 m (1.83 ft) at the Waterway Condominiums. Mean tide level and mean sea level are at the same relative elevation in the upper reaches of the Forge, indicating that the tide is neither flood- nor ebb-dominated. Being symmetrical (neither flood- nor ebb-dominated) with respect to flood and ebb implies that transport of suspended material out of or into the upper river is nearly balanced.

Salt transport up-river is a function of neap and spring tides with higher salinity water being associated with spring tides. For example, at station 2, the Brookhaven Town Pier, bottom salinities at spring tides (tide range $\approx$ 110 percent of mean) varied from 24.5-25.5 psu over a tidal cycle on 8 August 2006 (Figure 3). Under mean tidal conditions on 23 August, the salinity range over a tidal cycle was 22.1-24.5 psu.

A considerable quantity of fresh water enters the upper Forge. Surface salinities average about 4 psu less than bottom salinities. The major sources of surface discharge to the tidal Forge are East and West Ponds. These two ponds constitute about 80 percent of the total stream flow to the entire tidal Forge.

Mixing along the river is an important aspect of circulation. This can be observed in the 2006 Suffolk County Department of Health Services data collected along the length of the river. Total nitrogen concentrations are plotted versus surface salinity and indicate an inverse relationship between the two along the length of the river (Figure 12).

While the flow over the weirs at East and West Ponds seems to be uninterrupted, much of this water may be temporarily impounded north of the railroad bridge. Release may be a function of tidal stage and flux from the ponds. This may account for some of the salinity spikes observed in the continuous recordings at the Waterway Condominiums.

Ground water is also a major source of fresh water to the Forge, probably contributing on the order of 60 percent of dry weather flow entering the Forge above section 9.

At the temperatures and salinities experienced in the Forge during summer, most any change in density is due to a change in salinity. A change in salinity of 1 psu results in a change of 0.7 sigma-t (density) units. A change in water temperature of 1 °C alters sigma-t units ≈ 0.3. Seemingly, with a difference in salinity between the surface and the bottom of 4 psu, the water column would be stable and thus mixing somewhat limited. However, as mentioned above, this does not seem to be the case, with the exceptions of Wills Creek and the deepest parts of the main channel that are not affected by tributaries. See the changing shapes of the isohalines (lines of constant salinity) through the tidal cycle (Figure 8b). In particular, the east side of the river is stratified on the rising tide and well mixed on the falling -- perhaps a function of tidal energy and the shallowness of the river.

Density stratification is stronger and more persistent on the west side of section 9 while the tide is rising and through the first hour or so on the falling tide. On the east side of the channel, density stratification disappears following high water.

At the Wills Creek to Ely Creek section, the water column below 0.3 m (1 ft) in Wills Creek apparently remains stratified and somewhat sluggish (minimum change in sigma-t) throughout the day. From the Brookhaven Town Pier eastward into Ely Creek, where the depth is relatively shallow, density stratification breaks down following high tide when the salinity becomes fresher and uniform from surface to bottom, moving toward the east.

A number of physical forces and conditions affect circulation and DO concentrations in the Forge and its tributaries. Besides horizontal estuarine gravitational circulation, vertical mixing is enhanced by tidal and wind forcing. Fluctuations in stream flow and groundwater flow impact gravitational circulation. Because the river is shallow, any of these conditions can significantly alter the conventional views concerning estuarine circulation.

Physical alterations to the river modify the estuarine circulation that does take place. The combination of the dredged creeks and built up sills at the mouths of these creeks has tended to create relatively stagnant basins with limited circulation during summer when stratification is most intense. The sill and the dredged deep behind it in Wills Creek are clearly contributing to its sluggish, slough-like conditions (Figure 10). The entrainment (ponding) of water north of the LIRR by the shoal under the bridge may be modifying the natural flow of fresh water into the Forge, impeding estuarine processes. The dredged channel in the Forge apparently exacerbates stratification, possibly reducing mixing that had occurred historically.

Wind, at times, can be a dominating force controlling circulation in the Forge. The generally shoal-like nature of much of the river creates a situation whereby potential stagnant conditions can be alleviated by overturning the water column by turbulence.

Physical processes and bottom topography (dredged channels, sills) are influential in controlling dissolved oxygen concentrations. Data indicate that both surface and bottom waters can be anoxic at night. However, during daytime, photosynthesis can create supersaturated conditions, in some areas > 200 percent. In Wills Creek, percent saturation was somewhat less, perhaps 120-140 percent. The relatively low dissolved oxygen percent saturation of Wills Creek could be caused by trees shading the waterway and reducing photosynthesis or by turbidity in the water column creating chemical/biological processes that can also reduce photosynthesis.

However, in addition to biochemical processes such as photosynthesis, respiration, and sediment oxygen demand, estuarine gravitational flow transports relatively oxygen rich water at depth, and wind and tidal energy mixes oxygen vertically even if weakly during intensive stratification. Similar physical forcing has been noted in the Pamlico River and Cape Fear River – both microtidal estuaries (Lin et al., 2006).

For example, where vertical mixing takes place, such as on the shallow east side of the river, both at Ely Creek and section 9, supersaturated water mixes to depth to relieve hypoxic/anoxic conditions. Where the water column remains stratified, such as in the navigational channel, DO concentrations tend to remain low, but not necessarily hypoxic.

In Wills Creek, however, the severe hypoxia/anoxia is exacerbated by several conditions acting synergistically. Ground water, perhaps rich in nitrogen and stimulating primary productivity, seeps into the creek from its banks. The sill at the mouth of the creek prevents the free exchange of water with the Forge River. And the depth of the creek is deeper than the Forge, so that the creek behaves as a basin. Forge River water enters the creek on a rising tide; fresh water enters from the creek and its banks. Both contribute to strengthened stratification with little exchange with the Forge and minimal downward mixing of what oxygen-rich surface water there is. There may be a slight increase in bottom DO relative to mid-water in the creek on occasion. This increase may be a consequence of transport of dense river water with somewhat greater DO concentrations into the creek as the tide rises.

In summary, it is evident that the physical structure of the river bottom and its tributaries (bottom topography) exacerbates its tendency toward eutrophication and hypoxia. However, while density structure during summer can inhibit mixing DO from surface to depth, gravitational flow does transport DO upriver and on occasion turbulence by wind and tide can help vertically mix DO to depth.

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Figures

Figure 10d. Percent saturation along transect from Wills Creek to Ely Creek (from stations 4 through 8) at approximately 0700, 1000, 1430, and 1600 EDT.

Figure 11. North-South transects of temperature (°C), salinity (psu), dissolved oxygen (mg O_2/L), and percent saturation across Wills Creek through station 4 at approximately 1100 EDT.

Figure 12. Total nitrogen concentrations (mg/L) as function of salinity along the Forge River for stations 7, 1, 2, 9, 11, 12, and 13 on 12 September 2005, 10 November 2005, 5 June 2006. Data from Suffolk County Department of Health Services.

Tables

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Table 2. Flows from East Pond and West Pond between July 2006 and January 2007.

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Table 4. Measured parameters and calculated values used to estimate groundwater flux (Q_G).

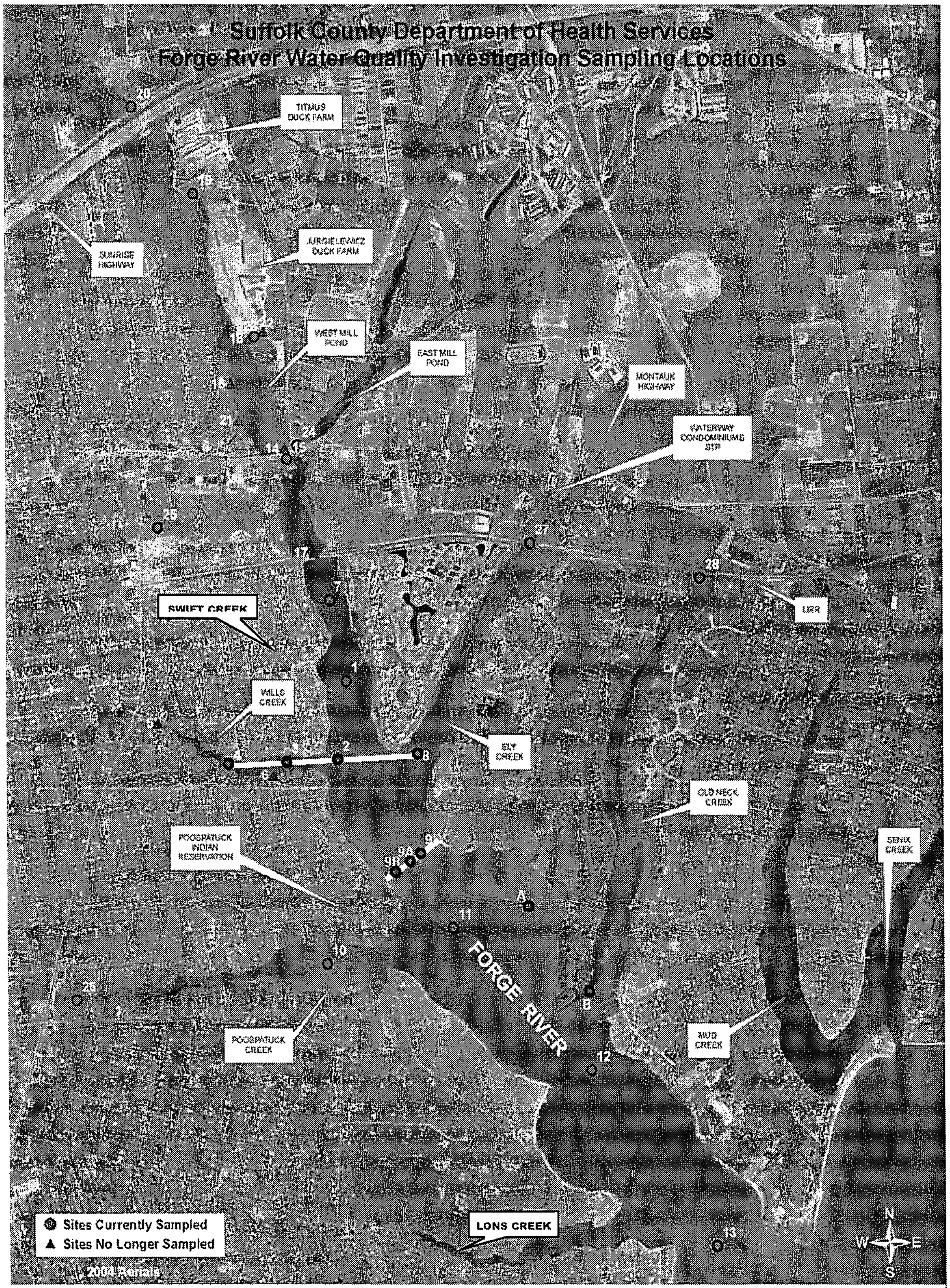


Figure 1. Map of Forge River showing Suffolk County water quality sampling stations and oceanographic sampling transects.

Figure 2. Aerial photograph of Moriches Bay.

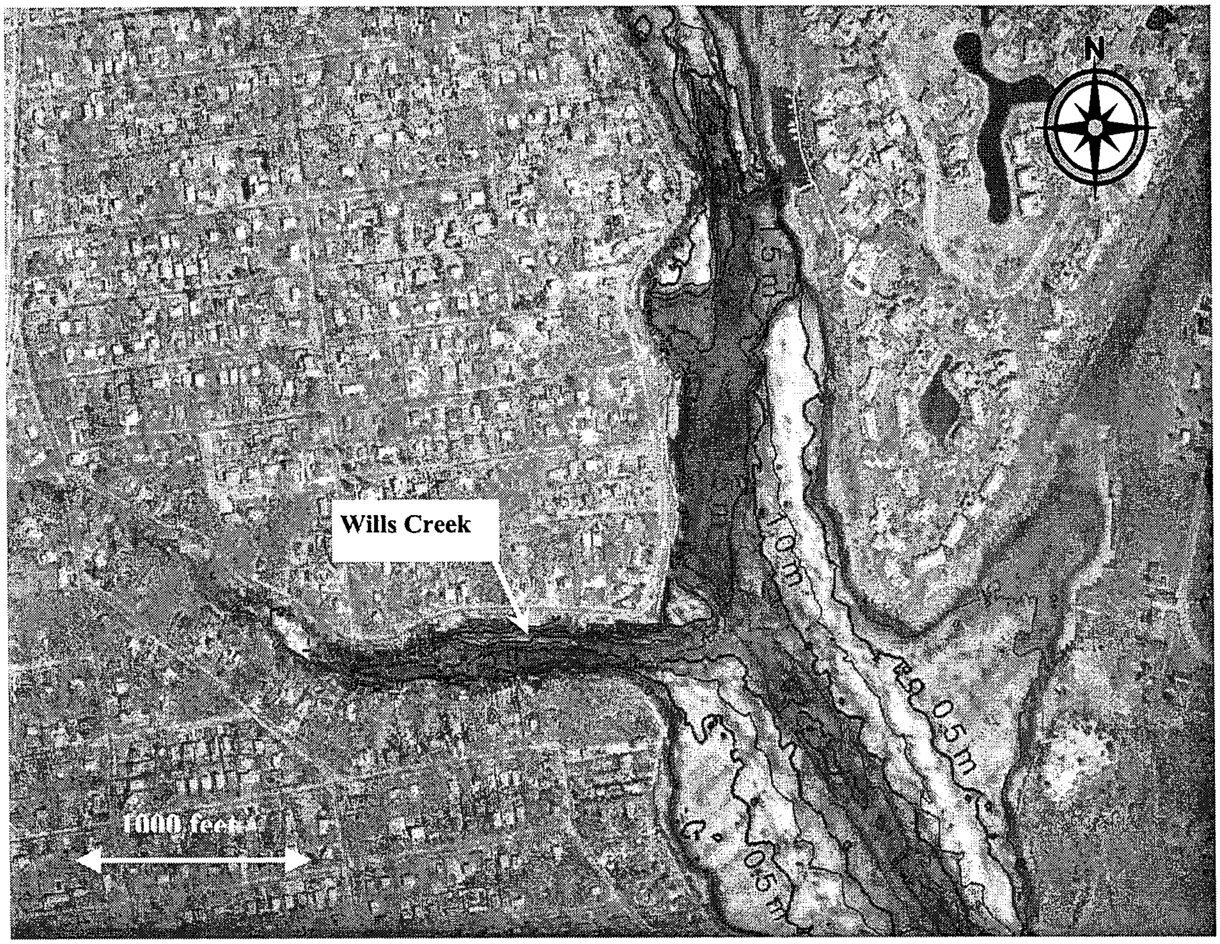


Figure 3. Section of bathymetric map near Wills Creek.

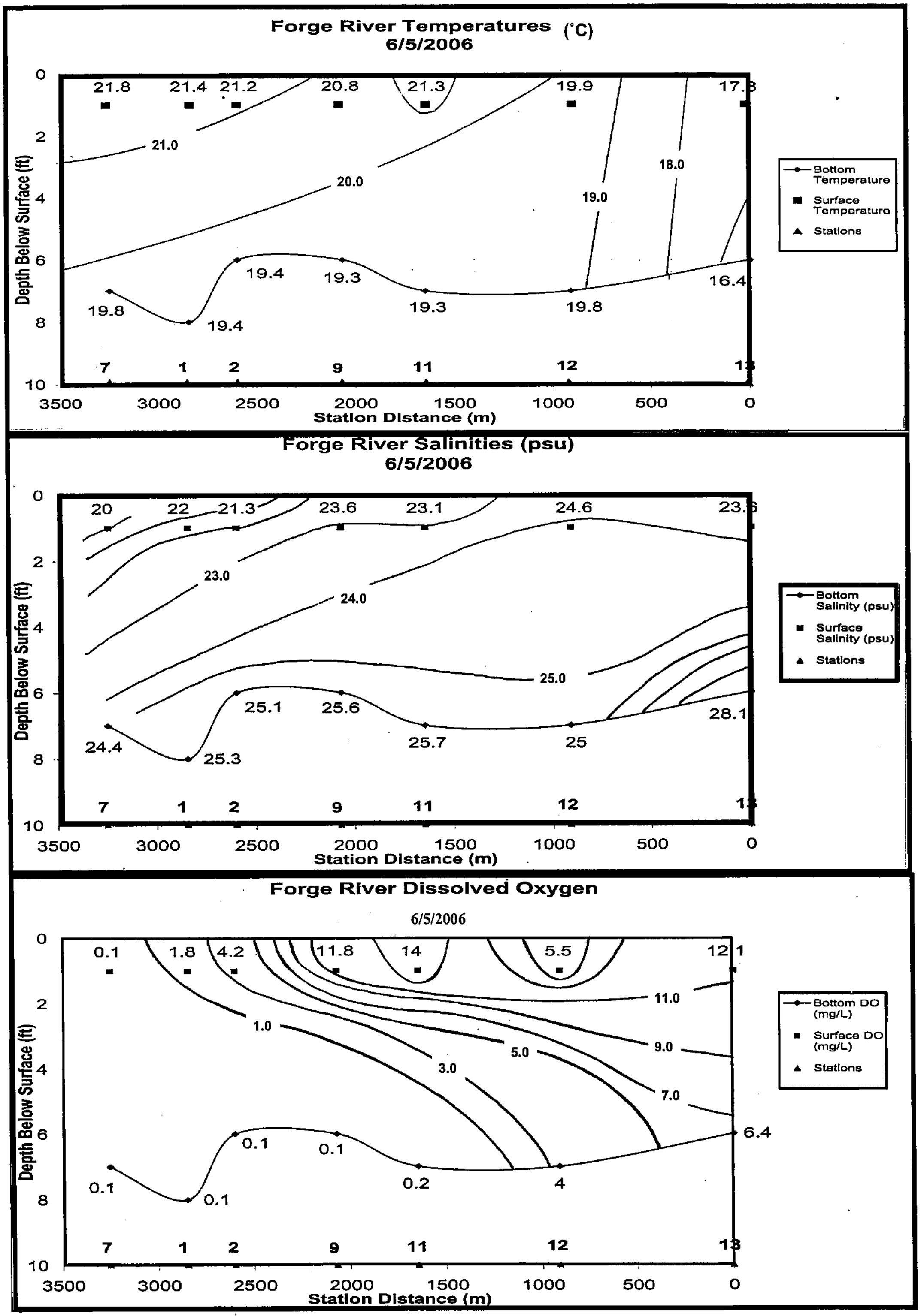
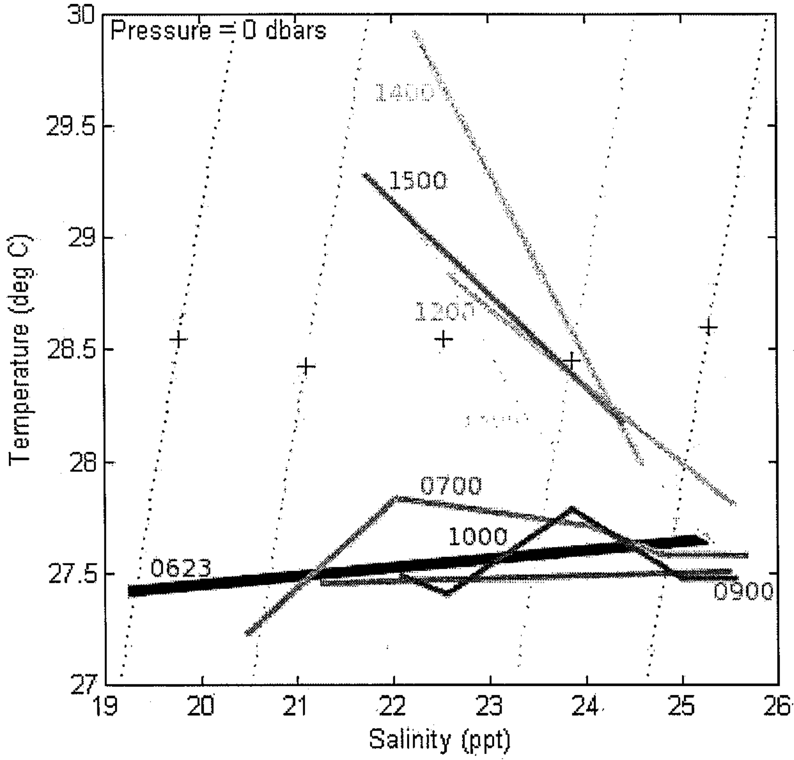


Figure 4. Longitudinal sections along Forge River on 5 June 2005 of a: temperature(°C), b: salinity (psu), c: dissolved oxygen concentration (mg O_2/L). Data at station 13 was from 8 June 2006. Data from Suffolk County Department of Health Services.



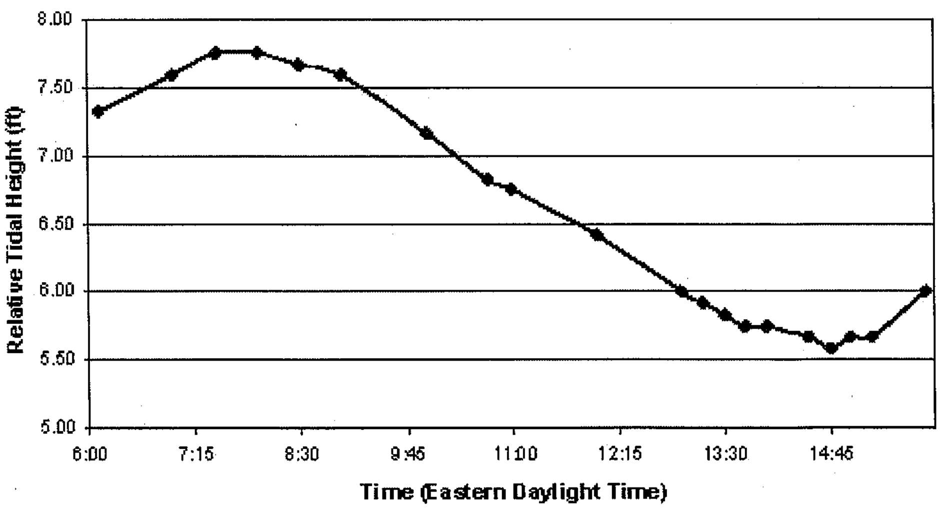


Figure 5a. T-S diagrams as a function of time (top).
Figure 5b. Forge River tidal height (ft) as a function of time at station 2 (bottom); 8 August 2006.

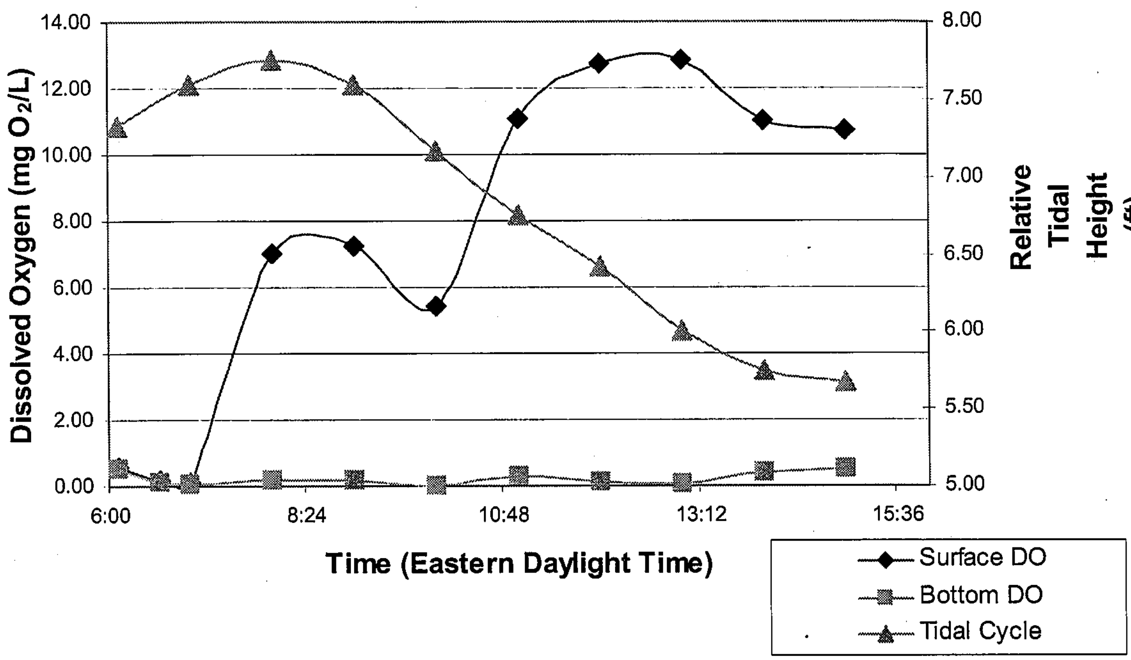


Figure 6. Forge River Dissolved Oxygen (mg O_2/L) and Tidal Height (ft) vs. Time, Brookhaven Town Pier, August 8, 2006.

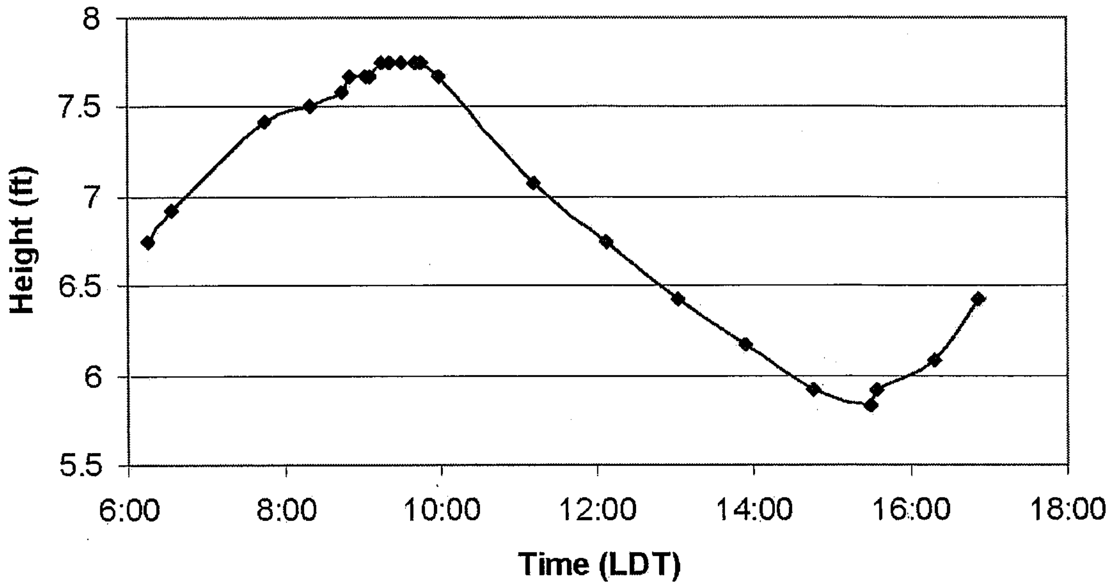


Figure 7. Tide curve at station 2, Brookhaven Town Pier; 23 August 2006.

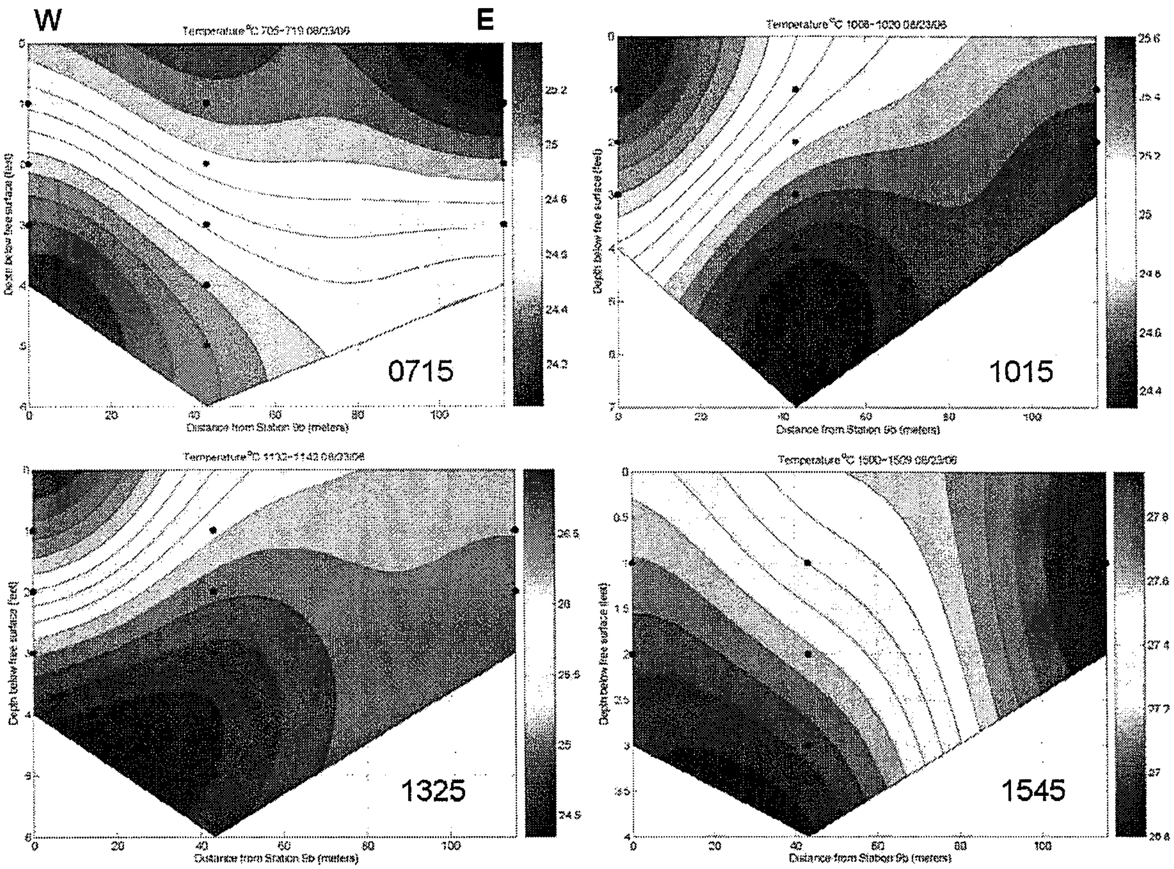


Figure 8a. Temperatures (°C) along transect 9 in Forge River at approximately 0715, 1015, 1325, and 1545 EDT.

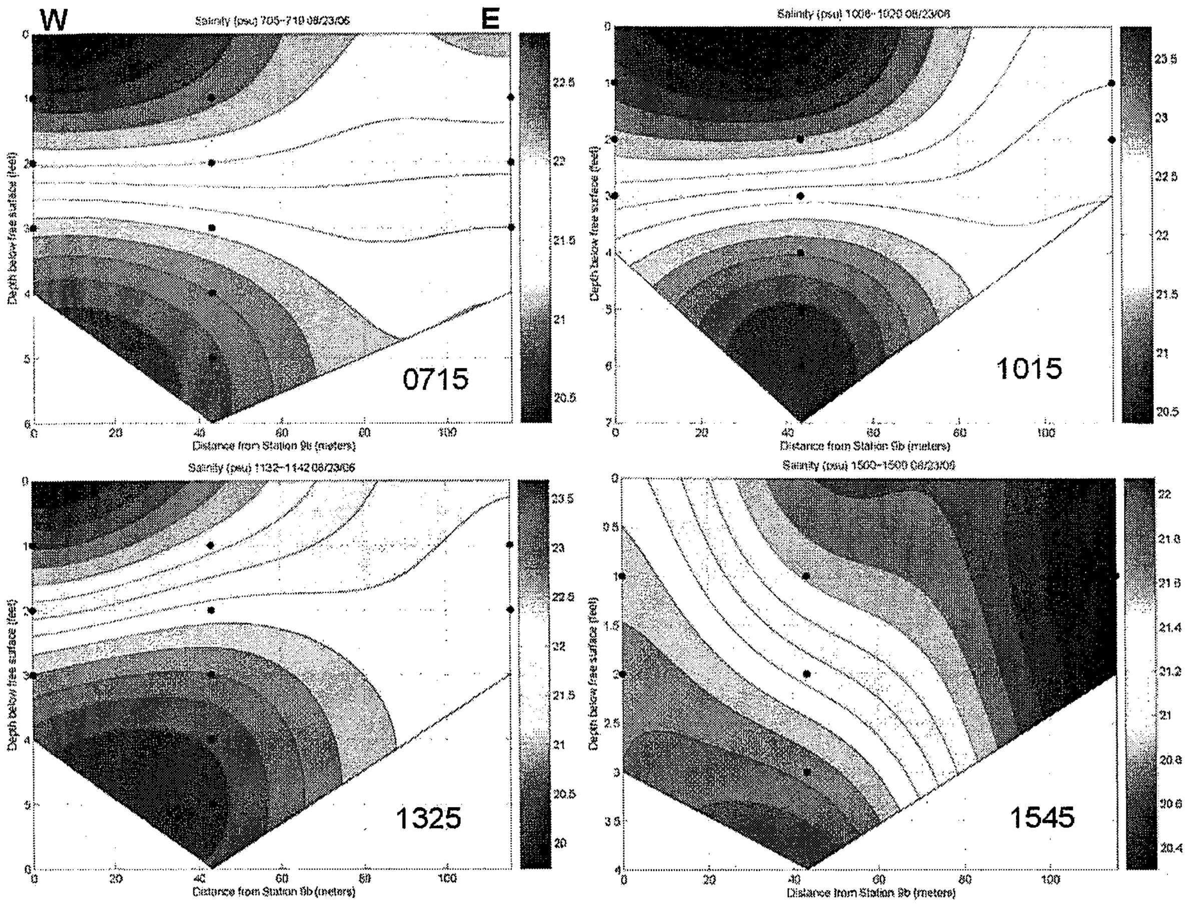


Figure 8b. Salinities (psu) along transect 9 in Forge River at approximately 0715, 1015, 1325, and 1545 EDT.

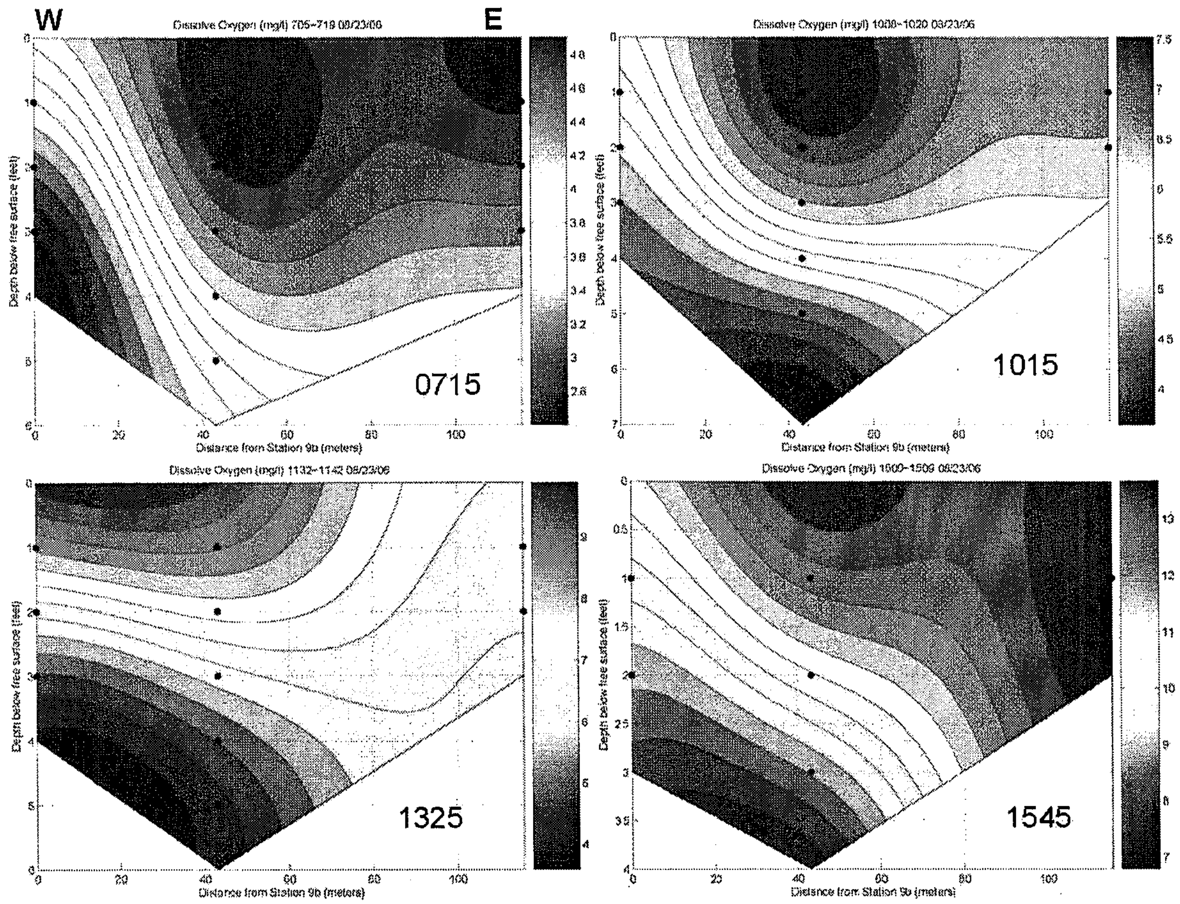


Figure 8c. Dissolved oxygen (mg O_2/L) along transect 9 in Forge River at approximately 0715, 1015, 1325, and 1545 EDT.

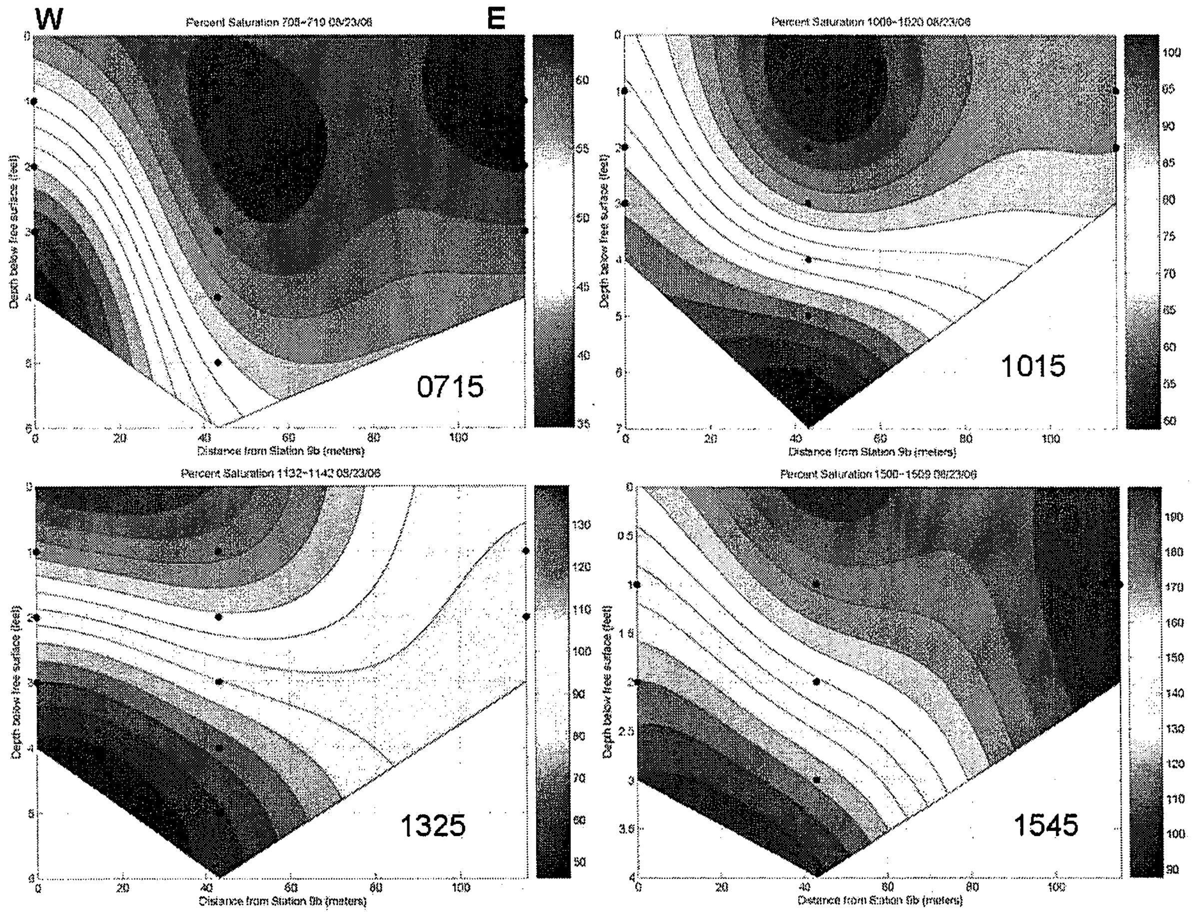


Figure 8d. Percent saturation along transect 9 in Forge River at approximately 0715, 1015, 1325, and 1545 EDT.

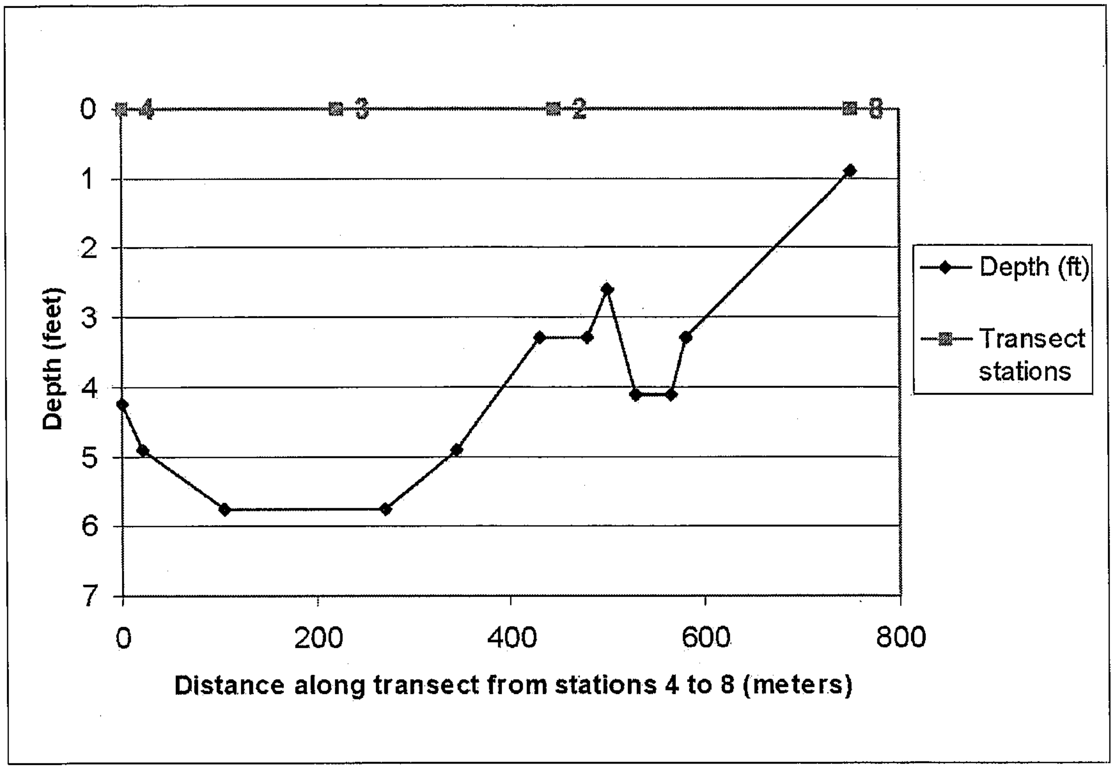
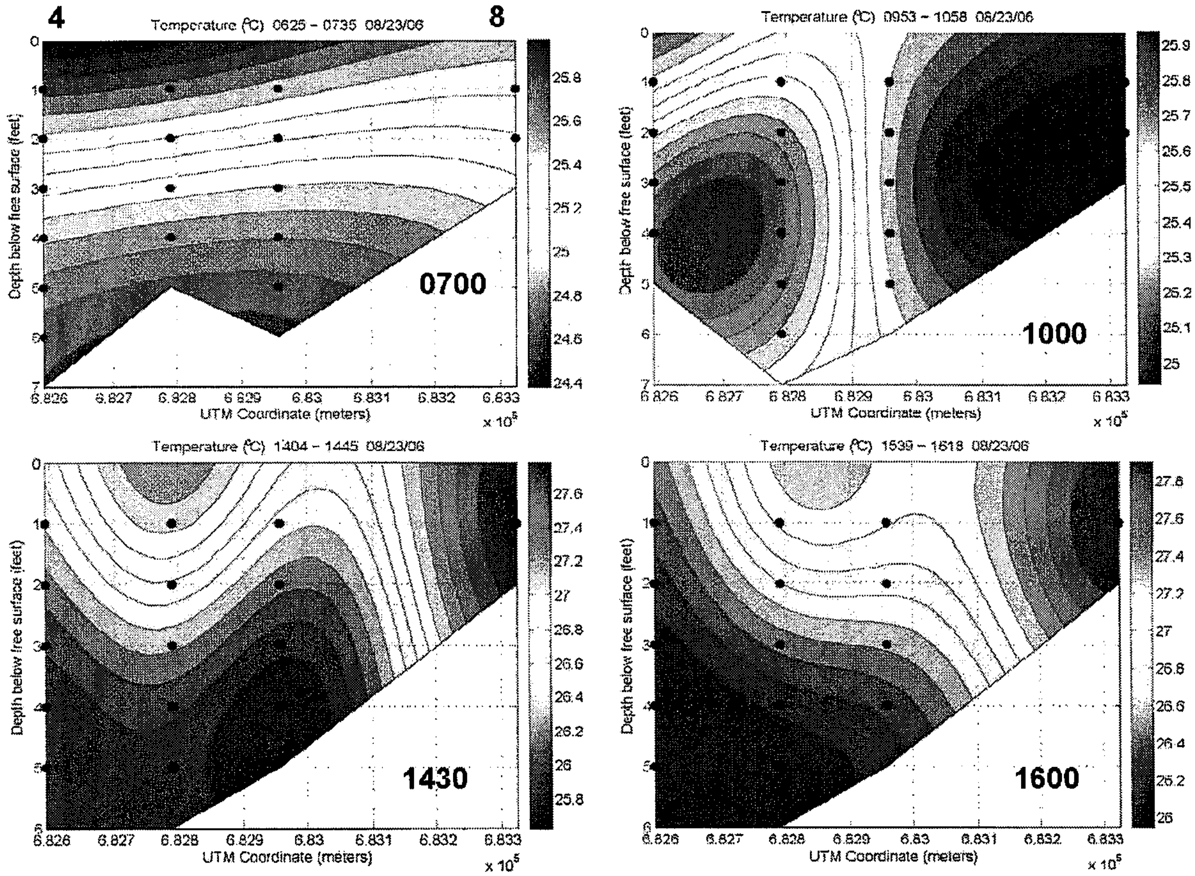


Figure 9. Bottom topography from Wills Creek to Ely Creek: Depths relative to mean low water along transect through stations 4, 3, 2, and 8.



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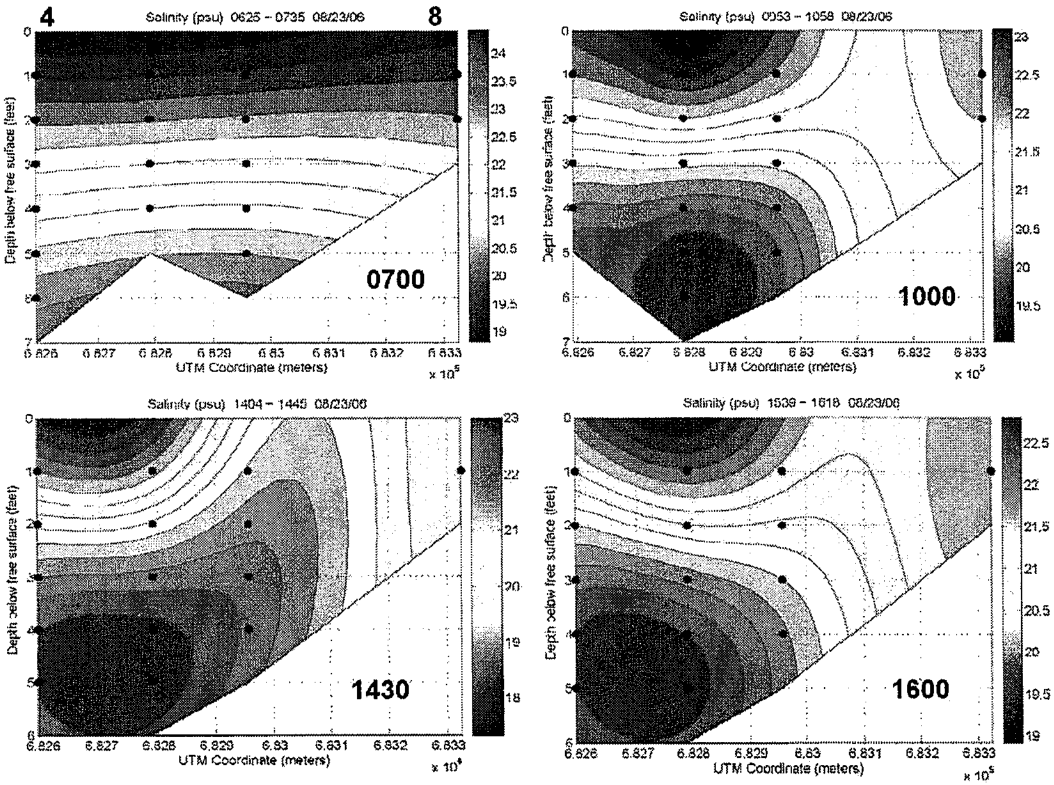


Figure 10b. Salinity (psu) along transect from Wills Creek to Ely Creek (from stations 4 through 8) at approximately 0700, 1000, 1430, and 1600 EDT.

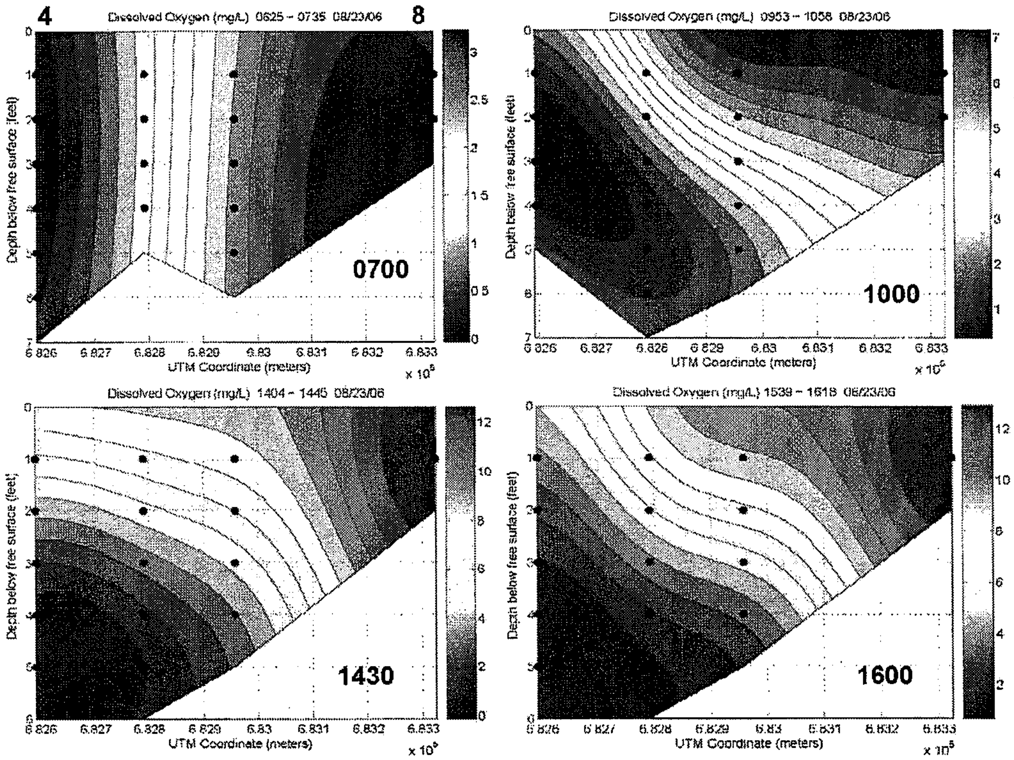
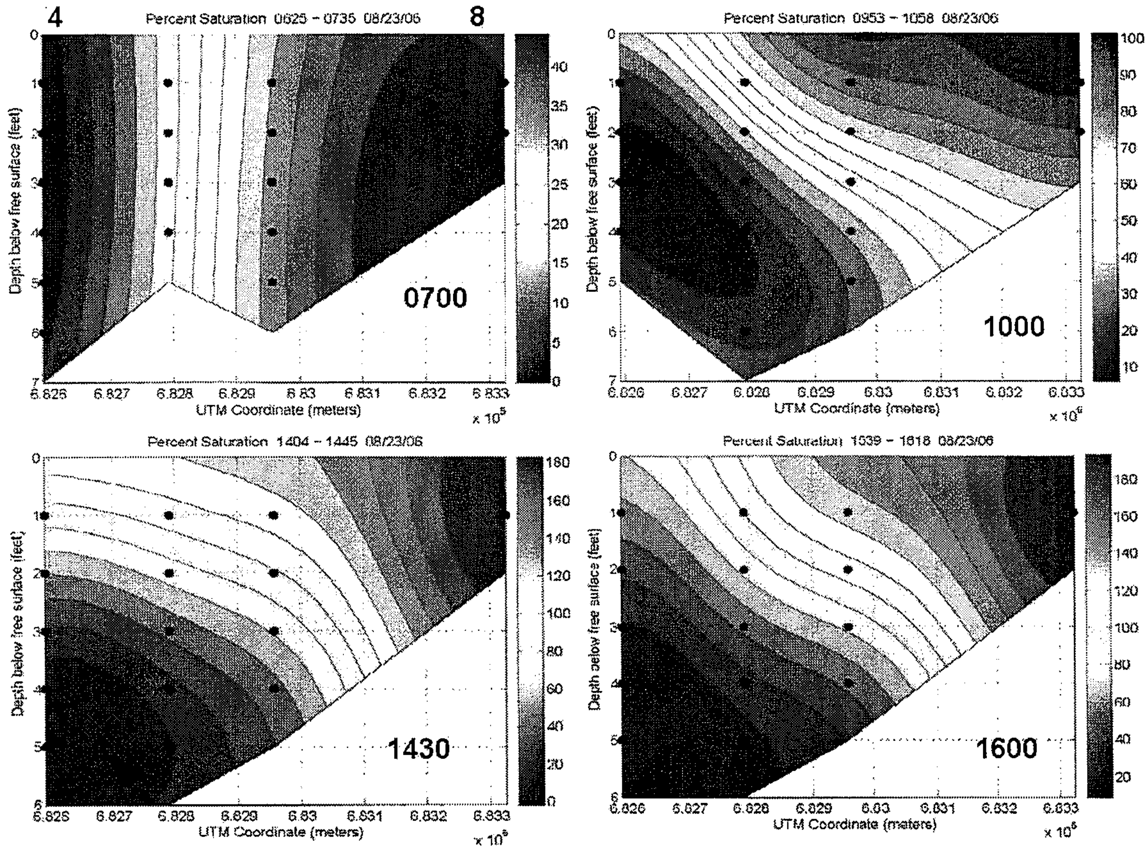


Figure 10c. Dissolved oxygen (mg O_2/L) along transect from Wills Creek to Ely Creek (from stations 4 through 8) at approximately 0700, 1000, 1430, and 1600 EDT.



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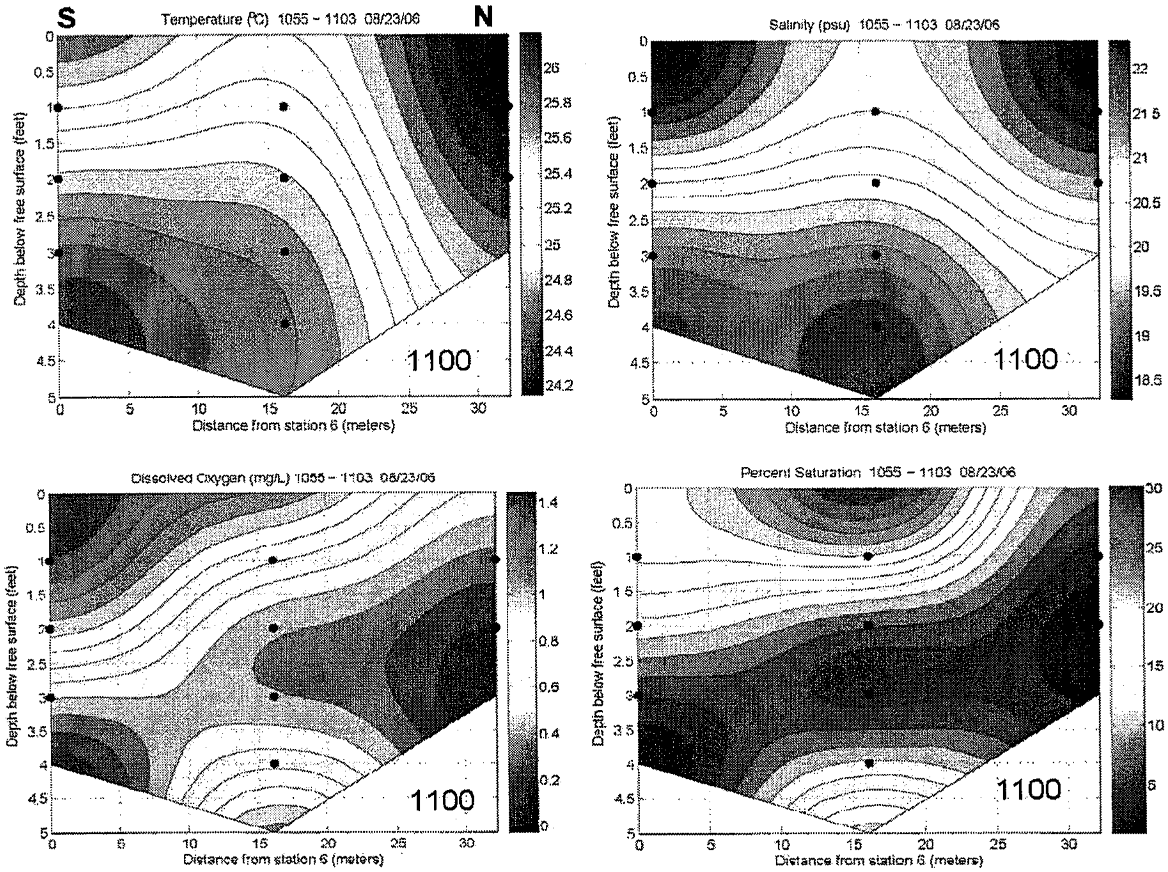

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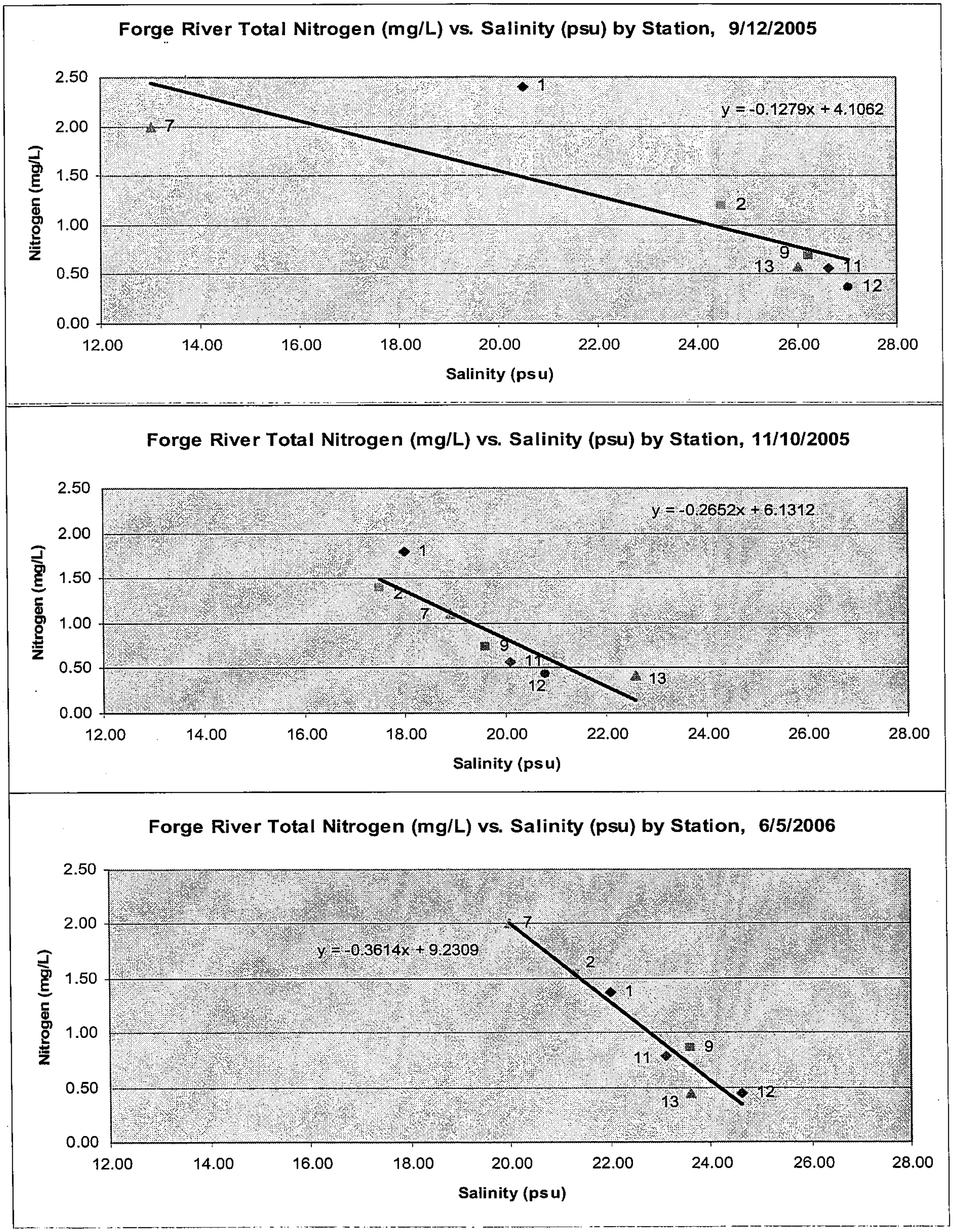

Figure 12. Total nitrogen concentrations (mg/L) as function of salinity along the Forge River for stations 7, 1, 2, 9, 11, 12, and 13 on 12 September 2005, 10 November 2005, 5 June 2006. Data from Suffolk County Department of Health Services.

1a. 18 June - 12 July 2007

Surface

	T (°C)	S (psu)
Mean	25.05	16.89
Stdev	2.01	4.23
Min	19.99	6.38
Max	30.94	24.05

Bottom

	T (°C)	S (psu)
Mean	24.21	21.85
Stdev	1.20	1.25
Min	22.09	19.46
Max	27.03	24.35

1b. 16 July - 6 August 2007

Surface

	T (°C)	S (psu)
Mean	27.03	17.20
Stdev	2.07	3.12
Min	20.91	7.94
Max	31.58	22.75

Bottom

	T (°C)	S (psu)
Mean	27.01	21.35
Stdev	2.03	1.66
Min	22.39	14.12
Max	31.14	24.54

Table 1a and 1b. Mean and standard deviations from continuous temperature and salinity measurements at surface and bottom; Waterways Condominiums; 18 June-12 July (a) and 16 July-6 August (b) 2007.

Flow over East and West Pond Weirs, m^3/min (ft^3/s)

Date	East Pond	West Pond	Total	West Pond (as % of Total)
7/11/06	5.4 (3.2)	14.3 (8.4)	19.7 (11.6)	72.4%
8/8/06	3.6 (2.1)	10.2 (6.0)	13.8 (8.1)	74.1%
8/23/06	3.1 (1.8)	7.3 (4.3)	10.4 (6.1)	70.5%
11/22/06	4.4 (2.6)	10.5 (6.2)	14.9 (8.8)	70.4%
1/16/07	5.4 (3.2)	13.4 (7.9)	18.8 (11.1)	71.2%

Table 2. Flows from East Pond and West Pond between July 2006 and January 2007.

Measured Freshwater Flow from Creeks Discharging to Forge River
16 January 2007

Location	m^3/min	ft^3/s
Poospatuck Creek	0.68	0.4
Wills Creek		
North stream	0.02	0.01
South stream	0.03	0.02
Swift Creek	3.4	2.0
West Pond	13.4	7.9
East Pond	5.4	3.2
Ely Creek	0.5	0.3
Old Neck Creek	0.02	0.01
Total	***23.45***	***13.8***

Table 3. Flows from tributaries discharging to the Forge River on 16 January 2007.

Measured

Surface Area m^2	Surface Area (ft^2)	Tidal Ht m	Tidal Ht (ft)	S_f psu	S_e psu	Q_f m^3/s	Q_f (ft^3/s)
504,095	(5,426,562)	0.59	(1.92)	23.1	21.3	0.21	(7.4)

Calculated

P m^3	P (ft^3)	V_e m^3	V_e (ft^3)	V_Q m^3	V_Q (ft^3)	Q_T m^3/s	Q_T (ft^3/s)	Q_G m^3/s	Q_G (ft^3/s)
294,990	(10,419,000)	307,280	10,853,120)	12,291	(434,120)	0.55	(19.4)	0.34	(12.0)

Table 4. Measured parameters and calculated values used to estimate groundwater flux (Q_G).

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