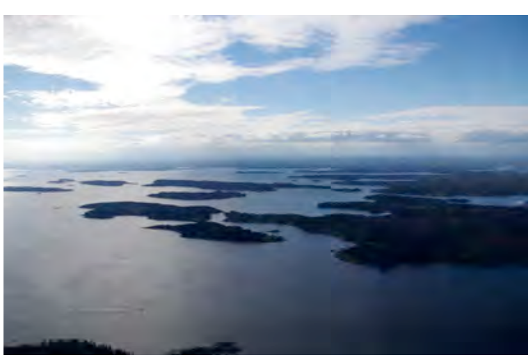
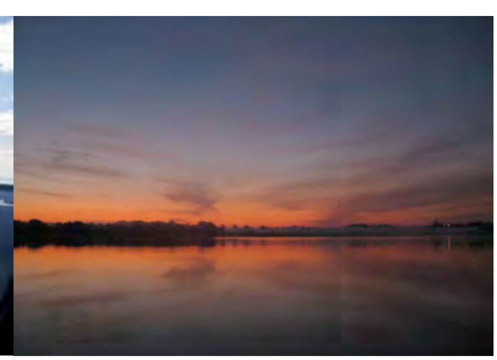
State of the St. George Estuary 2012

Georges River Tidewater Association





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The State of the St. George River Estuary in 2012

Introduction

The Georges River Tidewater Association has issued annual State of the St. George River Estuary reports in most years since the early 1990s. This year's report presents the first-year results of an ambitious water-monitoring program launched in spring 2012 and designed to measure three key interrelated indicators of estuarine health: **dissolved oxygen (DO), pH,** and **total nitrogen (TN).**

There is an urgent need to observe and predict the potential impacts on Maine estuaries of increasing seawater temperature, declining pH, nutrient run-off, and late-summer deficiencies of dissolved oxygen. Gulf of Maine surface-water temperatures increased by 2° to 3.5° C between 2008 and 2012 (Trotter, 12/17/2012). Declining pH (i.e., ocean acidification) has been observed worldwide, in the Gulf of Maine, and in Casco Bay and is occurring more rapidly in near-shore environments such as the Chesapeake Bay, the Gulf Coast, and Puget Sound due to nutrient run-off and the consequent overproduction and decay of organic matter (see under "The Water-Monitoring Program Rationale and Goals" below). Correlated declines of pH and dissolved oxygen with depth—possibly indicative of decaying organic matter that is consuming oxygen and producing carbon dioxide as it sinks--have been documented in Casco Bay and other near-shore waters and in our 2012 water-quality monitoring work (see Figure 27a-c below).

Little has been done to date to extend water-quality observations into Maine's numerous estuaries that are characterized by slow tidal flushing, low hydrodynamic energy, and nutrient enrichment and may therefore be especially vulnerable to pH and dissolved oxygen deficits. This project addresses that need.

The description of the St. George Estuary below is followed by a description of the water-monitoring program rationale and goals; the 2012 methods and results; the 2012 index of estuary health; and a discussion section with recommendations for 2013 and beyond.

The key take-away message: Our 2012 results suggest that the estuary is chronically stressed with respect to dissolved oxygen, pH, and nutrient over-enrichment.

Description of the St. George Estuary

The St. George Estuary (Figure 1) is representative of numerous estuaries that punctuate the Maine coast. At the head of tide, this long, narrow estuary is fed by the St. George River (Figure 2), which delivers a low volume of fresh water except during spring freshets or after heavy rains. In the summer of 2002, for example, the river delivered between 9 and 32 cubic feet per second to the estuary's headwaters. In the wetter summer of 2003, the freshwater river flow was 24 to 57 cfs over the period measured, and that volume increased up to 93 cfs in October 2003 (GRTA monitoring data, 2002-2003). Stream-flow measurements of the estuary's tributary streams in the summer of 2001 determined that these were collectively small enough to have no measurable impact on the flushing of the estuary (Rines, 2009).

Tidal flushing thus dominates river flushing, but tidal flushing is itself restricted by the estuary's long, narrow axis--the channel being just meters wide for much of its length—and by two major bottleneck constrictions (one in the Upper Estuary, one in the Lower Estuary) and two Upper Estuary sills. Flushing of the estuary's upper reaches requires up to 32 tide cycles or 15 days. Hydrodynamic models (Rines, 2009) have shown that the 6.3-mile-long Upper Estuary is thus prone to concentrate run-off nutrients such as nitrogen, creating a reservoir that "trickles" to the 11.3-mile-long Lower Estuary.

Figure 1. In this view from above Thomaston, the Lower Estuary (upper left) and Upper Estuary (lower right) are both visible.

Like other estuaries in Maine and elsewhere, the St. George renders a wide range of ecosystem services. Its primary fisheries include the spring harvest of elvers and alewives in the upper reaches of the estuary, year-round clam and marine worm harvesting from the 1,683 acres of mudflats in the Lower Estuary, and an intensive lobster fishery in the estuary's seaward reaches. The clam fishery and the alewife runs are among the largest in the state. Together, the landed value of these fisheries can be estimated as $10-15 million in 2012 (Table 1). In some years there is a recreational fishery for striped bass, and in most winters there are smelt shacks on the Mill River, a tributary in Thomaston. The estuary also hosts sea-run brown trout, and Atlantic sturgeon were sighted in 2012. Herring are sometimes taken from the Lower Estuary by purse seine or, historically, by stopping coves (such as Deep Cove) with twine. Mussels and urchins are harvested from the seaward reaches of the estuary. The shad runs of former times have not occurred in the past few decades.

In addition to its fisheries, the estuary provides employment for boatbuilders (notably the Lyman-Morse yard in Thomaston), marine service providers (including Jeff's Marine and Tibbets Marine in Thomaston), and recreational fishing and duck-hunting guides—perhaps 200-250 jobs overall (Table 2).

Other ecosystem services provided by the estuary are difficult or impossible to quantify. These include habitat for shorebirds, waterfowl, and raptors; recreation for paddlers, sailors, boaters, and anglers; scenic vistas; and protection of upland areas from storm tides. The salt marsh fringes of the Upper Estuary—and the salt marsh heads of Lower Estuary coves—absorb nutrients and pollutants from run-off, reducing contamination of estuarine and coastal waters.

Estuaries also provide a vital link in the life cycles of anadromous and catadromous fish, notably alewives and eels, respectively. Alewives ascend Maine's estuaries in late spring to spawn in fresh and brackish waters, and the young of the year descend the estuaries in August through November. Research now suggests that alewives provide critical forage for haddock, cod, and pollock, and that Maine's coastal groundfisheries will not recover until the alewife runs are fully restored to Maine's estuaries (Lichter and Ames 2012).

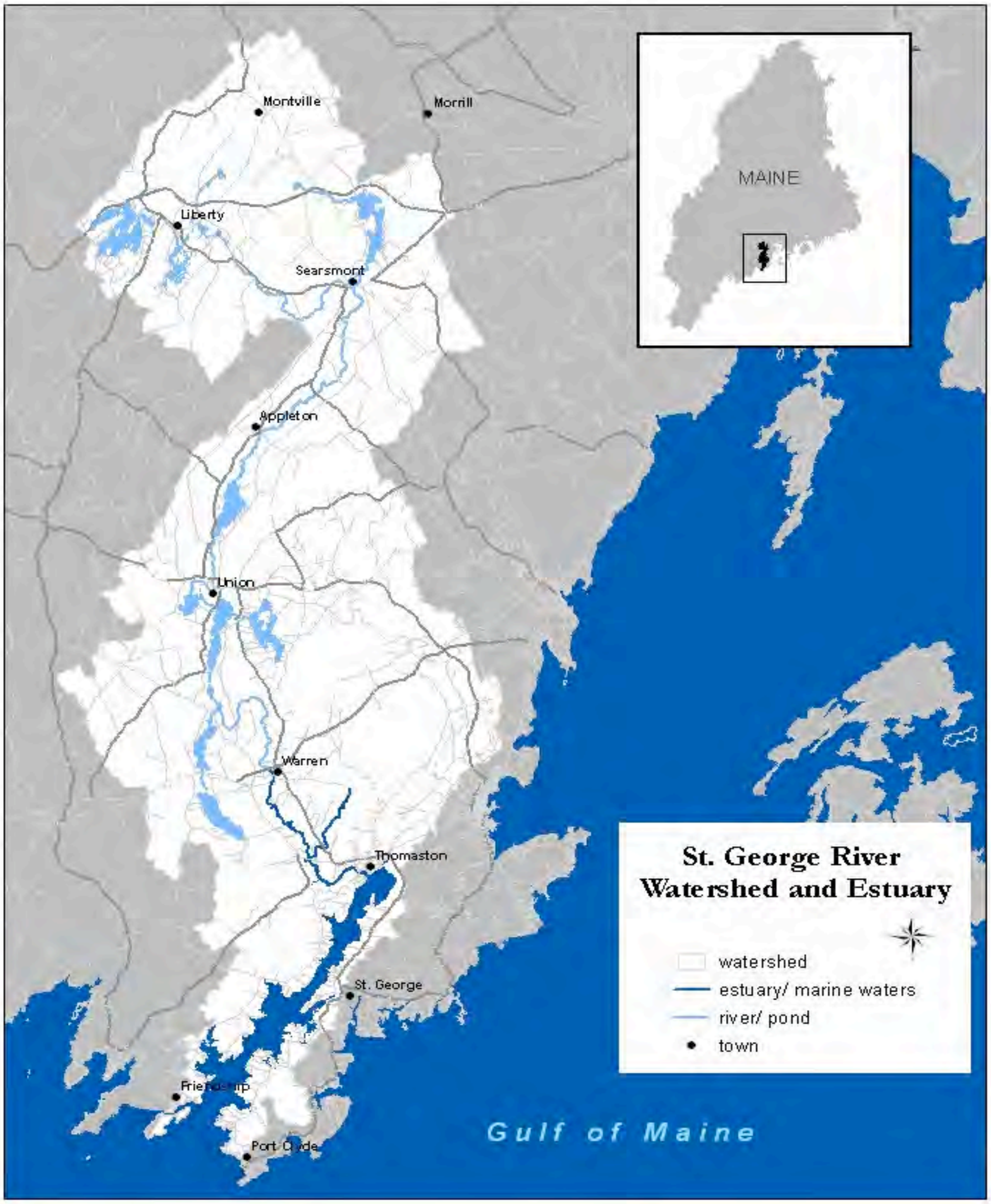


Figure 2. The St. George River watershed. The river (including estuary) is 51 miles long with its headwaters in Liberty, Montville, and Morrill and drains a watershed of 123.5 square miles. Head of tide is just below Payson Park, at Route 90 in Warren, and from there to the north shore of Caldwell Island in Muscongus Bay, the estuary is 17.6 miles long and drains a watershed area of 41 square miles.

- The landed value of all Knox County fisheries was $110 million in 2012 (Maine DMR).
- Statewide, the lobster fishery accounted for 65% of total fishery value.
- The St. George lobster fishery might therefore have been $5-8 million—a guesstimate.
- St. George clam fishery is $2-3 million annually, accounting on average for one-sixth of the Maine harvest (Maine DMR records).
- The state elver harvest was $38 million in 2012--perhaps $2-3 million for the St. George.
- Alewives, worms, and others, perhaps another $1 million as a guess.
- All-told, the St. George fisheries yielded perhaps $10-15 million to the harvesters, and there is a threefold multiplier effect as those dollars circulate through midcoast communities.

Table 1. One ecosystem service of the St. George Estuary is the value of its fisheries.

- There are 15-25 lobsterboats (30-50 crew) working the seaward reaches of the St. George Estuary on summer mornings. The pots are thick enough from Broad Cove seaward to imagine walking from the Cushing to the St. George shore on them.
- There are 133 licensed clam harvesters in the estuary, plus the depuration crews hired by the Spinney Creek depuration plant.
- Wormers, elver fishermen, fishing and duck-hunting guides, boat mechanics, and boatyard workers depend upon the estuary for some part of their employment.
- All-told, perhaps 200-250 jobs depend in whole or in part upon the St. George Estuary.

Table 2. Another quantifiable ecosystem service of the St. George Estuary is the jobs it provides.

American eels spawn in the Sargasso Sea, and the young elvers—called glass eels--migrate to estuaries like the St. George, ascending to fresh water in early spring to mature before descending to the sea to complete their life cycles up to 20 years later. There is a high-priced market for live elvers in Japan, where they are grown to market size in captivity. The landed value for elvers in 2012 was as high as $2,200 per pound, making the elver fishery, at $38 million, Maine's second most valuable fishery behind lobsters, which were valued at $320 million (Maine DMR records).

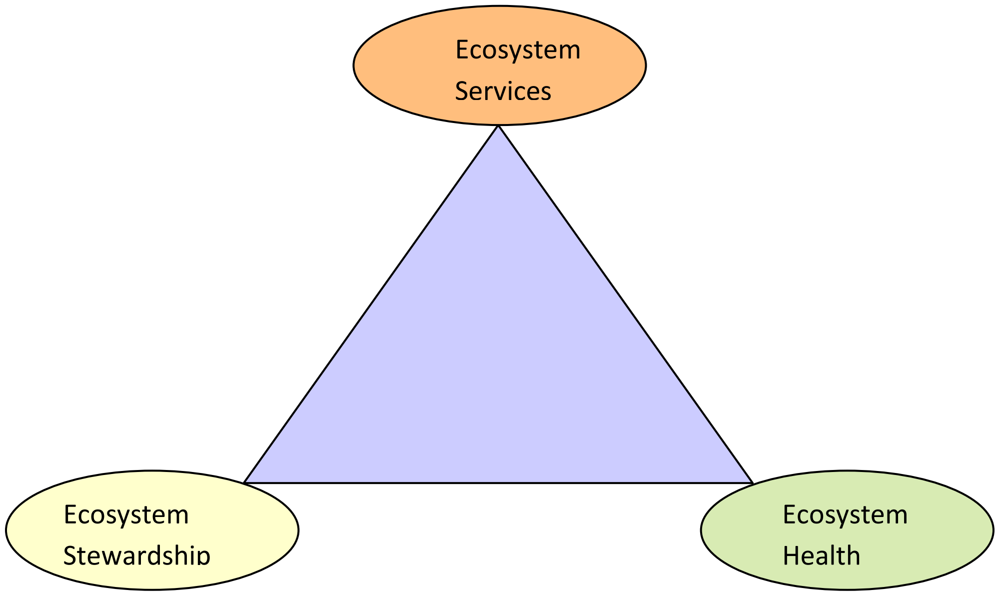


Figure 3. The ecosystem services provided by the St. George Estuary depend on the health of the ecosystem, which depends in turn on our stewardship. Conversely, a healthy ecosystem providing obvious benefits increases our will to provide the necessary stewardship. These interactive concepts can be pictured as the vertices of a triangle.

The St. George Estuary has a coastwide reputation as a "clam factory." This may be due in good part to the long, narrow axis of the Lower Estuary, which is 80% landlocked and sheltered at its mouth by the off-lying Georges Islands. The resultant low-energy hydrodynamic regime is ideal for the accumulation of mudflats as silt and organic matter settle from suspension. Because it is slowly flushed, the estuary may also retain many of the clam larvae that result from May/June spawning of soft-shelled clams. Eggs are fertilized in the water column and develop into tiny larvae, approximately 150 microns in diameter, that drift in the plankton for 2 to 3 weeks before settling to the bottom and metamorphosing into clam spat—miniature versions of adult clams. Many parts of the coast depend upon clam larvae carried westward in the Gulf of Maine's counterclockwise coastal current for recruitment to their clam fisheries, but it's quite possible that the St. George clam fishery is recruited in large part from local brood stock.

The characteristics that make Maine's estuaries such highly productive habitats also make them challenging environments for marine life. Seasonal variations of water temperature are greater than in nearby open coastal waters. Water temperatures in the St. George Estuary averaged 6° C on April 7, 2012 (note that water temperatures throughout the Gulf of Maine were unusually high in spring 2012, resulting in an unprecedentedly early shedder season for lobsters; Trotter 2012) and were greater than 21° C by midsummer. Salinity is even more variable through much of the estuary, typically holding between 29 and 32 parts per thousand in the lower reaches but ranging from less than 1 ppt to more than 21 ppt at station 2 (2.3 kilometers below the head of tide), while demonstrating a strong tidal signal. Fresh water has been observed as far down-estuary as the Thomaston waterfront after a heavy rainfall, and a surface lens of fresh water over parts of the Lower Estuary after heavy rain has also been observed.

Dissolved-oxygen deficits are not uncommon in the slowly flushed estuarine environment. In a 1996 survey of 16 Maine estuaries (including 14 Class SB, one Class SA, and one Class SC), Maine DEP observed dissolved oxygen levels below 85% of saturation in all but two of them. A minimum DO level of 77.8% was observed in the St. George Estuary in that survey (Sowles 1996)**.** Excursions of DO below 85% saturation were observed again in the St. George Estuary in the summer of 1999 while Maine DEP scientists were collecting data for a water-quality model of the estuary completed in early 2000 in advance of the construction of a new state prison in South Warren. Since then, the St. George Estuary has been included in the 305(b) list of Maine's impaired water bodies compiled by MDEP for the EPA as a requirement of the Clean Water Act.

On most days sampled in the summers of 2002 and 2003 during a GRTA monitoring program, DO levels below 85% saturation were observed throughout the Upper Estuary (with a low of 64%) and in Lower Estuary stations north of McCarthy Point. The only station seaward of McCarthy Point monitored in those two summers was off Otis Point, where surface waters met the 85% saturation requirement on the three dates sampled, but DO fell below 85% of saturation at depth (GRTA monitoring data, 2002-2003).

The estuary's water is markedly turbid, especially in the Upper Estuary, where a Secchi disk typically disappears at depths of 3 to 5 feet, versus 8 or 9 feet in the Lower Estuary (see Figure 13). Most of this turbidity is probably due to natural causes, especially silt and tannins, but a hydrodynamic regime that concentrates suspended matter to such an extent can also concentrate run-off pollutants and nutrients.

The Water-Monitoring Program

Rationale and Goals

Estuarine organisms have evolved to withstand the environmental challenges of an estuary. They can tolerate large ranges of temperature and salinity and are physiologically resilient. Even so, local die-offs of single or multiple species have been observed from time to time in Maine estuaries for generations and for various reasons. Menhaden herded into coves by hungry bluefish have consumed the available dissolved oxygen and died by the thousands, quite likely taking oxygen-starved benthic organisms with them. Adult clams have reportedly died en masse in mudflats—creating the "dead muds" described by clam diggers—perhaps due to high-temperature/low-salinity stress, perhaps in combination with a disease such as hemic neoplasia (Denis Marc Nault, Maine DMR, remarks at Casco Bay "Mud Summit," January 2013). Such events suggest that the estuarine environment, while highly productive, is also capable of imposing life-threatening extremes on its biota.

Our concern is that human activity, both local and global, might push conditions past the evolved limits of tolerance of estuarine organisms. The oceans have become 30% more acidic in the past century as the burning of fossil fuel has added carbon dioxide to the atmosphere. Some 40 to 50% of this CO_2 is ultimately absorbed by the oceans, where it produces carbonic acid, ultimately lowering ocean pH. This ocean sink for atmospheric CO_2 has slowed the rate of global warming, but at a price we are only now recognizing. Orr et al.'s (2005) findings that ocean acidification may be a serious consequence of carbon emission in 50 years or less was a wakeup call to climate scientists.

Some locales are already seeing negative impacts of ocean acidification. Between 2006 and 2008, oyster farms in estuaries and bays along the Pacific Northwest coast saw up to an 80% mortality rate of seed oysters due to upwelling of more acidic deep water (Grossman 2011). The upwelled water was more acidic in part because of higher rates of subsurface respiration, but also due to increased levels of sequestered anthropogenic atmospheric carbon (Feely et al 2008). The upwelled water moves into bays and estuaries, where hatcheries have been forced to adjust by changing pumping schedules and buffering tanks to prevent the corrosive water from adversely affecting oyster shell formation (Barton et al 2012; Grossman 2011).

Ocean acidification appears to be accelerated in other coastal environments as well. The pH decline in the Chesapeake Bay, for example, was 0.1 unit between 1995 and 2005, and the rate of the decline appeared to be accelerating toward the end of the 10 years (Jason Grear, EPA's Narragansett Lab, remarks at the Casco Bay "Mud Summit," January 2013). Since the pH scale is logarithmic, a 0.1 unit decrease is an order of magnitude larger than it might at first appear. The source of this near-shore acceleration of pH decline appears to be run-off nutrients, which fuel phytoplankton blooms in coastal waters and cause eutrophic conditions (Carpenter et al 1998). The decay of this overabundant organic matter consumes dissolved oxygen and releases carbon dioxide (Howarth et al 2002; Howarth and Marino 2006). In the northern Gulf of Mexico, perhaps only 40% of the observed pH decline is due to atmospheric CO_2; the other 60% is due to nutrients carried into the gulf from the Mississippi River (Jason Grear, EPA's Narragansett Lab, remarks at the Casco Bay "Mud Summit," January 2013).

Of particular concern for the Maine coast, a 2012 study found that the Gulf of Maine has less buffering capacity than the Gulf of Mexico or the southeast coast of the U.S. and is thus more vulnerable to acidification (Wang et al 2013). And the St. George and other Maine estuaries, being less saline than ocean waters, have less buffering capacity than the open Gulf of Maine. A slowly flushed estuary like the St. George, where nutrients have been shown to concentrate, is likely to be especially susceptible to acidification.

Young clams appear to be more vulnerable to environmental stress than larger clams. A 10% drop in salinity can wipe out an entire year class of clam petiveligers from affected flats. Clam spat covered by a bed of Enteromorpha (green algae) can die of hypoxia (Denis Marc Nault, Maine DMR, remarks at the Casco Bay "Mud Summit," January 2013). And studies have shown that shellfish (Barton et al 2012; Gazeau et al 2006) and shellfish spat (Green et al 2004, 2009; Talmage and Gobler 2009; Waldbusser et al 2010) are particularly vulnerable to pH declines because less aragonite (a particularly soluble form of calcium carbonate) is available for shell-building. Green (2009) demonstrated substantial erosion of clam spat shell after 72 hours in water of pH 7.5 (versus healthy shell at pH 8.0 and signs of reduced shell-building at pH 7.7). Excursions of pH below 7.3 have been demonstrated to decrease shellfish survival (Green et al 2009, 2004; Talmage and Gobler 2009; Waldbusser et al. 2010). Green has also demonstrated a 50% rejection by clam larvae of mud with pH 7.5 and a 100% rejection of mud with pH 7.2 (Green 2011).

The planet's thirteen warmest years have all occurred since 1998. Gulf of Maine water temperatures increased by 3.5° C between 2008 and 2012, and the sea surface temperature in the Gulf of Maine in March 2012 was 6° C above the long-term average for that time of year. The cumulative impacts of high temperature, low dissolved oxygen, and low pH are likely to be a significant stressor for estuarine life (Byrne 2011).

If the combined effects of temperature increases, pH declines, and dissolved oxygen deficits due to overproduction of organic matter are most extreme in a restricted-flow estuary, the St. George Estuary may be a coal mine, and the soft-shelled clam is a canary—i.e., an indicator organism that may give us early warning of a looming threat. Already, for example, there is evidence that the shells of adult clams in Casco Bay are running 30 to 40% thinner than their historical norm (Groening 2013).

These considerations prompted the GRTA to launch its St. George Estuary water-monitoring program in 2012. The goals are:

- Characterize the present levels and trends of dissolved oxygen in the estuary, including seasonal fluctuations. Evaluate how widespread the low excursions of dissolved oxygen might be along the head-to-mouth axis of the estuary, and whether this low dissolved oxygen spreads out of the channel—where prior measurements have been made—and up into the Lower Estuary coves where clams are concentrated.
- Characterize the estuary's degree of nutrient enrichment by monitoring concentrations of total nitrogen (TN) at boat stations. Nitrogen is the key nutrient in a marine habitat,

the “fertilizer” that, given adequate light, allows phytoplankton and marine algae to photosynthesize and produce organic matter. Nitrogen in seawater exists in multiple forms, both organic (incorporated in live and dead organic matter) and inorganic (as nitrite, nitrate, and ammonium ions). The organic and inorganic fractions of nitrogen cycle rapidly back and forth with photosynthesis, respiration, and decay, but their sum—the indicator called total nitrogen, or TN—is more stable, and it is therefore possible to characterize an estuary’s nutrient environment with a manageable number of total nitrogen measurements. The DEP is developing nitrogen standards for Maine coastal waters, and once those are adopted, nitrogen discharge limits will be developed for sewage treatment plants and other point sources discharging into or upstream of nitrogen-impaired waterbodies. It is hoped that this monitoring program will inform the DEP’s decision-making regarding nitrogen criteria and discharges.

- Characterize the pH environment of the estuary.
- Look for interactions or correlations among DO, TN, and pH.
- “Stress test” the estuary for these three key indicators—referring our Lower Estuary results to the soft-shelled clam as an indicator organism--while also gathering water temperature and salinity data.

Methods

The GRTA water-monitoring program deploys trained citizen volunteers and GRTA-contracted technicians to monitor water quality at 16 sites (Figures 4 and 5 and Table 3), including 8 sites that are accessible from shore and 8 that must be sampled from a boat. Program methods are detailed in our DEP-approved Quality Assurance Project Plan (QAPP).

Volunteers monitor water quality from shore sites for dissolved oxygen (DO), temperature, salinity, and pH using a Hanna Instruments Model HI 98128 Temperature and pH tester, a Vee-GEE Model STX-3 refractometer (for salinity), and a Lamotte Code 5856 Dissolved Oxygen Test Kit. Shore samples are collected once a month in April, May, June, and October and twice a month in July, August, and September, at high tide ± 30 minutes.

The boat sites are monitored by GRTA volunteers and contract technicians for temperature, DO, salinity, pH, water clarity, and total nitrogen surface samples (TN). Vertical profiles are obtained at each station using a YSI 6290 data sonde with sensors for temperature, DO, pH, and salinity. Water clarity is measured with a Secchi disk, and small vials of surface water are collected and frozen for mailing to a contracted laboratory for total nitrogen (TN) analysis. Boat profiles are collected once a month in April, May, June, and October and twice a month in July, August, and September, on the same dates as shore samples, at high tide ± 60 minutes.

Trainers and volunteers collect duplicate samples during phase 2 training sessions as well as during QC (quality-control) days during the season for new volunteers. (For more details, see the GRWQM Trainers' Manual). For replicate samples, volunteers are instructed to do a third Winkler titration to determine DO if the difference between the first two is greater than 0.6 mg/l (the upper warning limit).

Gathering a shore sample at high tide in a five-gallon bucket.

GRTA sends all TN samples for processing to the Chesapeake Biological Laboratory (CBL) of the University of Maryland. CBL uses glycerophosphate and glutamic acid to determine the percent recovery of the digestion process.

Hanna pocket pH and temperature testers are used by volunteers at shore sites to measure pH. The instruments are calibrated with a 7.01 pH buffer solution prior to each usage. The testers are calibrated according to the manufacturer's specifications using NIST-certified pH Buffer reference standards. To determine the accuracy of pH values measured using this method, comparison measurements are made with a YSI 6920 data sonde rapid pulse pH probe during QA sessions (the same instrument used to measure pH for for boat profiles).

To determine the accuracy and comparability of temperature values, comparison measurements are made during QA sessions with a NIST-certified thermometer. The tester is calibrated according to manufacturer's specifications using NIST-certified temperature reference standards.

Salinity is measured by volunteers at shore sites using a refractometer. To determine the accuracy and comparability of salinity values measured by this method, comparison measurements are made during QA sessions with a YSI 6920 sonde. The meters are calibrated according to manufacturer's specifications using NIST-certified conductivity standards.

Dissolved oxygen is measured by volunteers at shore sites using Micro Winkler Titration. To determine the accuracy and comparability of DO values measured by this method, comparison measurements are made during QA sessions with a YSI 6920 sonde.

Site Name	*Site Number	Site ID	Town	Latitude in decimal degrees	Longitude in decimal degrees
Payson Park foot bridge*	0	PP.0	Warren	44.12377778	-69.24672500
Warren Woolen Mill Park*	1	WMP.1	Warren	44.12003889	-69.24117778
House at Bend**	2	HB.2	Warren	44.10569444	-69.24375833
Second Bend**	5	SB.5	Warren	44.09175000	-69.22412500
Route 1 bridge*	8	RTB.8	Thomaston	44.07860833	-69.21875000
Warren Sanitary District**	9	WSD.9	Warren/Thomaston	44.06940833	-69.21232222
Behind old prison**	11	BP.11	Thomaston	44.07467500	-69.19316389
Thomaston Public Landing*	28	TPL.28	Thomaston	44.07164167	-69.18274444
Nun 16**	14	N16.14	Cushing/ S. Thomaston	44.06465028	-69.18313556
Upper Bay depuration**	21	UBD.21	South Thomaston	44.06648100	-69.16930000
Hyler cove Ln (WU 22)*	22	WU22.22	St. George	44.04950000	-69.20800000
Can 9**	23	C9.23	Cushing/ St. George	43.99824694	-69.23766556
Fales Store (WU 14.50)*	24	WU14.50.24	Cushing	44.01780000	-69.24200000
Turkey Cove (WU 48)*	25	WU48.25	St. George	43.95800000	-69.25400000
Can 7**	26	C7.26	Cushing/ St. George	43.97341556	-69.27115806
Maple Juice Ln. (WU 6.50)*	27	WU6.50.27	Cushing	43.97800000	-69.28300000

*** Shore   ** Boat**

Table 3: Site Locations for Georges River Water Quality Monitoring

The Maine DEP has approved the QAPP for the water-monitoring project and joined the GRTA for sampling on August 18, 2012. The DEP is using data from the program, as is the Gulf of Maine Council on the Marine Environment.

The GRTA did not do river staging or freshwater flow-gauge measurements during the 2012 sample season. In the following presentation of results, therefore, we have depended upon stream-flow measurements on the Sheepscot River in Whitefield, Maine, the location of the USGS gauging station that is nearest to the St. George River. Discharge and stage-height measurements on the Sheepscot River are shown in Figure 6. The areas, topography, geology, and climate of the Sheepscot and St. George watersheds are similar, and both have large lakes situated similarly within the watershed. In the GRTA's hydrographic study of 2001, the Sheepscot and St. George discharge volumes tracked reasonably well with one another.

Table 4 shows the weather conditions on the sample days and locally recorded rainfall totals for the three and four days including the day of sampling.

Collecting samples for total nitrogen analysis from the boat.

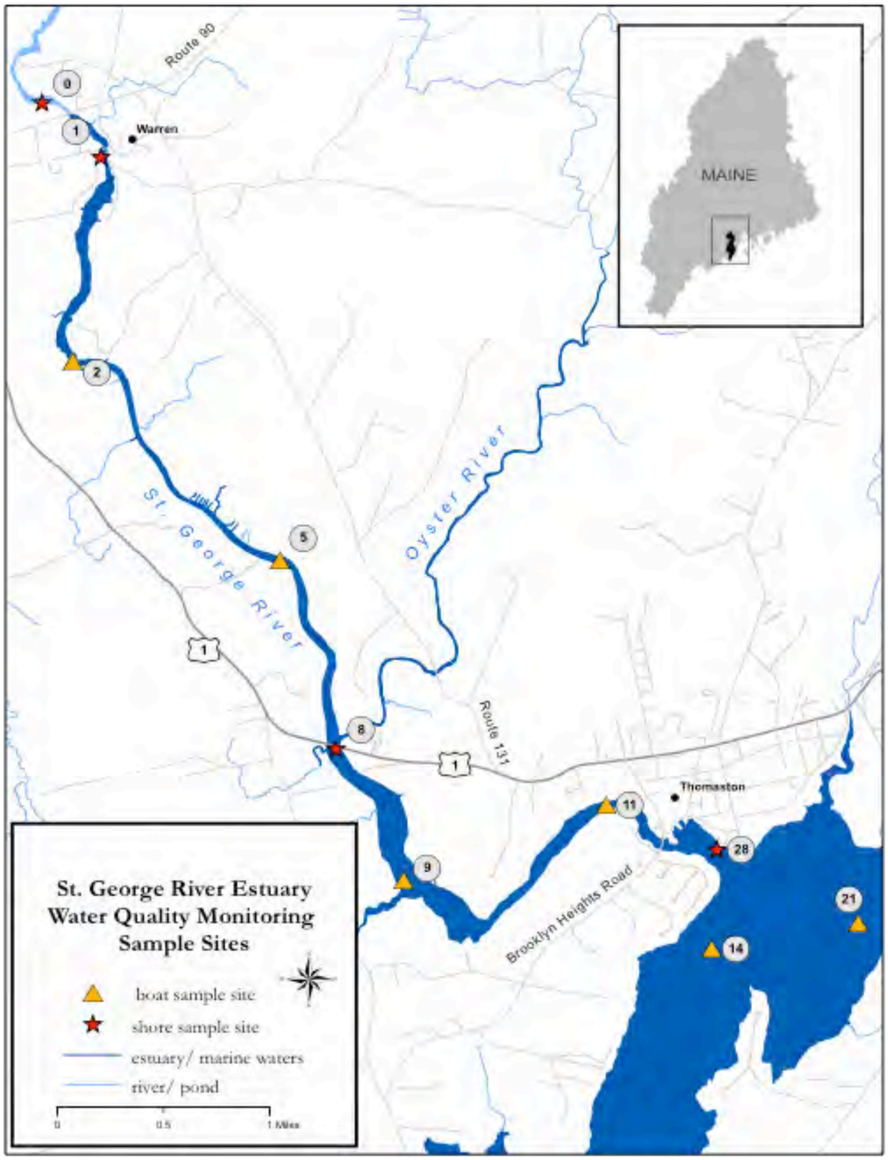


Figure 4. Locations of Upper Estuary sampling stations.

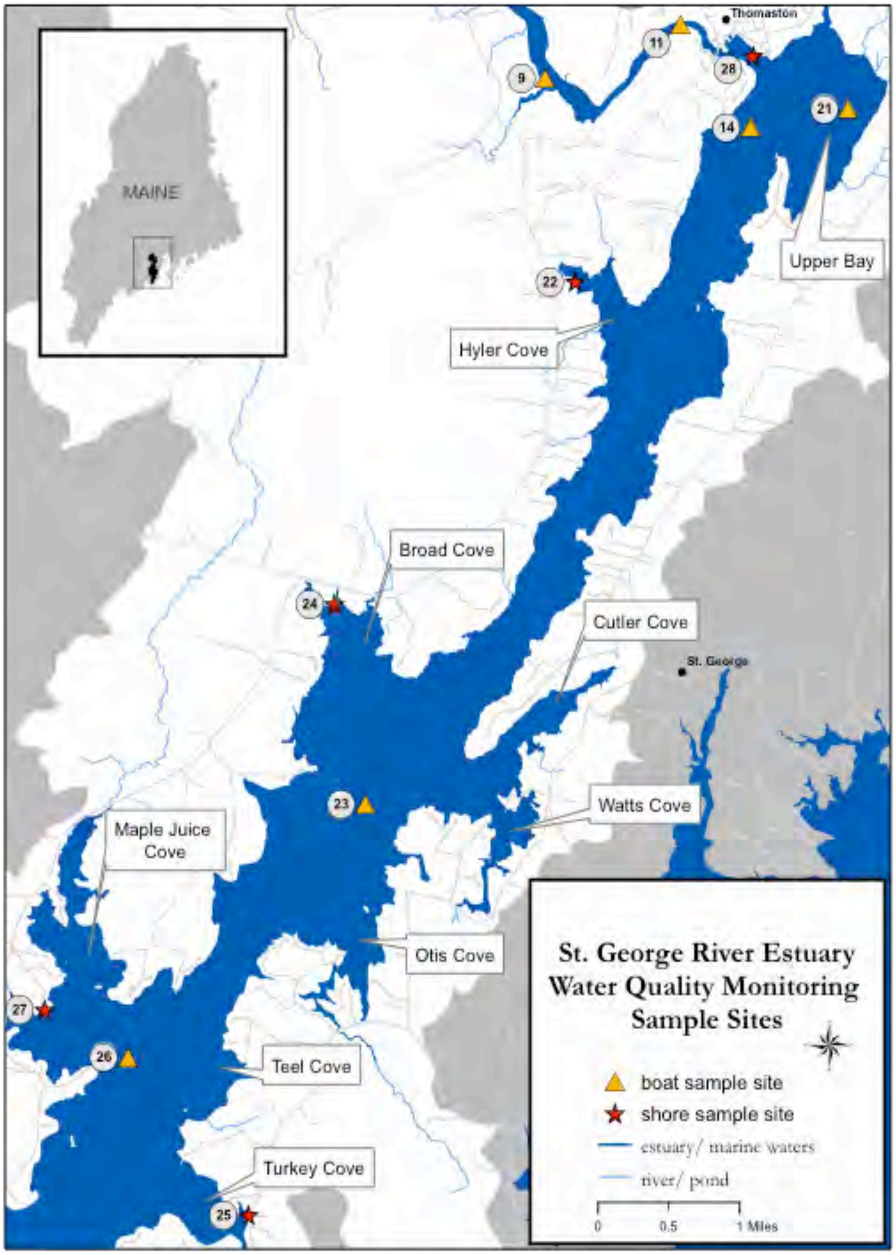


Figure 5. Locations of Lower Estuary sampling stations.

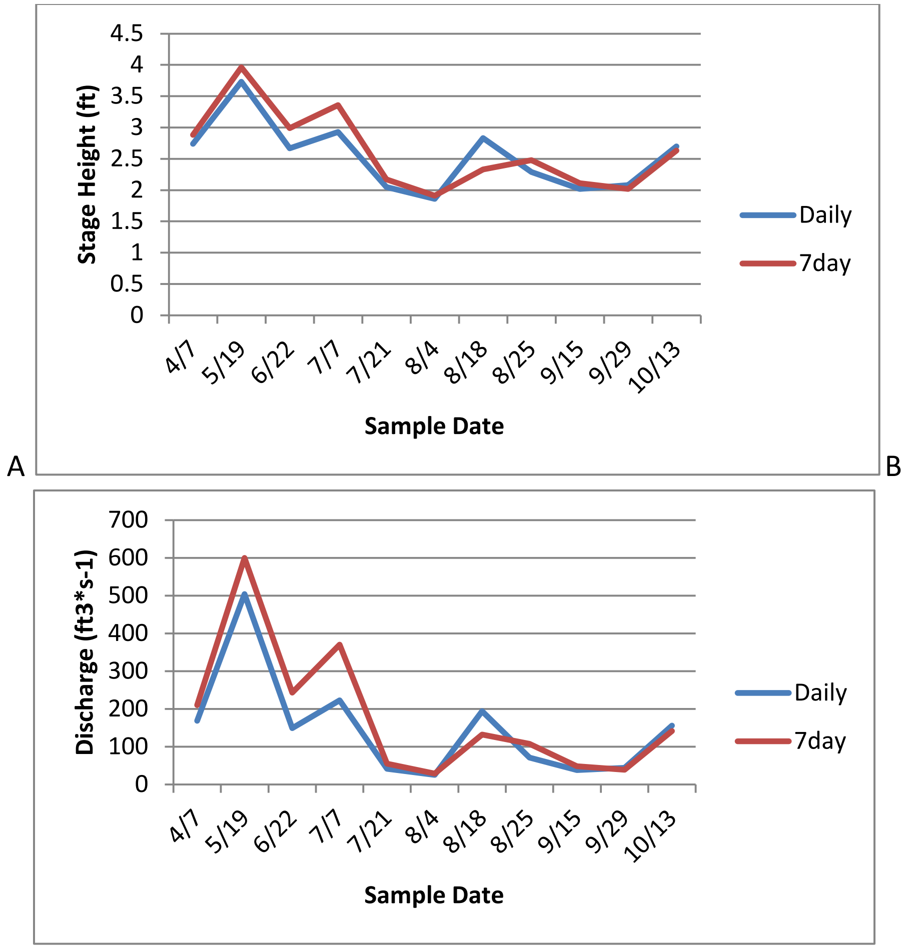


Figure 6. Discharge (A) and stage height (B) at the USGS gauging station on the Sheepscot River in Whitefield, ME, a nearby watershed of similar area and conformation. There is no USGS gauging station on the St. George. Daily data are averaged over a 24-hour period for that sampling date. Weekly data are averaged over the seven days preceding and including the sample date.

Date	Rainfall Prior 3 Days	Rainfall Prior 4 Days	Reported Conditions	Days w/ similar weather
	(inches)	(inches)		
4/7/2012	0	0	clear	5
5/19/2012	0.02	0.94	clear	3
6/23/2012	0.68	0.68	overcast	1
7/7/2012	0	0	clear	2
7/21/2012	ND	ND	partly cloudy	15
8/18/2012	1.88	1.88	overcast	2
8/25/2012	0	0	clear	7
9/15/2012	0.03	0.03	overcast	6
9/29/2012	0.89	0.90	rain	2
10/13/2012	0.14	0.48		

Table 4. Weather conditions on 2012 sample dates.

2012 Results

Temperature

The average water temperature across all boat stations in the Upper Estuary was 6.9° C (44.4° F) on April 7, 2012, increasing to 21.7° C on August 4 (Figure 7). The average surface-water temperature on April 7 was only slightly cooler in the Lower Estuary than the Upper Estuary, and there was only slight cooling with depth throughout the estuary on April 7 (Figure 8). By May 19, a warm-season pattern of warmer surface water in the Upper Estuary and more pronounced thermal stratification (cooling with depth) throughout the estuary was established and held throughout the summer. On September 29, however, the temperature declines with depth and with distance down-estuary had almost disappeared. By October 15 the summer pattern had been reversed: surface water was warmer in the Lower Estuary than in the Upper Estuary, and deeper water was warmer than surface water throughout the estuary (Figure 8).

Lower Estuary shore stations were noticeably warmer than the surface water at Lower Estuary boat stations in July and August, suggesting that the water was warmed as it overspread sun-warmed flats (Figure 9). All shore samples were gathered on middle-of-the-day high tides.

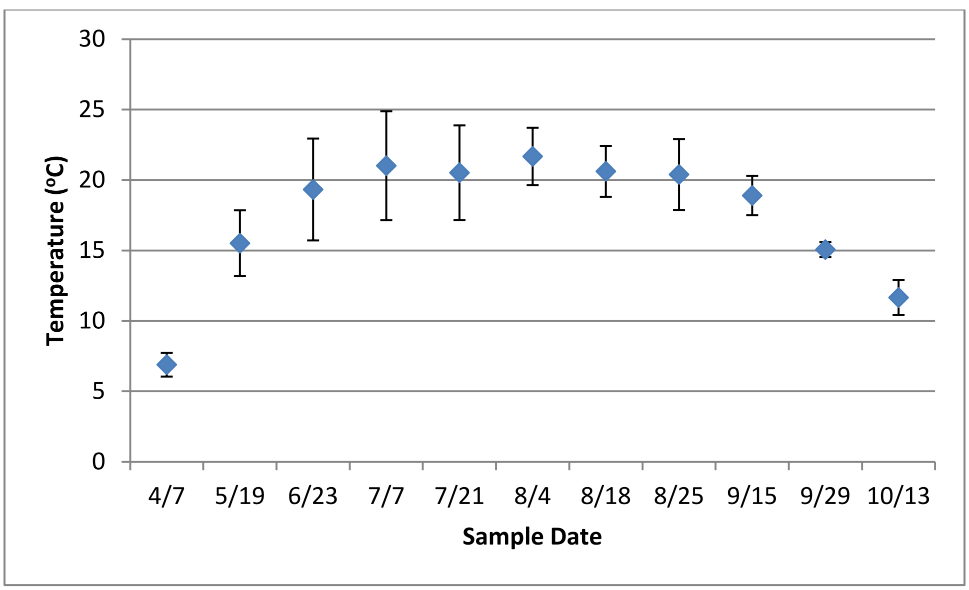


Figure 7. Water temperature by sample date, averaged across depths for Upper Estuary boat stations.

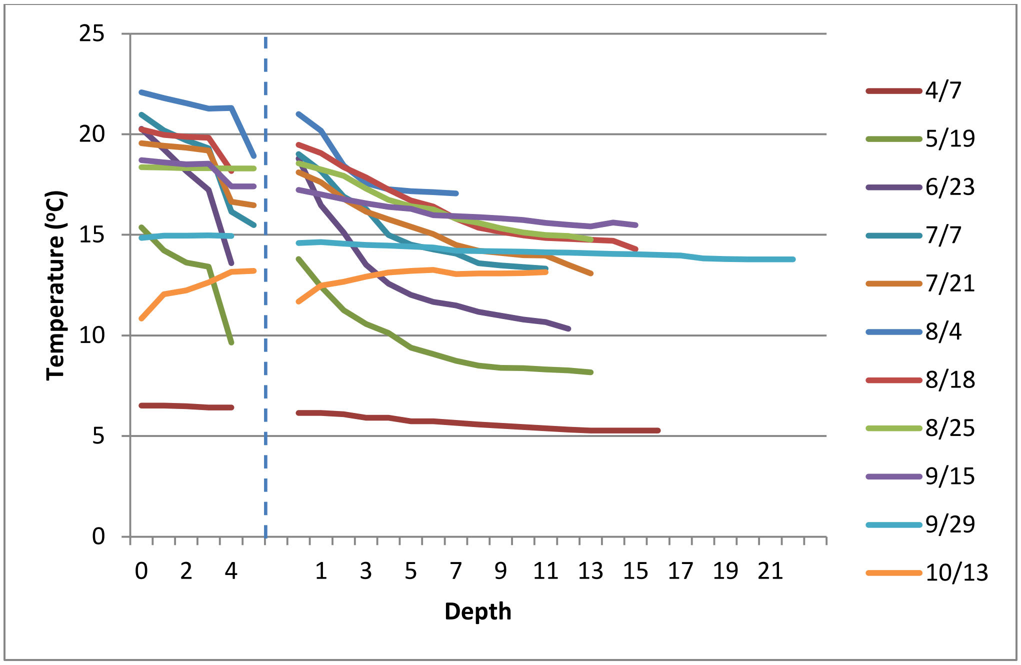


Figure 8. Temperature profiles separated by sample date and averaged across stations and depths in the Upper Estuary (stations 2, 5, 9, 11) or Lower Estuary (14, 21, 23, 26). Upper Estuary sites are to the left of the dashed line, and Lower Estuary sites are to the right.

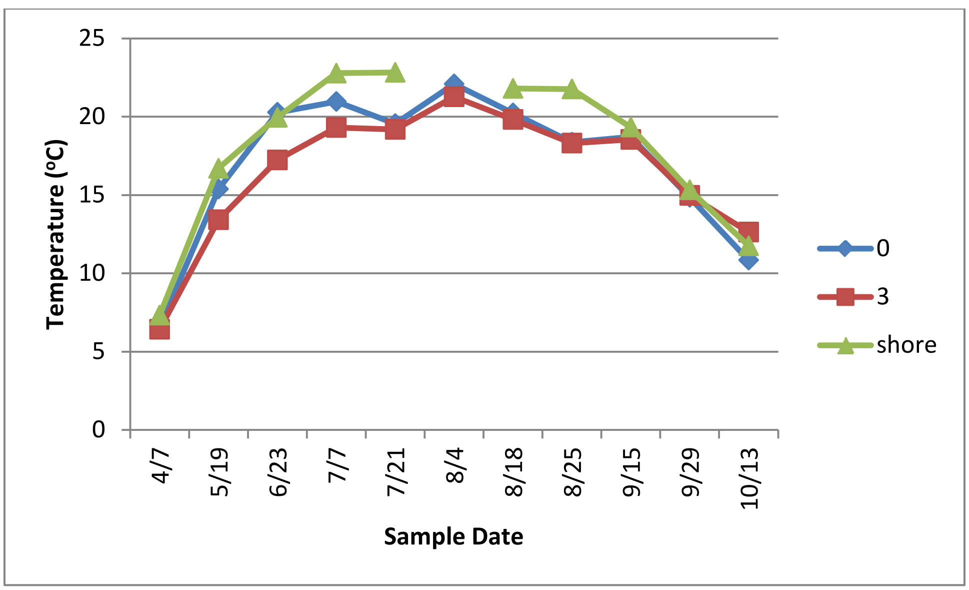


Figure 9. Water temperature averaged across stations and plotted by sample date and depth for the Lower Estuary. The 0 m and shore temperatures track closely in the spring and autumn, but shore temperatures are warmer in July and August, as expected of water that has flooded sun-warmed mudflats on an incoming tide.

Salinity

Salinity measurements at boat stations ranged from less than 1 ppt at station 2 (2.3 km below head of tide) to 32 ppt in the Lower Estuary. Upper Estuary surface-water salinities averaged 28 to 30 ppt in dry weather but dropped to 15 ppt in wetter weather when averaged across all Upper Estuary stations (Figure 10). Surface water was markedly fresher in the Upper Estuary at such times, indicative of a surface lens of freshwater streamflow and run-off. This phenomenon was also observable though much less pronounced in the Lower Estuary (Figure 10). The head-to-mouth salinity gradient in the estuary can be illustrated by the July 7 sample date (Figure 11).

The salinity of Lower Estuary surface water was very similar throughout the year with the salinity of Lower Estuary shore samples (Figure 12). This suggests that the water sampled at the heads of Lower Estuary coves at high tide is surface water from the channels that has overspread the flats on the incoming tide.

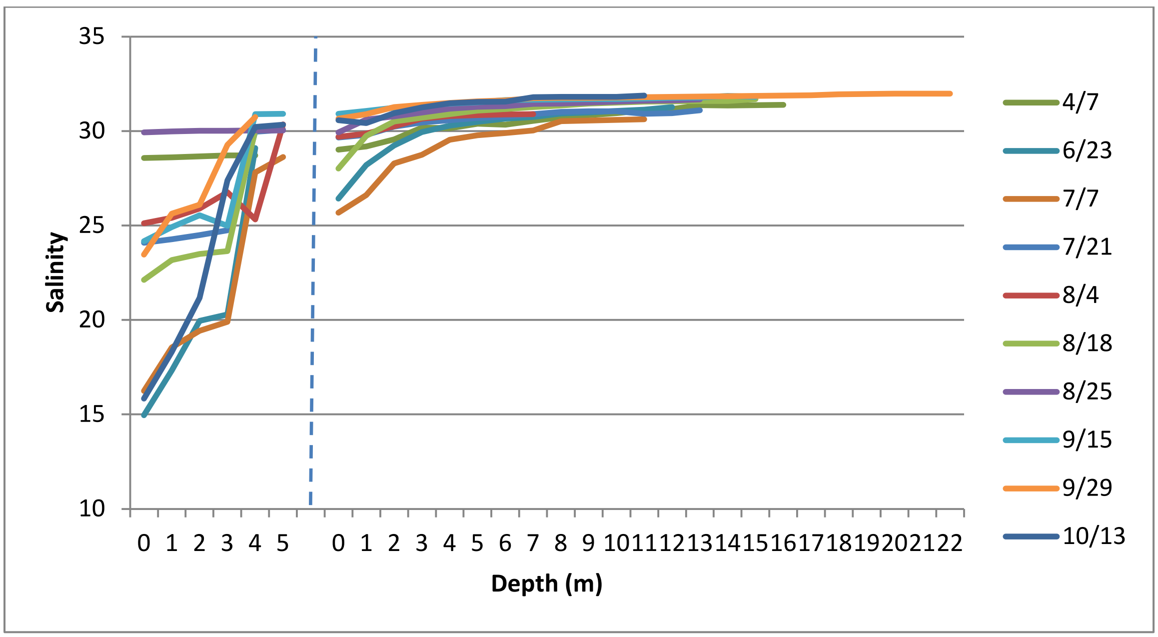


Figure 10. Salinity profiles separated by sample date and averaged across boat stations and depths in the Upper (stations 2, 5, 9, 11) or Lower Estuary (14, 21, 23, 26). Upper Estuary sites are to the left of the dashed line, and Lower Estuary sites are to the right. The salinity sensor malfunctioned on the May 19 sample run.

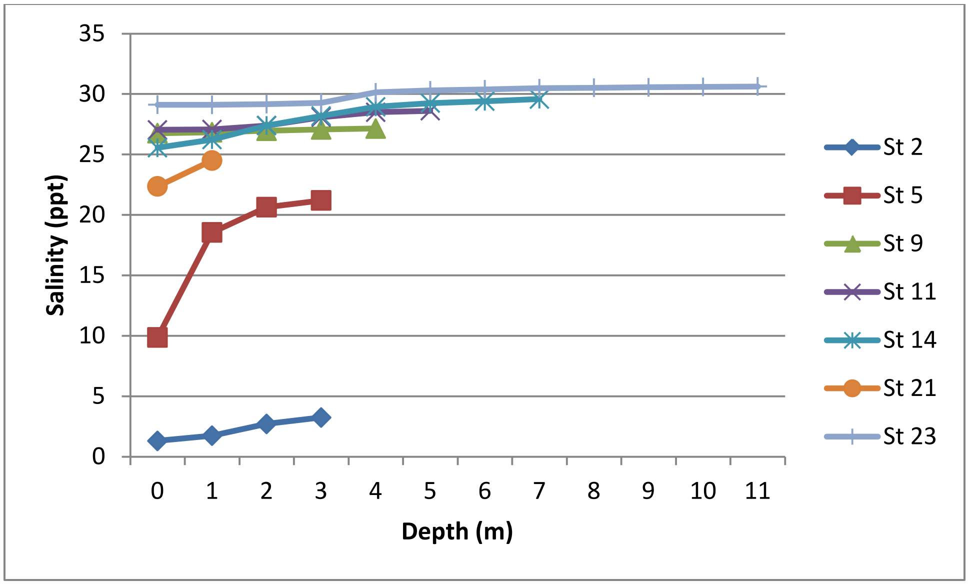


Figure 11. Salinity profiles broken out by site for July 7, 2012.

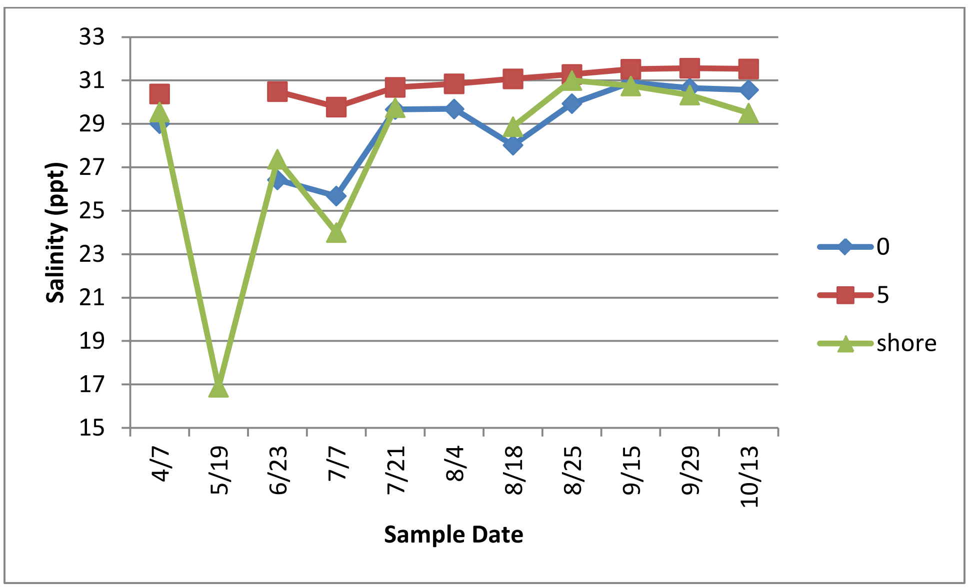


Figure 12. Average salinity of depth strata plotted against sampling date for the Lower Estuary stations. The 0m and shore salinities track closely with one another, suggesting a common origin.

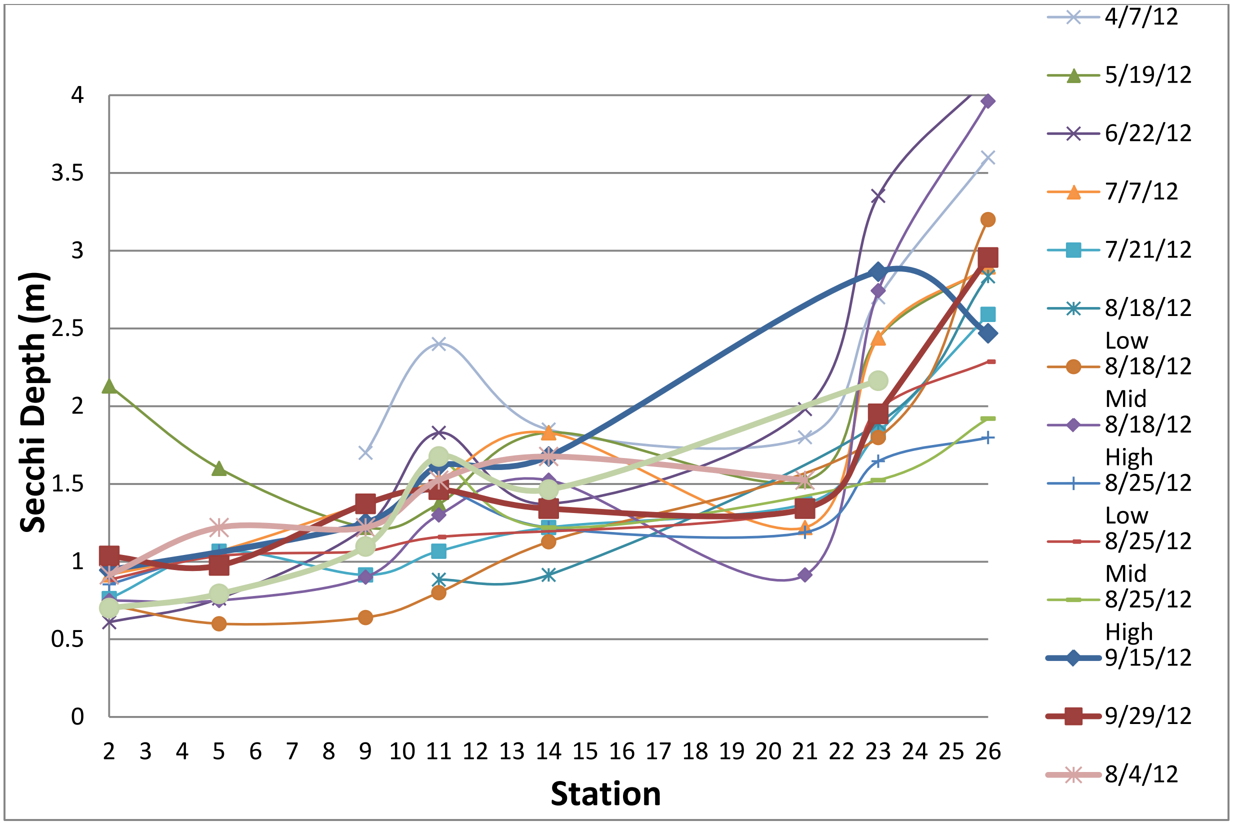


Figure 13. Longitudinal (head-to-mouth) profiles of water clarity from Secchi disk readings at boat stations, separated by sample date and plotted by station on the x axis.

Water Clarity

Secchi disk depths were typically 0.5 to 1.5 meters in the Upper Estuary, increasing to 2 to 4 meters in the Lower Estuary while becoming more variable (Figure 13). Station 21 interrupted the general trend toward greater clarity with distance down-estuary, probably because Station 21 is away from the channel and over the Upper Bay mudflats.

Dissolved Oxygen

Dissolved oxygen (DO) levels met or exceeded the DEP requirement for a Class SB estuarine habitat (85% saturation) on most 2012 sampling dates when averaged across all Upper Estuary or Lower Estuary boat stations (Figure 14). Nevertheless, signs of potential oxygen stress were still evident. On August 18, boat samplers recorded a low of 76.2% of saturation at a 2-meter depth at Station 5 in the Upper Estuary (Figure 15). In the Lower Estuary a low of 79.2% of saturation was recorded at Station 23 (Figure 15). Low DO conditions were also detected by the shore sampling effort, particularly at Station 0 on July 7 and at Station 8 on August 18 (Figure

16). Both stations 0 and 8 were below Class SB attainment levels on August 18, with DO saturations of 64.7% and 44.9%, respectively.

There was a significant inverse relationship between DO in the Upper Estuary profile stations and the daily Sheepscot River discharge volume ($p<0.02$, $F=9.1$, $df=8$, $r2=0.53$). That is, high discharge was correlated with low DO in the Upper Estuary. The Sheepscot River discharge volume also showed a non-significant inverse relationship with Upper Estuary shore sample DO ($p=0.06$) but no apparent relationship with Lower Estuary shore or boat DO (Figure 17).

Analysis of Variance on shore vs. profile data required constraining the depth strata compared between the two types of sampling. Profile data was limited to 0m and 3m depths in the Upper Estuary and 0m and 5m depths in the Lower Estuary. Choosing two depth strata allowed comparisons of shore water mass to the main channel water at the surface or at depth. ANOVAs were set up as 3 (depth) x 10 (date) full factorial to assess differences through time and at depth, with a nested shore vs. profile within depth. The test averaged across Lower Estuary and Upper Estuary stations.

There were no significant interaction terms between depth and date for either the Upper Estuary or Lower Estuary analysis. That is, there were no consistent pattern changes in the DO depth profile as the sampling progressed through the season. DO did vary significantly by date in the Upper Estuary (Table 5); in particular, a Tukey's Post-hoc test demonstrated that DO was significantly lower on July 7 compared to September 29 and was significantly lower on August 18 than on August 4. Other date comparisons did not show significant differences (Figure 18). In the Lower Estuary there was a significant difference in DO at depth, particularly when comparing surface and shore values (Table 5). Shore station DO, averaged across all estuary sites, was significantly lower than that for surface measurements (0 m) at profiling stations (Figure 19), even though shore samples and 0-meter boat samples showed very similar salinities, suggesting common origin (Figure 12).

On August 18 and 25, the high-tide profile samplings at Upper and Lower Estuary sites were augmented by mid-tide profiles in the Upper and Lower Estuary and low-tide profiles in Lower Estuary sites. Station 21 was not included in the analysis of these data because it was sampled at high tide only. The early-morning low tide on August 18 and early-morning high tide on August 25 provided an opportunity to investigate the effects of stage of tide and time of day on the indicators under observation.

ANOVA (analysis of variance) of the August 18 data, consisting of tide (H, M, L) and x station (14, 23, 26), highlighted significant differences in station percent DO and an interaction between tide and station, but no significant tidal effect alone (Table 6). That is, DO increased significantly in the down-estuary direction at low tide but did not vary significantly among stations at mid or high tide (Figure 20). Low tide DO at station 14 was significantly lower than all tides at all other stations, except high tide at station 14. The lowest recorded percent saturation for station 14 was 75.2%. ANOVA analysis of the August 25 data showed tide, station, and tide x station interactions were all significant (Table 6). Again, DO increased significantly in the down-estuary direction at low tide. The strongest contrasts were between low tide at site 26, with a high percent saturation, and mid tide at site 23, with a comparatively low DO value. However, none of the DO values for August 25 were below 80% saturation. ANOVA analysis for Upper Estuary sites sampled on August 18 did not show a significant difference in percent DO based on tide, but there was a significant difference between average DO by station (Table 6). Stations 5 and 9 had significantly lower DO than upstream (station 2) or downstream (station 11) sites. See Figure 20 for site x tide contrasts. There were not enough data for ANOVA analysis of Upper Estuary stations on August 25.

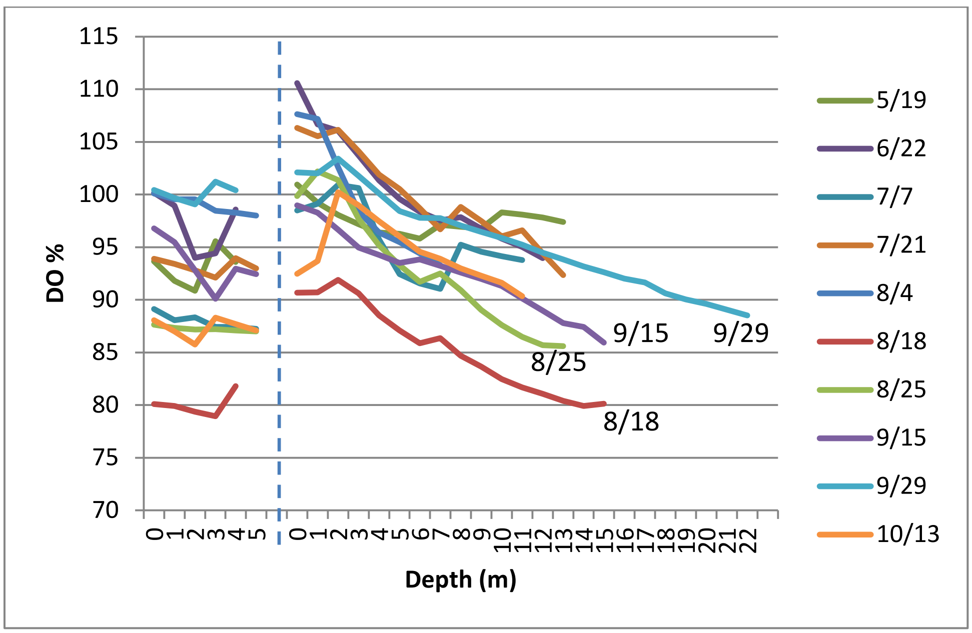


Figure 14. Dissolved oxygen profiles presented by sample date and averaged across boat stations in either the Upper (stations 2, 5, 9, 11) or Lower Estuary (14, 21, 23, 26). Upper Estuary sites are to the left of the dashed line, and Lower Estuary sites are to the right. All data are for high tide samples. Profiles that included DO readings <85% saturation are indicated with their dates.

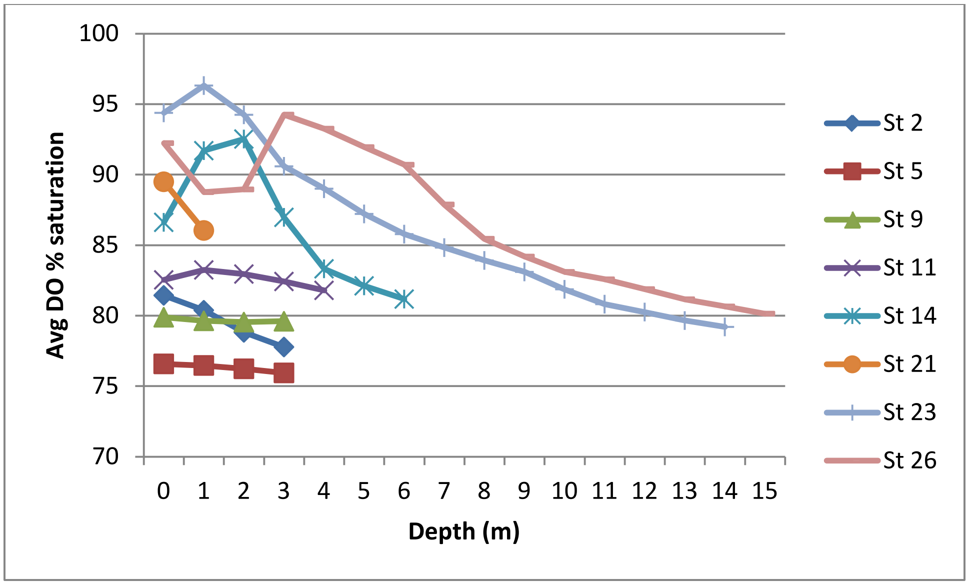


Figure 15. Dissolved oxygen profiles collected during the August 18, 2012, boat sampling. This figure breaks out individual stations to identify which ones are contributing most to lower DO conditions. All Upper Estuary stations fail to attain the 85% threshold, while Lower Estuary stations are below attainment at depth.

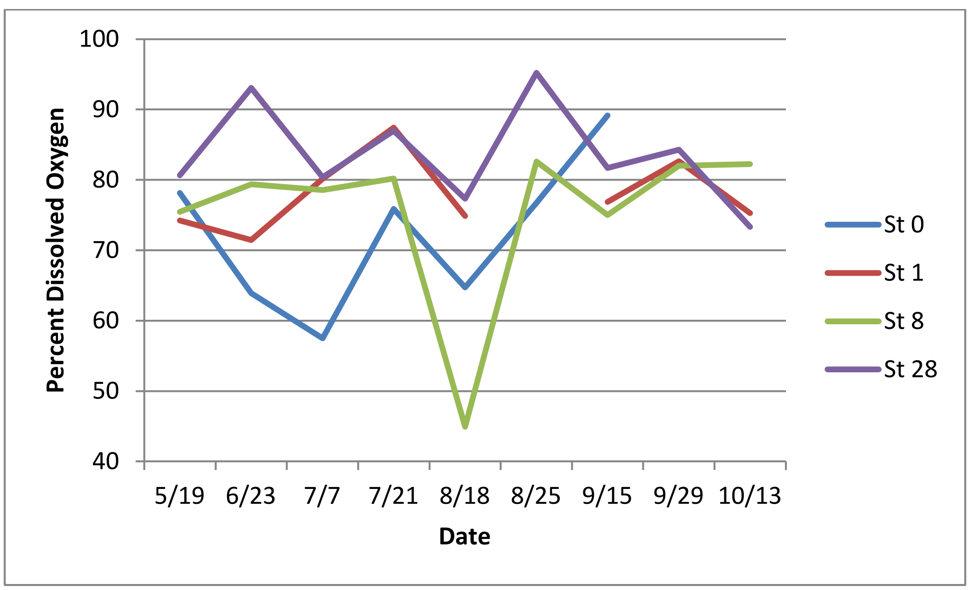


Figure 16. Average dissolved oxygen values throughout the season for Upper Estuary shore sampling stations plus Station 28, which is sampled from the Thomaston town dock at the edge of the navigation channel. DO at station 8 is below the 85% threshold for almost all sampling events. The remaining stations also show low DO excursions for most sampling dates.

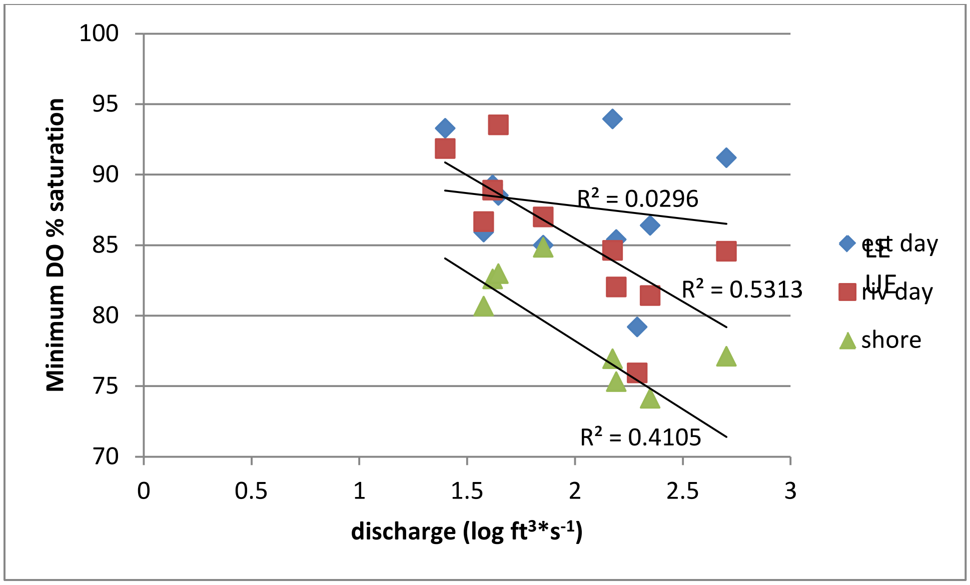


Figure 17. Scatter plot of lowest recorded readings of DO on a sample date--across all stations and depths--plotted against the average daily discharge (log10) of the Sheepscot River for that sample date. There was a strong negative correlation between daily discharge and lowest DO recorded in the Upper Estuary sites ("riv" = Upper Estuary). There was a non-significant trend between Upper Estuary shore sampling sites and daily discharge, but no apparent trend between Lower Estuary shore or boat DO and daily discharge rate ("est" = Lower Estuary).

Table 5. ANOVA results for percent dissolved oxygen using water depth and sample date. In the Lower Estuary shore sample DO was different from surface DO, possibly indicating high oxygen demand on flooding mudflats. In the Upper Estuary DO was different between specific dates, but not other date combinations. Input variables are DO at selected depths (Upper Estuary = 0 m, 3 m, and shore; Lower Estuary = 0 m, 5 m, and shore) averaged across all sites (Upper Estuary = stations 2, 5, 9, 11, 0, 8, and 28; Lower Estuary = stations 14, 21, 23, 26, 22, 24, 25, and 27) for a given sample date. Contrasts listed are significant ($p<0.05$) pairwise comparisons using Tukey's Post-hoc test. F values indicate that the significant contrasts are relatively weak in magnitude.

	Effect	**F value**	**p**	**Significant contrasts**
Upper Estuary	Depth	0.8	0.5	
	Date	*4.4*	*0.001*	*7/7 vs 9/29, 8/4 vs 8/18*
	Depth x Date	0.6	0.9	
Lower Estuary	*Depth*	*4.5*	*0.006*	*0 vs shore*
	Date	1.8	0.09	
	Depth x Date	0.8	0.7	

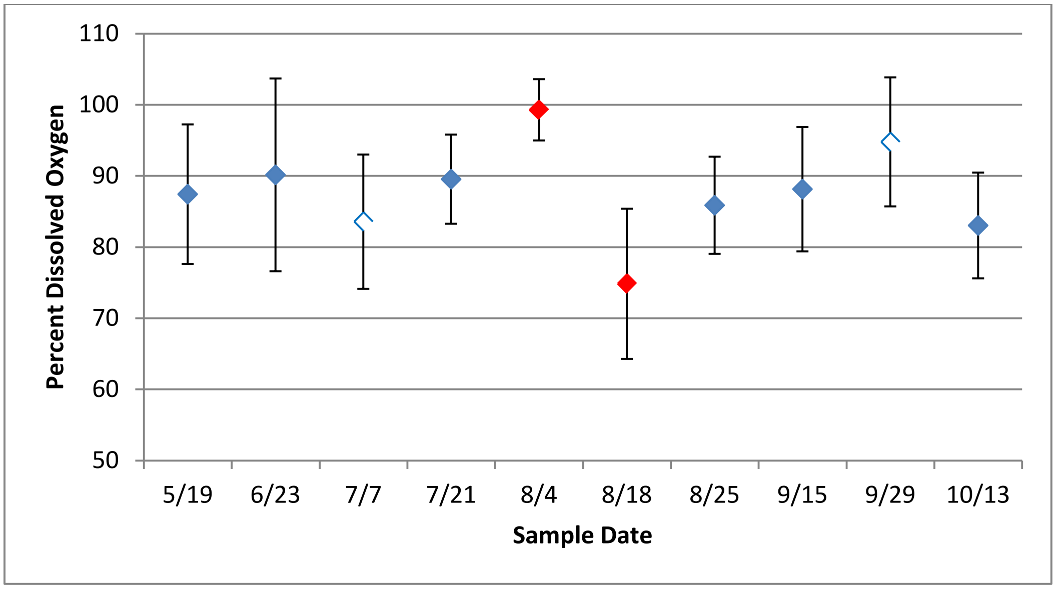
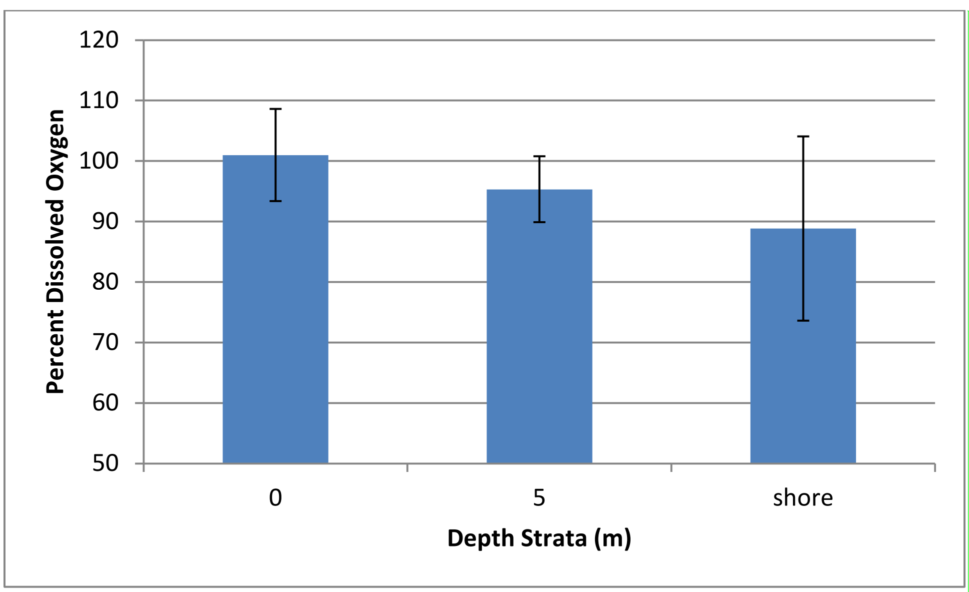


Figure 18. Variation in percent dissolved oxygen through time for Upper Estuary samples. The drop in DO on 8/18 corresponds to an increase in discharge that may have resulted in flushing nutrients and/or stagnant, hypoxic wetland run-off with high organic content into the estuary, increasing oxygen demand. Similarly, 7/7 is a wet period during which lower DO was observed than on 9/29, which was the second week of a dry period. Blue diamonds are not significantly different. Red diamonds are significantly different from each other and open blue diamonds are different from each other, but red and open blue diamonds are not different from any of the three groups.



[c2]

Figure 19. Bar graph of average percent dissolved oxygen in Lower Estuary shore samples versus Lower Estuary boat samples at surface (0 meters) and at 5 meters. Shore samples had significantly lower DO than 0 m samples collected from a boat.

Table 6. ANOVA results for percent dissolved oxygen using tide cycle and station. Tide was not a significant factor in DO patterns on 8/18 but was on 8/25, with mid tides having lower DO than other tides. There were differences between stations that were not consistent across tides, so the relationship between tide and station is complex. Input variables are DO averaged across all depth strata for either August 18 or August 25, 2012. Contrasts listed are significant (p<0.05) pairwise comparisons using Tukey's Post-hoc test. F values indicate that the significant contrasts are relatively weak in magnitude.

	Date	Effect	F value	p	Significant contrasts
Upper Estuary	Aug 18	Tide	0.01	0.9	
		Station	*7.3*	*0.001*	2 vs 5, 2 vs 9, 5 vs 11, 9 vs 11
		Tide x Station	6.7	0.002	
Lower Estuary	Aug 18	Tide	2.1	0.13	
		Station	*3.5*	*0.03*	*14 vs 26*
		Tide x Station	3.5	0.01	
	Aug 25	*Tide*	*6.9*	*0.002*	*high vs mid, low vs mid*
		Station	*13.7*	*< 0.001*	*14 vs 26, 23 vs 26*
		Tide x Station	3.0	0.02	

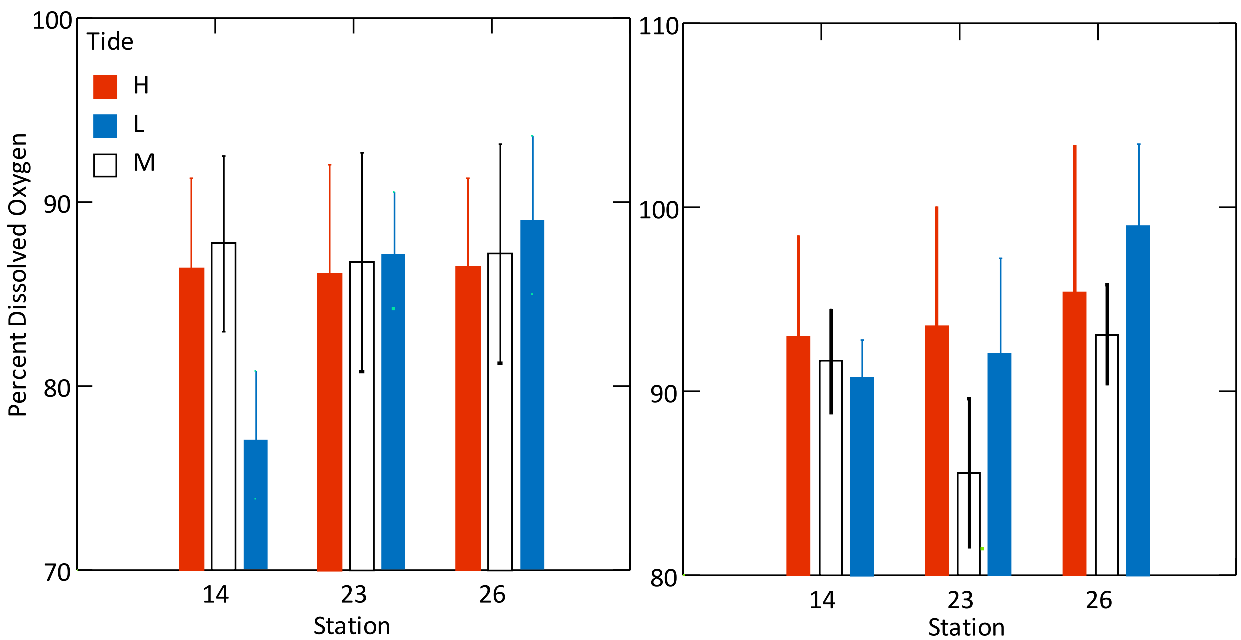


Figure 20. Percent DO from multiple-tide samplings in the Lower Estuary on 8/18 (a) and 8/25 (b). DO increases consistently down-estuary at low tide but not on other tides, indicating a complex interaction between station and tide. Error bars are one standard deviation. Station 21 was omitted from the analysis because it was sampled at high and mid tide only. H = high tide, L = low tide, M = mid tide.

pH

The negative log of hydronium ion concentration, pH, was measured during each profile and shore sampling episode. Profile data showed considerable variation in pH by sample date when averaged across all Upper Estuary or Lower Estuary sites (Figure 21). The pH readings from August 25 were noteworthy because of the acidic conditions recorded in the water column at depth. Surface pH levels in the Lower Estuary were similar on that date to readings recorded on prior and following dates, but pH declined over 1 pH point between 2 and 4 m depth. The May 19 and June 23 profiles were noteworthy because pH in the Upper Estuary was higher (more basic) at depth. This condition persisted through July 7 and reflected the pronounced increase of salinity with depth on these dates (Figure 10). Thereafter the pH and salinity profiles showed less gradient with depth until October 13, when a dramatic increase of salinity with depth in the Upper Estuary (Figure 10) was once again mirrored by an increase of pH with depth (Figure 21). As expected, Upper Estuary shore samples had lower pH than Lower Estuary shore samples, with the exception of July 7, when a 6.16 reading at station 25 pulled down the Lower Estuary average (Figure 22).

Examining Lower Estuary pH changes in finer detail, the largest changes recorded on August 25 were at stations 11, 14, and 23 (Figure 23). The pH decline at the seaward station (station 26) began at greater depth than at stations 11, 14, and 23 and was not as precipitous. By September 15, the subsurface pH at stations 11, 14, and 23 had partially recovered, but the pH at seaward station 26 was lower at all depths than it had been on August 25 (Figure 24).

Several associations were explored as possible explanations for the Lower Estuary pH trough between August 25 and September 29. August 18 had the third highest discharge of the 2012 sampling season, so the 8/25 pH trough could be connected to flushing of nutrients and/or hypoxic wetland run-off with high organic content into the estuary (see Figure 18). Upper Estuary pH was also depressed on 8/25 (Figure 21). High tide heights were particularly high for the period from 8/18 to 9/3, with only four high tides below 9.5 feet, so the low pH on 8/25 could also have been imported from offshore. Wind may been have an additive component; the primary wind direction during August 2012 was south or south-southwest, which could have pushed shelf ocean water into the estuary.

Statistically, the pH aberration in late August defied explanation with the available variables because the fit of pH to other variables was poorest when the pH decline was most pronounced. There was a significant tidal effect on pH ($p < 0.01$, $F = 6.4$, $df = 132$), but this was likely a date or change through time signal as the pH effect lessened. There were significant relationships between pH and percent DO, pH and temperature, and pH and salinity (Table 7). The relationship between DO and pH was tightest for September 29, followed by September 15 then August 25 (Figure 25a). The pattern displayed on August 25 was likely a reflection of the strong decline in pH at Station 23. As pH drifted to more basic conditions the fit increased, demonstrating a return to stable pre-August 25 levels. The DO/pH plots for all three dates had similar Y intercepts, indicating a consistent relationship between the two variables even though the tightness of fit varied by date. Temperature also followed a pattern of improved fit with pH over time, but the Y intercepts of the three regression lines were significantly different and intersected, meaning that temperature did not provide a simple, clean signal for pH, and date was a significant variable (Fig. 25b). There was a significant negative relationship between salinity and pH, but no difference between dates or slope of the Y intercepts and thus no clear causative connection (Fig. 25c).

Multi-tide sampling data from August 25 were also examined for insights into more acidic pH levels recorded in the estuary on that date. Tide was a statistically significant factor when regressed against pH with depth as replicates ($p < 0.001$, $F = 15.6$)—i.e., when pH was averaged by depth strata across the Lower Estuary. But when stations rather than depths were used as replicates—i.e., when pH values were averaged across depths—there were no significant patterns ($p = 0.5$). Low-tide pH values for depth strata were significantly higher (less acidic) than high- and mid-tide values. Temperature was a significant correlate of pH when sites were used as replicates ($p = 0.03$, $F = 6.4$; Fig. 26a), and sites were most acidic at high and mid tides. Salinity was statistically significant as a factor when depth was used as the replicate ($p = 0.04$, $F = 475.9$; Fig. 26b), and the most acidic conditions occurred at mid tide. Readings of pH were lowest (most acidic) at higher salinities and cooler temperatures, possibly suggesting an oceanic origin for the pH conditions. Salinity may be a proxy for a more dynamic high-tide variable that was affecting pH in the Lower Estuary.

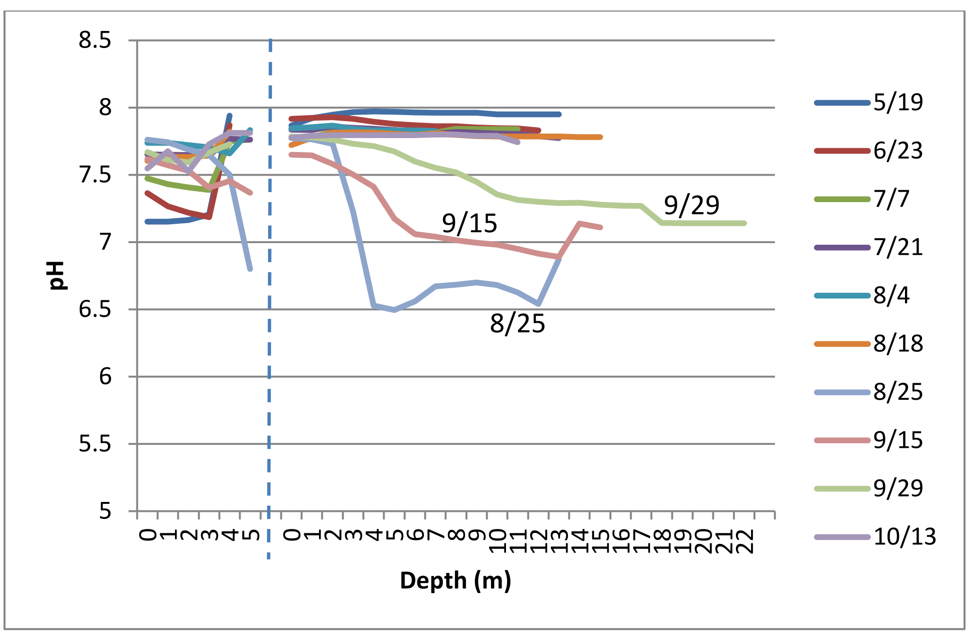


Figure 21. Profiles of pH separated by sample date and averaged across stations and depths in either the Upper (stations 2, 5, 9, 11) or Lower Estuary (14, 21, 23, 26). Upper Estuary sites are to the left of the dashed line and Lower Estuary sites are to the right. Dates of particular concern are marked with the sample date.

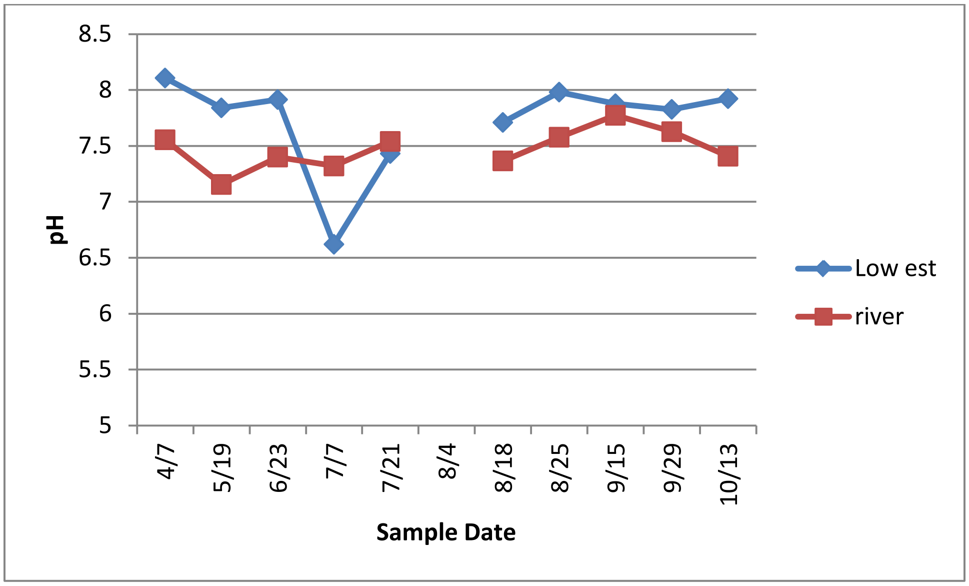


Figure 22. Shore sampling pH values throughout the sampling season. Upper Estuary sites are denoted as "river."

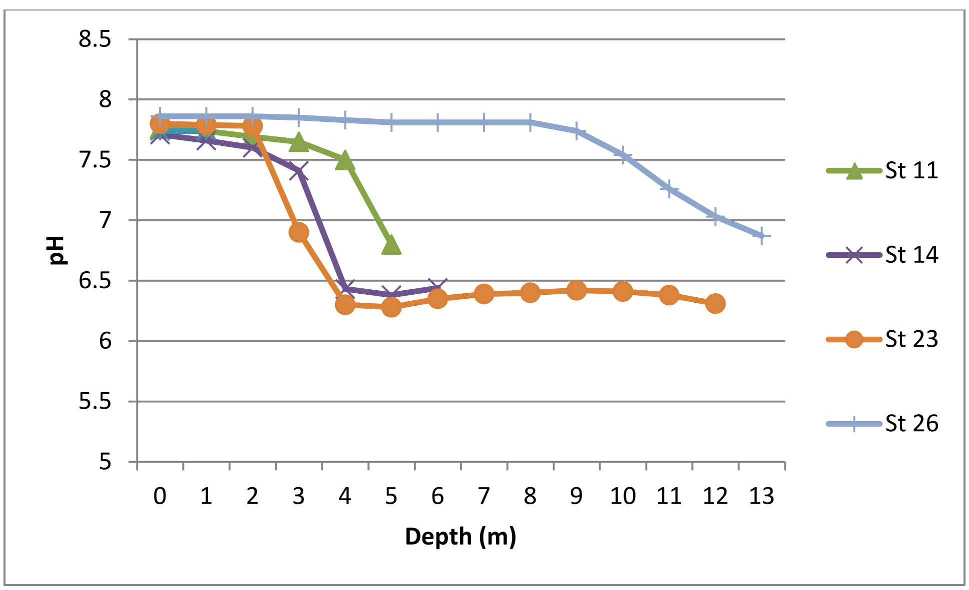


Figure 23. Profiles of pH separated by site for August 25, 2012, showing abnormally low pH at depth.

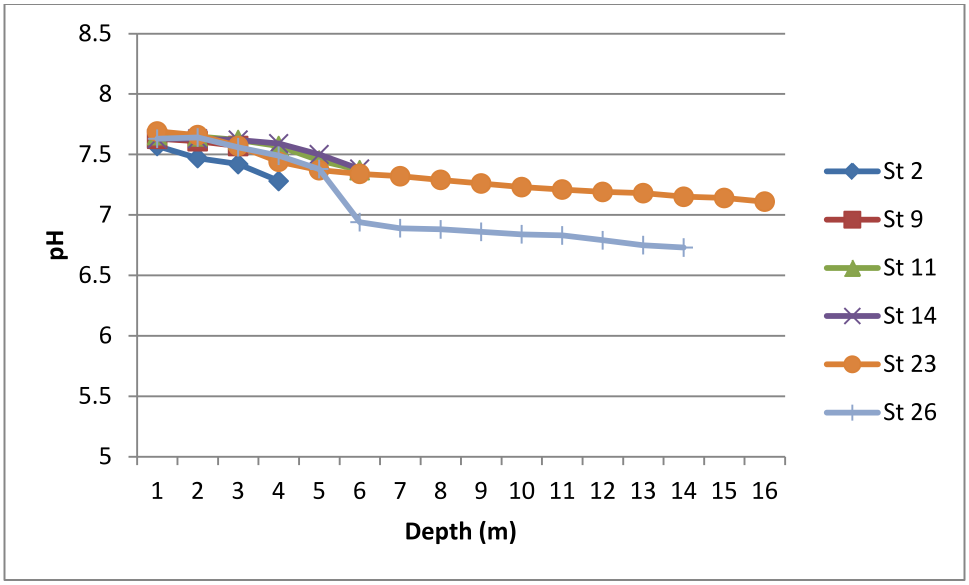


Figure 24. Profiles of pH separated by site for September 15, 2012.

Table 7. ANOVA results for pH using date and DO (as percent saturation), temperature, or salinity as explanatory variables. DO and salinity were significantly related to pH. Temperature was also significantly related, though in a more complex way not independent of sampling date. Input variables were pH values by 1 m depth strata for stations 11, 14, 23, and 26 on August 25, September 15, and September 29.

	Effect	**F (t) value**	**p**
DO%	Full model	26.4	< 0.001
	DO	*(3.6)*	*<0.001*
	Date	(0.08)	0.9
	DO x Date	(-0.01)	1.0
Temp	Full model	20.5	< 0.001
	Temp	*(4.92)*	*< 0.001*
	Date	*(2.83)*	*0.005*
	Temp x Date	*(-2.03)*	*0.04*
Salinity	Full model	18.5	< 0.001
	Salinity	*(-3.0)*	*0.003*
	Date	(-0.05)	1.0
	Salinity x Date	(0.2)	0.9

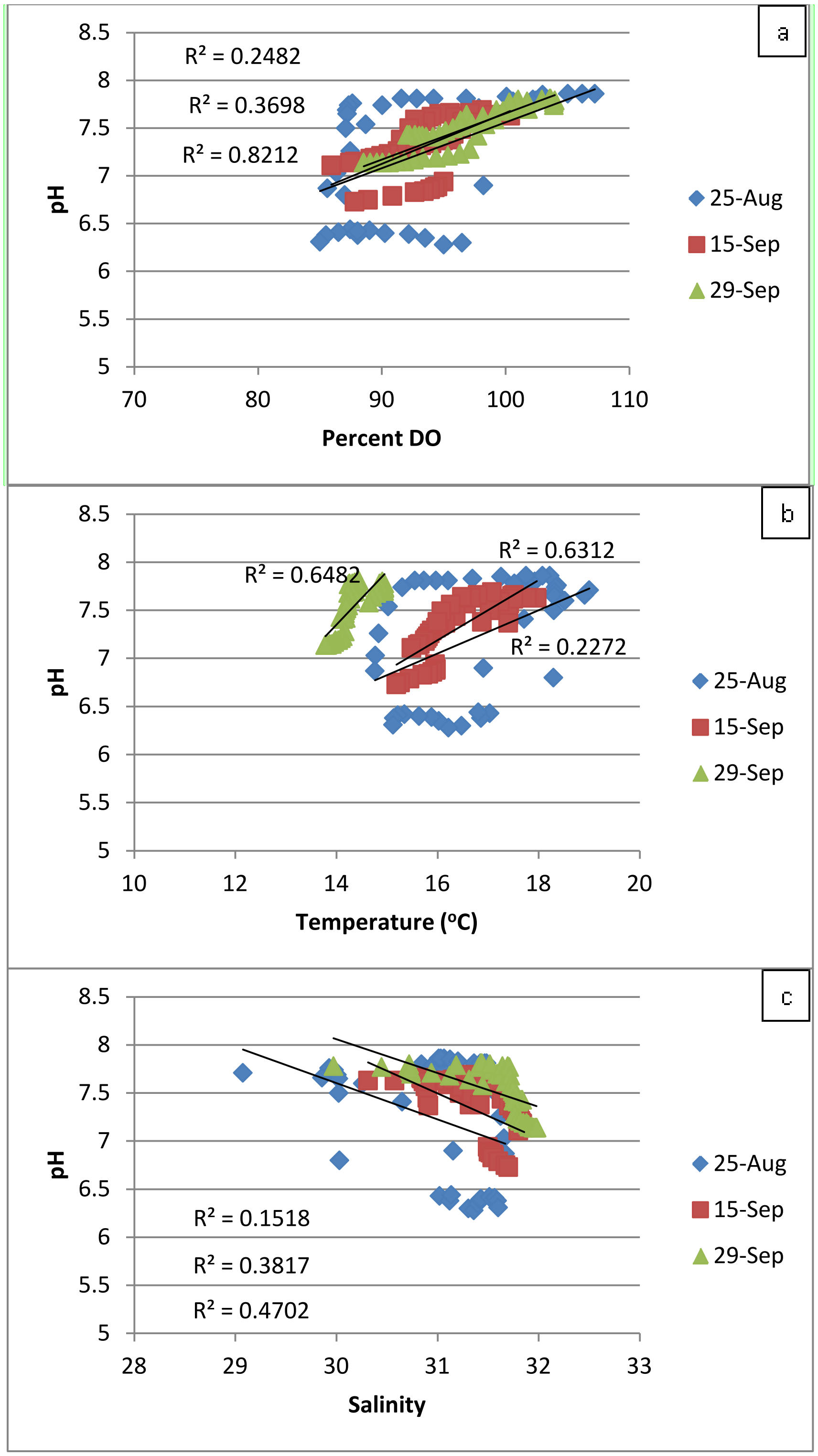


Figure 25. Scatter plots of boat profile pH readings for stations 11, 14, 23 and 26 for three sample dates: pH vs DO (a), pH vs temp (b), and pH vs salinity (c). In all plots, the weakest fit between pH and the regression variable occurred on August 25, the sample date with the most aberrant pH readings. Low pH readings were not consistently associated with extreme DO, temperature, or salinity measurements.

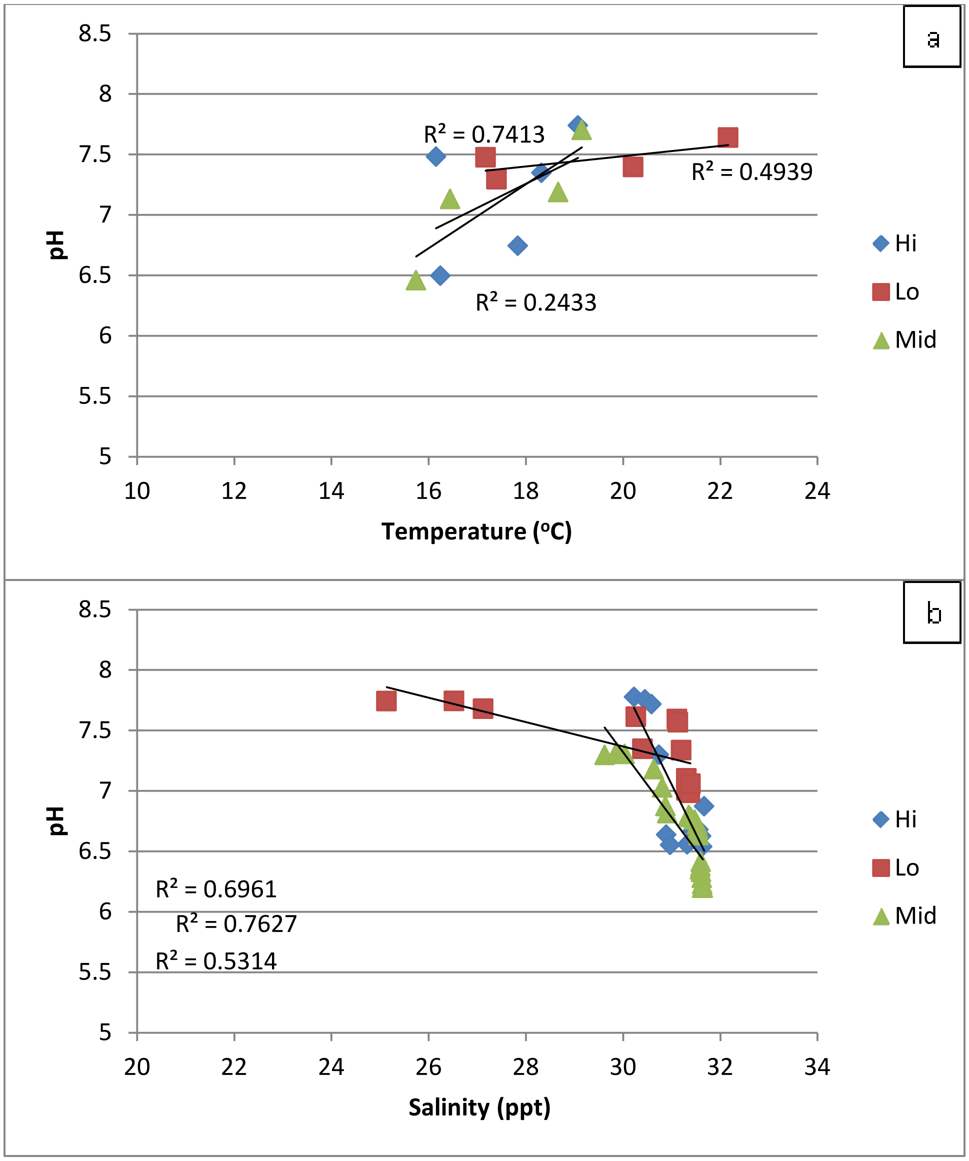


Figure 26. Regressions of pH against temperature (a) using sites as replicates and pH against salinity (b) using depth as the replicate measure. Low pH readings were not associated with low-tide conditions, but were associated with mid- and high-tide conditions, possibly indicating an oceanic source to reduced pH readings.

Dissolved Oxygen vs pH in Vertical Profiles

Figure 25a plots pH vs DO for Lower Estuary stations, but plots of vertical profiles at chosen stations provide another way to examine this relationship. On August 18, DO decreased markedly with depth at stations 23 and 26 in the Lower Estuary, but pH was constant with depth at a midday high tide (Figure 27a) as well as an early-morning low tide (not shown here). On the 8/25 early-morning high tide, DO had recovered somewhat but still decreased with depth, whereas pH showed a dramatic decrease with depth (Figure 27b), a pattern that held on the midday low tide as well. The pH trough was still in place on September 15 (Figure 27c) and September 29.

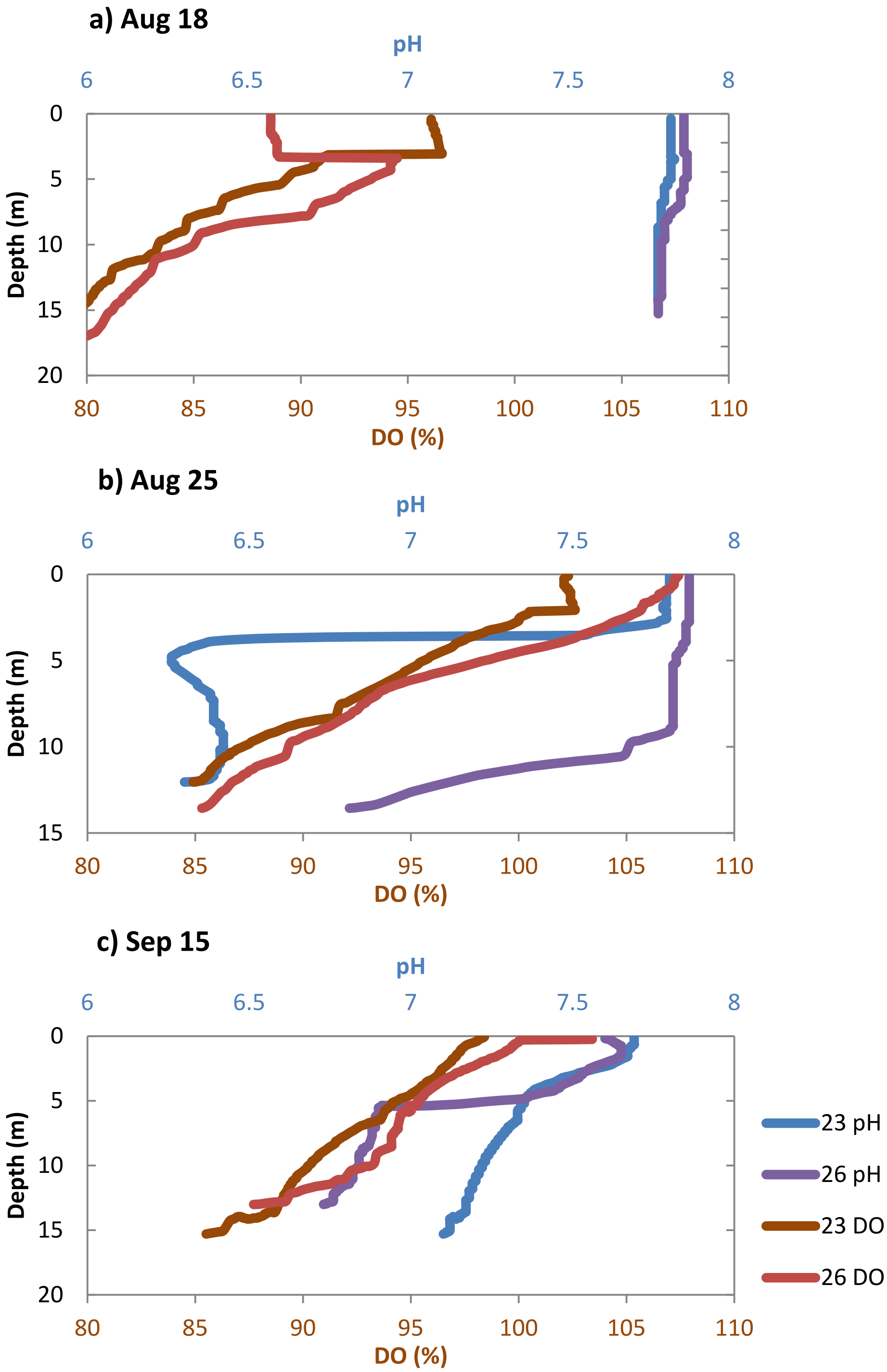


Figure 27a-c. The pH was steady with depth at stations 23 and 26 on August 18 but declined dramatically with depth on 8/25 and 9/15. Recovery was not observed until 9/29.

Total Nitrogen

Water samples for total nitrogen were collected as surface grabs from profile locations on each sample date. Nitrogen, as nitrate or ammonia, can be a persistent cause of algal blooms and eutrophication in estuaries. The discharge of treated effluent from the Warren sewage-treatment facility may introduce a significant amount of nitrogen to the estuary. The Thomaston discharge is seasonal (January, February, and March only) and therefore did not impact our sample dates. The locations of these outfalls and a known Upper Estuary overboard discharge are shown in the map in Figure 30.

The Maine DEP has identified 0.4 mg/L total nitrogen as a lower threshold for possible nutrient over-enrichment. Total nitrogen concentrations at or above 0.4 mg/L were measured on each of the ten sample dates in 2012. Average concentrations were higher in the Upper Estuary, but high concentrations were also observed in the Lower Estuary. Samples from Station 2 were most consistently above 0.4 mg/L TN, with a seasonal average of 0.47 mg/L (Figure 27). The TN data from October 13 arrived too late to be included in Figure 27, but the concentration at Station 2 was 0.76 mg/L on that date, the highest value recorded in 2012. Values for TN at Stations 9 and 11 were, on average, below 0.4 mg/L, but those locations had high standard deviations associated with maximum seasonal values of 0.68 and 0.72 mg/L respectively. Those high values occurred at Station 9 on June 22 and at Station 11 on July 7 (Figure 27). Lower Estuary TN values were not measured above 0.4 mg/L as consistently, but several stations and dates were above the 0.4 mg/L threshold. TN values were high on July 7 in particular at Stations 14 and 21.

High TN events in the estuary were correlated with other measured water-quality variables in 2012. In the Upper Estuary, high TN was strongly associated with lower salinity (Figure 28), possibly indicating a link with rain events that flush nutrients into the Upper Estuary from its watershed and tributaries. High TN in the Upper Estuary also was positively correlated with surface-water temperature, which may be a reflection of seasonality, with higher TN levels during the summer growing season (Figure 28) when much of the nitrogen is incorporated in plankton. Dissolved oxygen in the Upper Estuary was lower at elevated TN concentrations.

In the Lower Estuary, high TN concentrations were again associated with lower surface salinity values (Figure 29), possibly reflecting a run-off or discharge signal propagating through the estuary. Indeed, weekly average discharge was also correlated with TN concentrations. The positive correlation between discharge and TN is driven almost entirely by events during the week of July 7. The second highest discharge event of the summer occurred in association with that sampling.

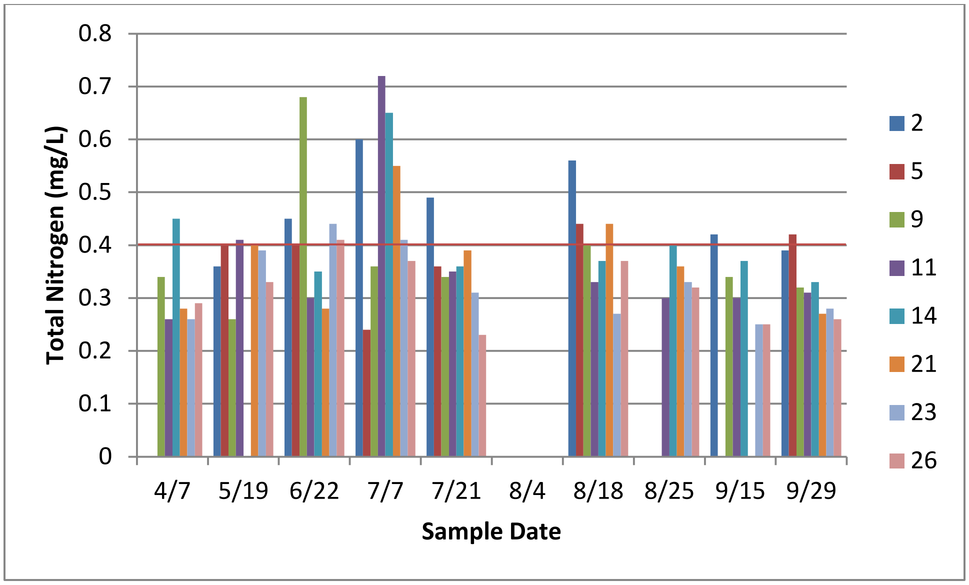


Figure 27. Values of total nitrogen for profile stations, listed by station nested within sample date. The red line represents the Maine DEP's preliminary concentration of concern for nitrogen in estuaries. All concentrations are measured from surface (0 m) grabs. Data from July 7 showed the most stations over the 0.4 mg/L threshold.

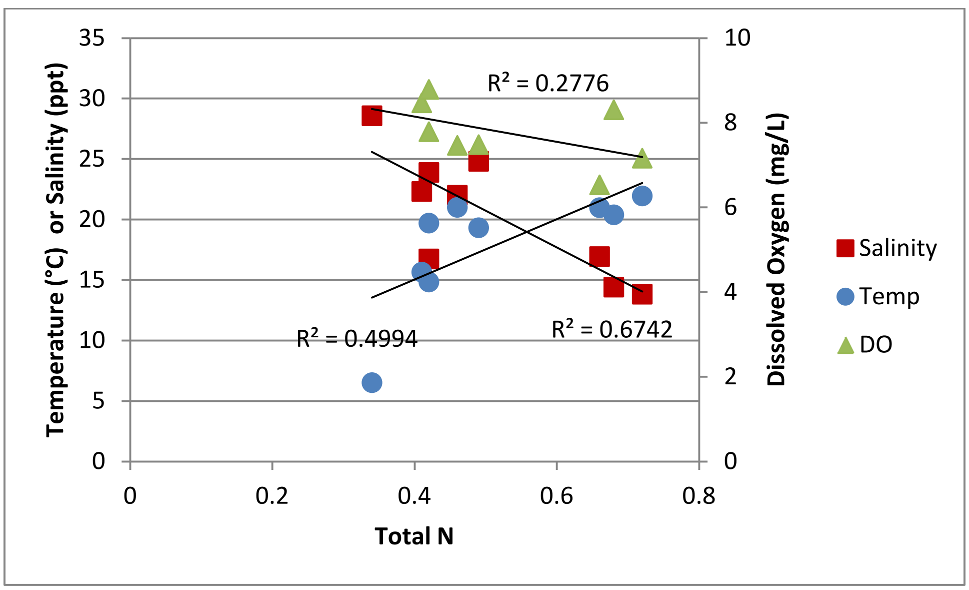


Figure 28. Water quality measures plotted against TN for samples and data collected from the Upper Estuary in 2012. All values correspond to surface (0 m) data. DO, temperature, and salinity data are surface-water averages from stations 2, 5, 9, and 11 on a sample date.

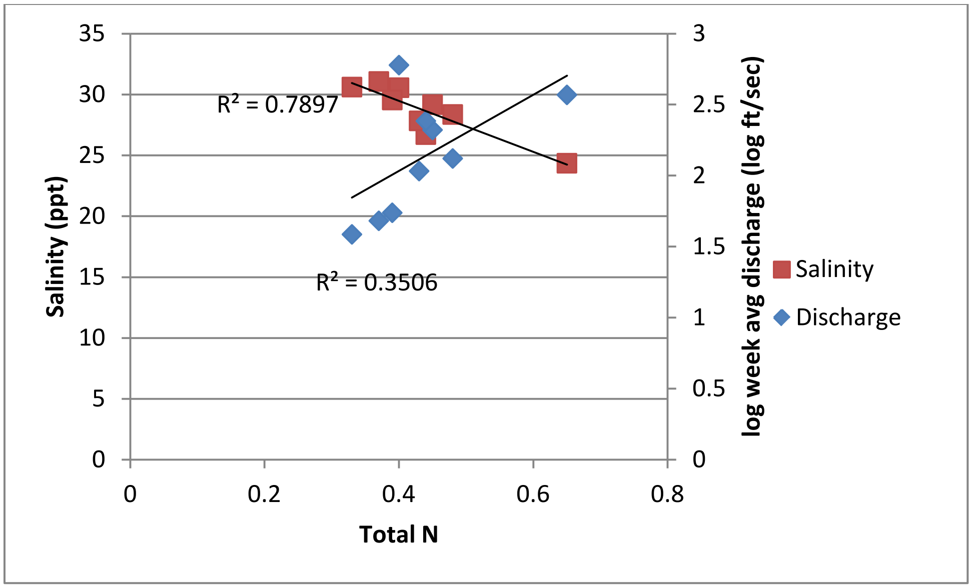


Figure 29. Water quality measures plotted against TN for samples and data collected from the Lower Estuary in 2012. All values correspond to surface (0 m) data. DO, temperature, and salinity data are surface-water averages from stations 14, 21, 23, and 26 on a sample date. There was a significant inverse correlation of TN with salinity.

The 2012 Index of Estuary Health

Indicator #1, Dissolved Oxygen

Like most Maine estuaries, the St. George is classified by the Maine Department of Environmental Protection as a Class SB estuary, which means that it should at all times be swimmable and fishable and should support all forms of marine life. The waters of a Class SB estuary are intended to be at least 85% saturated with dissolved oxygen at all times. Sampling by the DEP and the GRTA since the mid-1990s has shown repeatedly that the Upper Estuary of the St. George, above the Thomaston waterfront, occasionally fails to attain that standard in late summer. This pattern held in 2012. Oxygen depletion was measured in the Lower Estuary as well as the Upper Estuary in late summer, as far seaward as Maple Juice Cove, in waters that support abundant harvests of lobster and clams.

Conclusion #1: The St. George Estuary exhibits symptoms of DO stress in summer, when water temperatures are highest (and therefore contain less DO) and the processes that consume dissolved oxygen (uptake by sediments, respiration by marine life, and decomposition of dead organic matter) are greatest. These symptoms recur more frequently in the Upper Estuary but are also manifested in the Lower Estuary. They are not necessarily entirely or even largely caused by human activity; they could result in significant part from natural processes, just as high cholesterol is not necessarily the result of a poor diet. But just as people with high cholesterol should watch their diets with particular care, we should take any realistic measures to reduce nutrient run-off and over-enrichment of the estuary, which is the most immediate way in which human activity contributes to dissolved-oxygen stress.

Indicator #2, pH

As taught in high-school chemistry, a low pH is indicative of an acidic solution and a high pH is indicative of an alkaline solution. Rain has a pH of about 5.5. Maine's natural freshwater pH range is 6 to 7 (it's higher in other parts of the country and world), and seawater, being a highly buffered solution of salts, has a normal pH of 8.0 to 8.2, which is optimal for marine life. A significant drop in pH is a stressor for marine life. Research in Maine has shown that the shells of young soft-shelled clams exhibit pitting and erosion after 72 hours of exposure to seawater of pH 7.5. In one observation, half of the larval clams settling out of the water column to undergo metamorphosis rejected mud with a pH of 7.5; total rejection of mud with a pH of 7.2 (as exhibited by failure to settle and metamorphose) was observed.

The St. George Estuary in 2012 showed persistent decreases of pH along a salinity gradient from the more saline waters at the mouth of the estuary to the brackish waters of the Upper Estuary. This was expected. What we did not expect were the dramatically low pH values we measured in subsurface waters of the Lower Estuary between August 25 and September 29—numerous measurements below 7.2, and some as low as 6.2—lower than the lowest Upper Estuary measurements.

Conclusion #2: The St. George Estuary in 2012 exhibited signs of pH stress. As with dissolved-oxygen depletion, low pH values do not necessarily result entirely or even mostly from human activity, nor are pH probe data as reliable in seawater as in fresh water. (Essentially, the alkalinity of seawater is a complex chemistry for which pH is an overly simplified proxy, though no realistic alternative to pH has been developed.) But we know that ocean acidification is occurring worldwide due to human causes, and a growing body of research shows that acidification can be accelerated in near-shore waters due to nutrient-laden runoff and the resultant overproduction and decay of organic matter, which depletes dissolved oxygen as it lowers pH. Declines in pH with depth in the Lower Estuary in late summer were correlated with declines in dissolved oxygen. These declines could have been caused *in situ* by decay of organic matter or benthic oxygen demand. Alternatively or in addition, oxygen-poor, low-pH water could have been transported from up-estuary or from offshore with tidal flux.

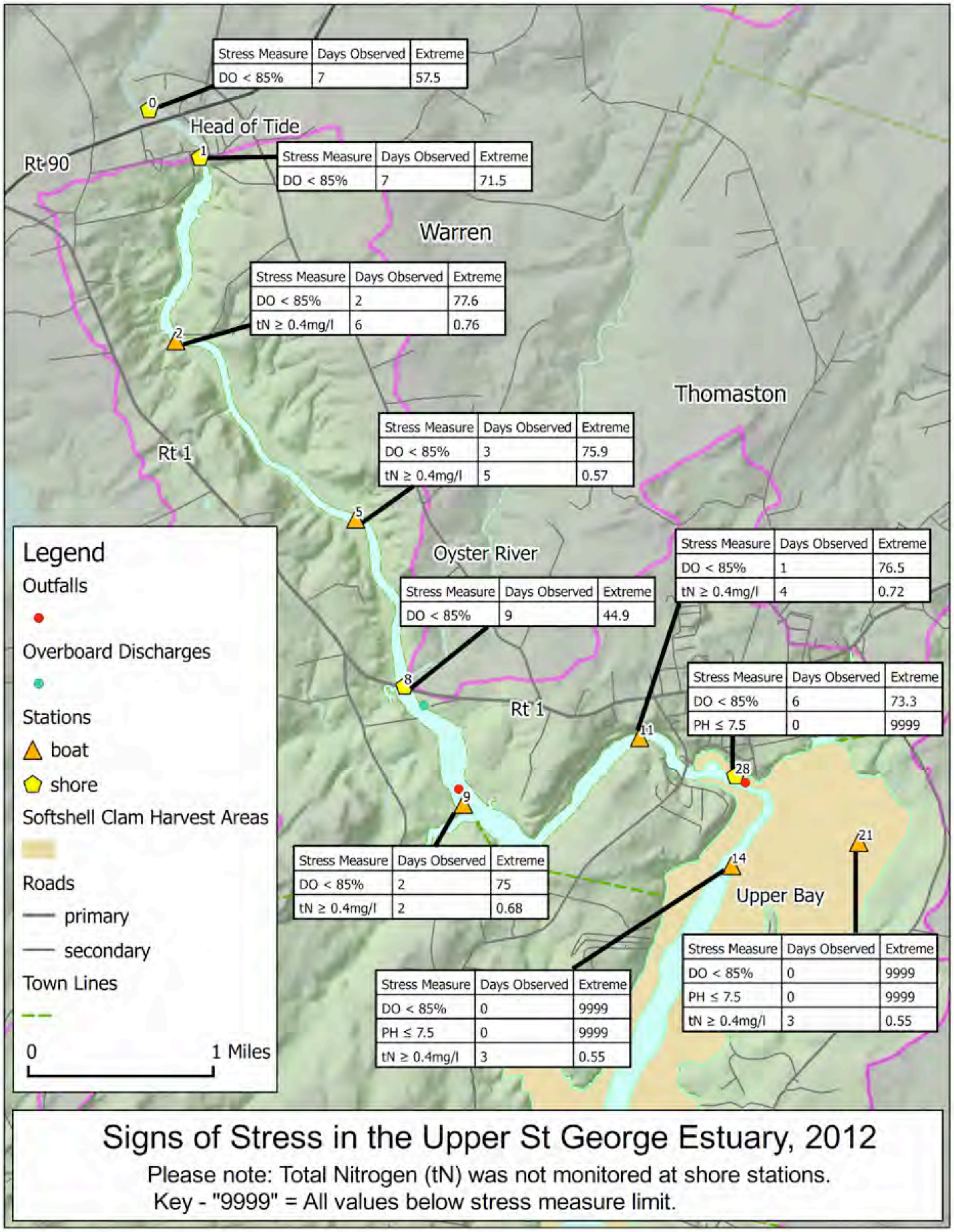
Indicator #3, Total Nitrogen

Nutrient-rich marine waters carrying too much nitrogen can experience algae blooms, the decay of which consume dissolved oxygen and lower pH (just as happens when a pond turns eutrophic).

Conclusion #3: The St. George Estuary in 2012 contained high levels of total nitrogen that could have contributed to overproduction of organic matter and thus to pH and DO stress. A TN above 0.4 mg/liter is considered cause for concern in marine waters (Angela Brewer, Maine DEP, personal communication), and on every 2012 sample date, one or more stations in the St. George had TN's at or above 0.4 mg/L. The highest TN's were measured in the Upper Estuary, but TN's above 0.4 mg/L were also measured in the Lower Estuary throughout the summer. These TN's ran substantially higher than those that have been observed in the Damariscotta River Estuary (Dr. Lawrence Mayer, personal communication). Non-point sources of elevated TNs could include nutrient flux from the St. George Estuary's extensive mudflats, subtidal mud bottoms, and fringing salt marsh, and/or runoff from the surrounding watershed and the main stem of the St. George. The primary point source of nitrogen into the St. George is the Warren Wastewater Treatment Plant, which discharges nitrogen-rich treated effluent to the Upper Estuary near Station 9.

The 2012 Index of Estuary Health

The maps in Figures 30 and 31 summarize in graphic form three of our four stress indicators in 2012. Recorded in the map are instances of dissolved oxygen below 85% of saturation value (the state requirement for a Class SB estuary); pH equal to or less than 7.5 (the level at which erosion of clam spat shell and rejection of sediment by clam larvae have been observed), and total nitrogen above 0.4 mg/L. Note that the numerous Upper Estuary pH measurements of 7.5 or lower are not indicated here because the lower-salinity waters of the Upper Estuary are expected to have a lower pH and because our threshold of pH stress was chosen with the soft-shelled clam in mind as an indicator organism, and the soft-shelled clam fishery is confined to the Lower Estuary. Note too that measurements of total nitrogen were not made at shore station sites. There were 10 sample days in 2012. Thus, a station with 7 recorded instances of dissolved oxygen below 85% of saturation failed to meet the state requirement on 70% of the sample dates.



Stress Measure | Days Observed | Extreme
DO < 85% | 7 | 57.5
Head of Tide
Stress Measure | Days Observed | Extreme
DO < 85% | 7 | 71.5
Rt 90
Warren
Stress Measure | Days Observed | Extreme
DO < 85% | 2 | 77.6
tN ≥ 0.4mg/l | 6 | 0.76
Thomaston
Rt 1
Stress Measure | Days Observed | Extreme
DO < 85% | 3 | 75.9
tN ≥ 0.4mg/l | 5 | 0.57
Oyster River
Stress Measure | Days Observed | Extreme
DO < 85% | 9 | 44.9
Stress Measure | Days Observed | Extreme
DO < 85% | 1 | 76.5
tN ≥ 0.4mg/l | 4 | 0.72
Stress Measure | Days Observed | Extreme
DO < 85% | 6 | 73.3
PH ≤ 7.5 | 0 | 9999
Rt 1
Stress Measure | Days Observed | Extreme
DO < 85% | 2 | 75
tN ≥ 0.4mg/l | 2 | 0.68
Upper Bay
Stress Measure | Days Observed | Extreme
DO < 85% | 0 | 9999
PH ≤ 7.5 | 0 | 9999
tN ≥ 0.4mg/l | 3 | 0.55
Stress Measure | Days Observed | Extreme
DO < 85% | 0 | 9999
PH ≤ 7.5 | 0 | 9999
tN ≥ 0.4mg/l | 3 | 0.55
Legend
Outfalls
Overboard Discharges
Stations
boat
shore
Softshell Clam Harvest Areas
Roads
primary
secondary
Town Lines
0
1 Miles
Signs of Stress in the Upper St George Estuary, 2012
Please note: Total Nitrogen (tN) was not monitored at shore stations.
Key - "9999" = All values below stress measure limit.

Figure 30.

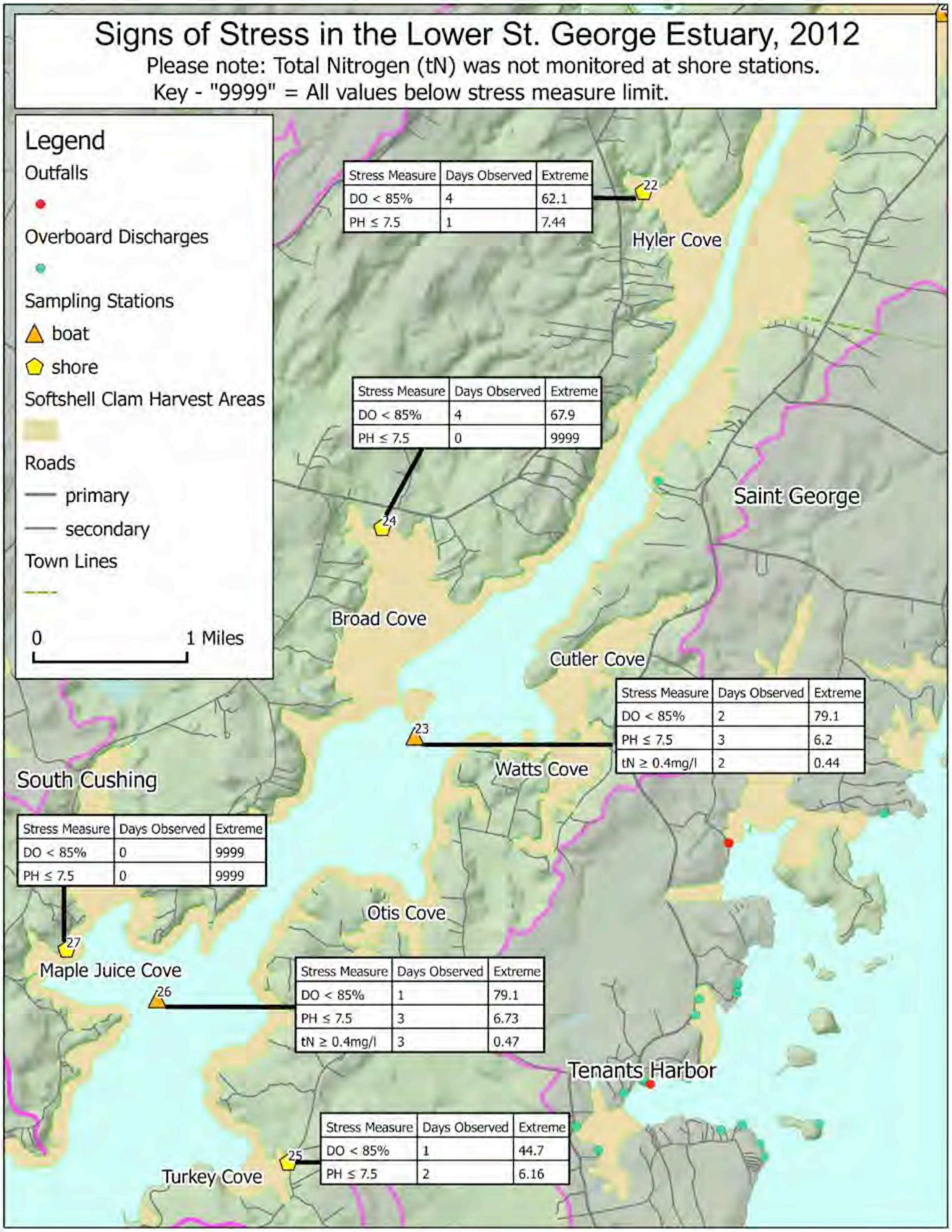

Signs of Stress in the Lower St. George Estuary, 2012
Please note: Total Nitrogen (tN) was not monitored at shore stations.
Key - "9999" = All values below stress measure limit.
Legend
Outfalls
Overboard Discharges
Sampling Stations
boat
shore
Softshell Clam Harvest Areas
Roads
primary
secondary
Town Lines
0
1 Miles
Stress Measure | Days Observed | Extreme
DO < 85% | 4 | 62.1
PH ≤ 7.5 | 1 | 7.44
22
Hyler Cove
Stress Measure | Days Observed | Extreme
DO < 85% | 4 | 67.9
PH ≤ 7.5 | 0 | 9999
24
Saint George
Broad Cove
Cutler Cove
Stress Measure | Days Observed | Extreme
DO < 85% | 2 | 79.1
PH ≤ 7.5 | 3 | 6.2
tN ≥ 0.4mg/l | 2 | 0.44
23
Watts Cove
South Cushing
Stress Measure | Days Observed | Extreme
DO < 85% | 0 | 9999
PH ≤ 7.5 | 0 | 9999
Otis Cove
27
Maple Juice Cove
26
Stress Measure | Days Observed | Extreme
DO < 85% | 1 | 79.1
PH ≤ 7.5 | 3 | 6.73
tN ≥ 0.4mg/l | 3 | 0.47
Tenants Harbor
Stress Measure | Days Observed | Extreme
DO < 85% | 1 | 44.7
PH ≤ 7.5 | 2 | 6.16
25
Turkey Cove

Figure 31.

We have created an overall Index of Estuary Health that combines and weighs the three indicators introduced above. This index has five levels as summarized in Table 8.

5. Healthy (Green)
4. Healthy with Occasional Symptoms of Stress (Light Green)
3. Exhibiting Chronic Symptoms of Stress (Yellow)
2. Unhealthy (Orange)
1. Life-Threatening to Marine Organisms (Red)

Table 8. Our Index of Estuary Health is a composite summary of three indicators of estuarine stress: dissolved oxygen, pH, and total nitrogen.

The St. George Estuary in 2012 rated a "3" on this Health Index due to its excursions of low dissolved oxygen, its dramatically low late-summer subsurface pH values, and its high values of total nitrogen. Taken together, these indicators suggest a habitat under stress.

For a note of humility, however, see Figure 32.

Figure 32. Note the visible surface-water boundary—cause unknown--stretching from one shore of the Lower Estuary (just south of Turkey Cove) to the other in this October 2012 photo. How much DO, pH, or TN variability would there be across this boundary?

Recommendations for 2013 and Beyond

The GRTA will continue its water-monitoring program in 2013 in the ongoing effort to characterize DO, pH, and total nitrogen (TN) in the St. George Estuary as described in the QAPP approved by MDEP in 2012. Returning volunteers will be prepped and new volunteers will be trained on April 13 and April 20, 2013, to sample the estuary's eight established shore stations. The sample season will begin in late April and will run through early October, as in 2012. Several modifications are envisioned, however. These include:

- Eliminate three of the eight 2012 boat stations in order to reduce travel and profiling time and make it more feasible to cluster the sampling around the time of high tide when shore-station volunteers are gathering their samples.
- Establish a new station at the mouth of the estuary to help characterize the vertical profile of water entering the estuary from Muscongus Bay on a flood tide. On any sample date in which low pH and/or dissolved oxygen is observed at that seaward station, we will get a vertical profile from an offshore Muscongus Bay station.
- Based on the recording of low dissolved oxygen in the Lower Estuary on August 18, 2012, and low pH there between August 25 and September 29, 2012, we hope to augment the discrete vertical profiles collected in the St. George Estuary in 2013 with long-term data gathered from an untended sonde (YSI 6920 or equivalent with optical DO, pH, temperature, and salinity sensors) moored in the Lower Estuary from early August into September. This objective will have to be abandoned if we are unable to afford or borrow a second data sonde.
- If the late-summer Lower Estuary pH trough observed in 2012 appears again in 2013, use Niskin bottles to gather shallow and deep water samples along with the vertical sonde profile. The Niskin samples will be fixed with mercury. We will return to the same station the next day and repeat the Niskin sampling, then ship the Niskin bottles to Dr. Joseph Salisbury of University of New Hampshire, who will analyze their alkalinity. The objective is to investigate whether the dramatically low pH values observed in 2012 were accurate indicators of alkalinity and acidification.
- Offer shore-station volunteers the option of "fixing" their DO samples in the field (i.e., rendering the samples inert with reagents), then submitting them to the contracted volunteer coordinator for the Winkler titrations rather than performing the titrations themselves.
- Beginning in 2014, sample rain events to monitor the run-off input in Upper and Lower Estuary.
- Beginning in 2014, monitor the possible effects of estuary acidification on clams, mussels, and starfish. All three are benthic, but clams live in sediments, mussels anchor

themselves to the intertidal via byssal threads, and starfish are mobile through the low intertidal and subtidal zones. All three incorporate calcium carbonate for growth, and all three have been shown to be pH sensitive (Burns 2012; Collard et al 2011; Knight 2011). A program monitoring recruitment, growth, and signs of pH stress will need to be designed. There is anecdotal evidence from shorefront residents of the lower St. George estuary of the disappearance of mussel beds and starfish.

In addition, the GRTA intends to expand the monitoring program from the St. George Estuary into the adjacent Medomak Estuary to the west and Weskeag Estuary to the east. This will give us comparative data and observations from three small neighboring estuaries, all of which are characterized by slow tidal flushing, low hydrodynamic energy, and nutrient concentration.

The St. George and Medomak estuaries are closely linked in geography and character. Both are flushed from and empty into Muscongus Bay. The St. George Estuary contains 1,683 acres of clam flats, the Medomak Estuary contains more than 2,000 acres of flats, and together they account for approximately one-fourth of the state's average annual clam harvest and an average landed clam value of $4 million or more. The St. George River drains 125 square miles, the Medomak River 140 square miles. Both are long, narrow, and slowly flushed; both experience frequent clam-flat closures due to high coliform bacteria scores despite relatively thinly developed shorelines. The estuaries support smelt, alewife, elver, and marine worm fisheries, and both also support lucrative lobster fisheries in their lower reaches.

The Weskeag Estuary has its headwaters in the Weskeag Marsh, one of the most high-value shorebird habitats in the state. The Maine Department of Inland Fisheries and Wildlife owns and manages the R. Waldo Tyler Wildlife Management Area there, and the state and the Georges River Land Trust improved public access to the marsh in 2012 with Maine Outdoor Heritage Fund help. The Weskeag Estuary supports oyster farming and a clam fishery that is managed by the five-town Georges River Regional Shellfish Management organization.

We have begun recruiting additional steering committee members and citizen volunteers to extend our monitoring program into the Medomak and Weskeag estuaries. We will establish three shore stations in the Weskeag and five in the Medomak. These will be sampled on the same ten dates and at the same times (high tide) as the St. George shore stations.

Between July and September, we will sample each estuary twice by boat, collecting vertical profiles, Secchi disk readings, and surface-water samples for total nitrogen analysis at four or five stations in each estuary. Each of these four boat-sampling events will be on a Sunday, the day after a corresponding sample event on the St. George Estuary, and each will be timed around high water as on the St. George.

We are in the process of building an oversight committee of representatives from all three estuaries and from the midcoast education and fishing communities to help sustain this monitoring program in future years.

Results from the Medomak, St. George, and Weskeag estuaries will improve our understanding of midcoast estuarine habitats while addressing DEP's paucity of data for the Weskeag and Medomak. Similarities and differences in the degree to which these three adjacent estuaries experience DO, pH, and temperature stress will supply insights on whether and to what extent Maine's estuaries are vulnerable to harm from rising seawater temperatures, declining pH, and nutrient over-enrichment.

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