2002 WATER QUALITY AND CURRENT SURVEYS IN THE NORTON BASIN/LITTLE BAY COMPLEX

Final Report
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EXECUTIVE SUMMARY

Deep pits and shallow areas of Little Bay and Norton Basin, in addition to stations in the Norton Basin and Little Bay Entrance Channels and Grass Hassock Channel, were surveyed monthly from May to October 2002 to characterize water quality conditions and currents in the Norton Basin/Little Bay complex. Replicated profiles of temperature, salinity, dissolved oxygen, and turbidity were made in each area, and water samples were analyzed for dissolved and particulate nutrients, chlorophyll, and total suspended solids. Short-term measurements of current speed and direction were made in the Little Bay and Norton Basin pits and their entrance channels in June, July, September, and October.

The profiles indicated that the water column in the Little Bay pits remains highly stratified from spring through the summer and into early fall. A thermocline, low temperature, and anoxic conditions were persistent features of the Little Bay pits in all surveys but were not present in profiles from all other areas. Also, a turbidity layer was present above the thermocline, and salinity was higher in the lower water column of the Little Bay pits. Near bottom waters in Little Bay pits were characterized by very high sulfide; high ammonium, phosphate, and dissolved silica; and low nitrate+nitrite, biogenic silica, total chlorophyll, and phaeophytin. In contrast, the upper water column in the Little Bay pits and shallows, and the Norton Basin pits and shallows along with the Norton Basin Entrance Channel and Grass Hassock Channel were similar in terms of most water chemistry parameters. Water quality in areas of the Norton Basin/Little Bay complex other than the lower water column in the Little Bay pits was good. The water chemistry data indicated high rates of anaerobic decomposition in the lower water column of Little Bay, and that it is likely a major contributory factor to persistent anoxia (<1 mg/l O_2) in the Little Bay pits. Anaerobic decomposition generate high levels of toxic sulfides in the near bottom in Little Bay pits.

There were generally slow and complex flow patterns in the Little Bay and Norton Basin pits and their entrance channels. Current speeds in the Little Bay pit near bottom were comparable in general with current speeds in the Little Bay pit midwater and near surface along with currents in the Norton Basin and the two entrance channels. The current meter data indicate that the slow currents in the Little Bay pit near bottom do not respond to daily tidal changes as much as the near surface, and midwater levels in Little Bay and the Norton Basin pits and entrance channels. The profile, water chemistry, and current data provide strong indications that there is little exchange between the near bottom and upper water column in Little Bay. Given that current speeds in the low water column in the Little Bay pits were similar to those in the entrance channels and Norton Basin, differences in basin morphology, e.g., the deep pits make up a greater proportion of the total surface area of Little Bay compared to Norton Basin, may explain the difference in water quality conditions between Little Bay and Norton Basin. The pronounced thermocline, slow currents, and greater proportion of deep pits that exhibit high oxygen consumption rates in the Little Bay pits result in persistent anoxic conditions.

The poor water quality of the Little Bay near bottom waters, particularly anoxia and the presence of high levels of sulfide, indicates conditions that are inhospitable to the aerobic organisms that would be desirable in an estuarine environment, e.g., fish and shellfish. The presence of high levels of poisonous sulfide along with persistent anoxic conditions in Little Bay pits are compelling evidence that water quality conditions are very poor. The poor water quality conditions would preclude use of the Little Bay pits as a habitat for desirable estuarine organisms for at least the late spring through the early fall.

1.0 INTRODUCTION

The beneficial uses of dredged material for recontouring and reshaping the bottom of artificially deepened areas such as borrow pits is a component of the Dredged Material Management Plan for the Port of New York/New Jersey developed by U.S. Army Corps of Engineers, New York District. The use of dredged material for recontouring borrow pits is an alternative placement option being considered to help address difficulties in the disposal of dredged material in the Port. The Norton Basin/Little Bay complex, located in the southeastern corner of Jamaica Bay, is composed of two originally shallow embayments where historical dredging for fill material used for the Edgemere landfill left deep borrow pits. The goal of the Norton Basin/Little Bay Project is to demonstrate the feasibility of habitat restoration by recontouring deep borrow pits to return the borrow pits to a more natural state, restore good water quality conditions, and provide better habitat for estuarine organisms. Recontouring would involve filling in deep pits and reshaping the bottom to an average depth of approximately 15 ft.

As part of the Norton Basin/Little Bay Project, the Phase I Baseline Environmental Study was initiated in 2001 to further characterize environmental conditions within the study area. This report summarizes the results of the water quality and current meter surveys conducted from May to October 2002. The primary objective of this study was to characterize water quality and currents in the Norton Basin/Little Bay complex through water column profiles, analysis of water samples, and measurements of current speed and direction. Of particular interest was characterization of the anoxic phenomena within the Norton Basin/Little Bay complex.

The study area and methods used in the surveys are described in **Sections 2.0**, and **3.0**. The summarized results for the water column profiling, water chemistry analysis, and current meter measurements are provided in **Section 4.0** and a discussion is presented in **Section 5.0**. A summary and conclusions are presented in **Section 6.0**. Detailed data, additional descriptive summaries, and current meter calibration records are provided in the **Appendices**.

2.0 STUDY AREA

The study area is composed of a pair of small deadend embayments, collectively called the Norton Basin/Little Bay complex, located on the Rockaway Peninsula, in the Borough of Queens, New York. It lies along the southeastern corner of Jamaica Bay connected by a common entrance to Grass Hassock Channel (**Figure 1**). The Edgemere landfill forms the western side of the Norton Basin/Little Bay complex and separates it from Grass Hassock Channel.

Norton Basin is an elongated embayment generally oriented in a north-south direction with an entrance channel at its northern end. It is approximately 1,500 m (4,900 ft) in length and 400 m (1,300 ft) wide with a surface area of approximately 730,000 m^2 (7,855,000 ft^2). Norton Basin has three deep pits of varying depths and sizes arranged approximately along the long axis of the basin. The northern pit is about 15.2 m (50 ft) deep and is the smallest in area. The middle and southern pits are much larger than the northern pit and are of about the same area. The middle pit is deeper 15.2 m [50 ft]) compared to the southern pit (13.7 m [45 ft]).

Little Bay is much smaller than Norton Basin, roughly ovoid in shape with a roughly northeast to southwest orientation, and is connected to the western side of Norton Basin by a short channel (referred to as Little Bay Entrance Channel), which is navigable at even the lowest stages of the tide. Little Bay is approximately 370 m (1,200 ft) long and 400 m (1,300 ft) wide and covers an area of approximately 132,000 m^2 (1,420,000 ft^2). There are three pits, 18 to 20 m (60 to 65 ft) deep, each of roughly the same area, arranged along the main axis of Little Bay.

The northern end of Norton Basin narrows into the Norton Basin Entrance Channel and connects with Grass Hassock Channel through a shallow sill at its mouth. The Norton Basin Entrance Channel is very shallow at low tide. Grass Hassock Channel, a major tidal channel of Jamaica Bay, is approximately 400 to 500 m (120 to 150 ft) in width and 12 to 15 m (40 to 50 ft) deep in the vicinity of Norton Basin. Tidal waters of southeastern Jamaica Bay pass through Grass Hassock Channel as strong currents.

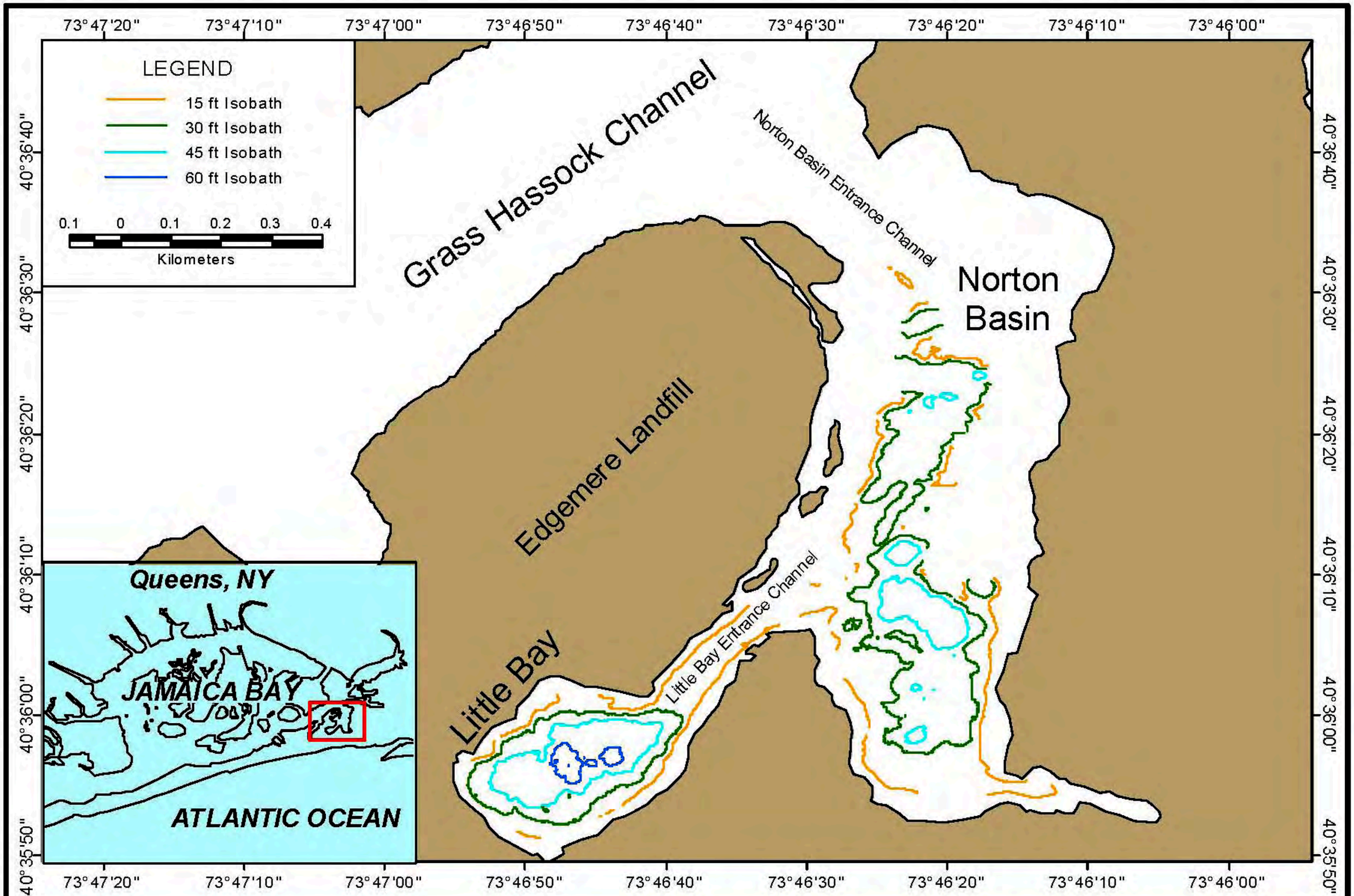

Figure 1. Location of study area within Jamaica Bay and bathymetry.

3.0 METHODS

3.1 WATER COLUMN PROFILES

Water column profiles of temperature, salinity, DO, and turbidity were taken during surveys conducted between May and October 2002 as summarized in **Table 1**. During each survey, three stations located in the deep pits and three stations located in the shallows in Little Bay and Norton Basin were sampled. Profiles were taken also at three stations along the Norton Basin Entrance Channel and Grass Hassock Channel. Beginning in July, profiles were taken also at two stations along Little Bay Entrance Channel. The location of each water column profile was recorded using a GPS receiver along with the water depth taken from the survey vessel's fathometer. The locations of profile stations for each survey are depicted in **Figures 2** to **8**.

A factory-calibrated Seabird SBE19 SeaCat profiler was used in all surveys except in August when a Hydrolab H20 Multiprobe was used. Profilers had sensors to measure temperature, salinity, DO, and turbidity. At each station, the SeaCat profiler was secured to a calibrated nylon line and allowed to equilibrate before being lowered to the bottom. After completing profiles during a survey, data were downloaded and raw data processed to produce average values for each parameter at 1-m depth increments, which were plotted as water column (vertical) profiles. During the August survey, the SBE19 profiler required repair by the factory, and a Hydrolab H20 Multiprobe, equipped with a pH sensor, was used in its place. The Hydrolab H20 was calibrated in the field according to protocol, allowed to equilibrate at the surface, and lowered to depth using a calibrated line. Upon completing the survey, data were downloaded and processed to produce water column profiles.

3.2 WATER CHEMISTRY

Water samples were collected during monthly surveys to characterize water chemistry (**Table 1**) from May to October 2002. The locations of water chemistry stations sampled during each monthly survey are depicted in **Figures 2**, **3**, **5**, **6**, **7**, and **8**. Samples were collected at near bottom, midwater, and near surface levels at one pit station each in Norton Basin and Little Bay. A midwater sample was collected also at a one shallow station each in Norton Basin and Little Bay. Reference samples also were collected from midwater at three stations along the Norton Basin Entrance Channel. In **Figures 2**, **3**, **5**, **6**, **7**, and **8**, although only the locations of the near surface samples in the Little Bay and Norton Basin pits are indicated (e.g., "LBPitNS" and "NBPitNS"), the midwater and near bottom samples were located at the same points.

From June to October, samples were collected also from midwater at a reference station in the Grass Hassock Channel for comparison with the primary samples. During surveys from July to October, additional near bottom samples were collected in the Little Bay and Norton Basin pits to supplement the primary near bottom samples. Supplemental samples collected in October were only analyzed for ammonium, phosphate, nitrate+nitrite, and total dissolved phosphate.

At each station, a 5-L Niskin water sampling bottle was lowered to the desired depth and triggered to close using a messenger. The samples were collected into pre-cleaned 1-L polyethylene bottles, which were placed on ice in a cooler and transported to shore. Sulfide

Table 1. Summary of survey schedule and effort.

Survey	Survey Date(s)	Water Column Profiles	Water Chemistry	Current Meter Moorings
1	6 May 2002		11 samples	None
	9 May 2002	18 stations		None
2	19 June 2002	18 stations	13 samples	Little Bay Pit (3)*
	20 June 2002			Norton Basin Pit (3)
	25 June 2002	18 stations		None
3	30 July 2002	20 stations	16 samples	Norton Basin Entrance Channel (2), Little Bay Entrance Channel (2), Norton Basin Pit (1)
4	30 August 2002	20 stations	16 samples	None
5	24 September 2002	20 stations		Little Bay Pit (3), Little Bay Entrance Channel (2), Norton Basin Pit (3), Norton Basin Entrance Channel (2)
	25 September 2002		16 samples	Norton Basin Entrance Channel (2), Little Bay Entrance Channel (2), Little Bay Pit (1)
6	22 October 2002	20 stations		Norton Basin Pit (3), Norton Basin Entrance Channel (2), Little Bay Pit (3), Little Bay Entrance Channel (2)
	23 October 2002		16 samples	Norton Basin Entrance Channel (2), Little Bay Entrance Channel (2), Little Bay Pit (1)

* - number of current meters on mooring deployed

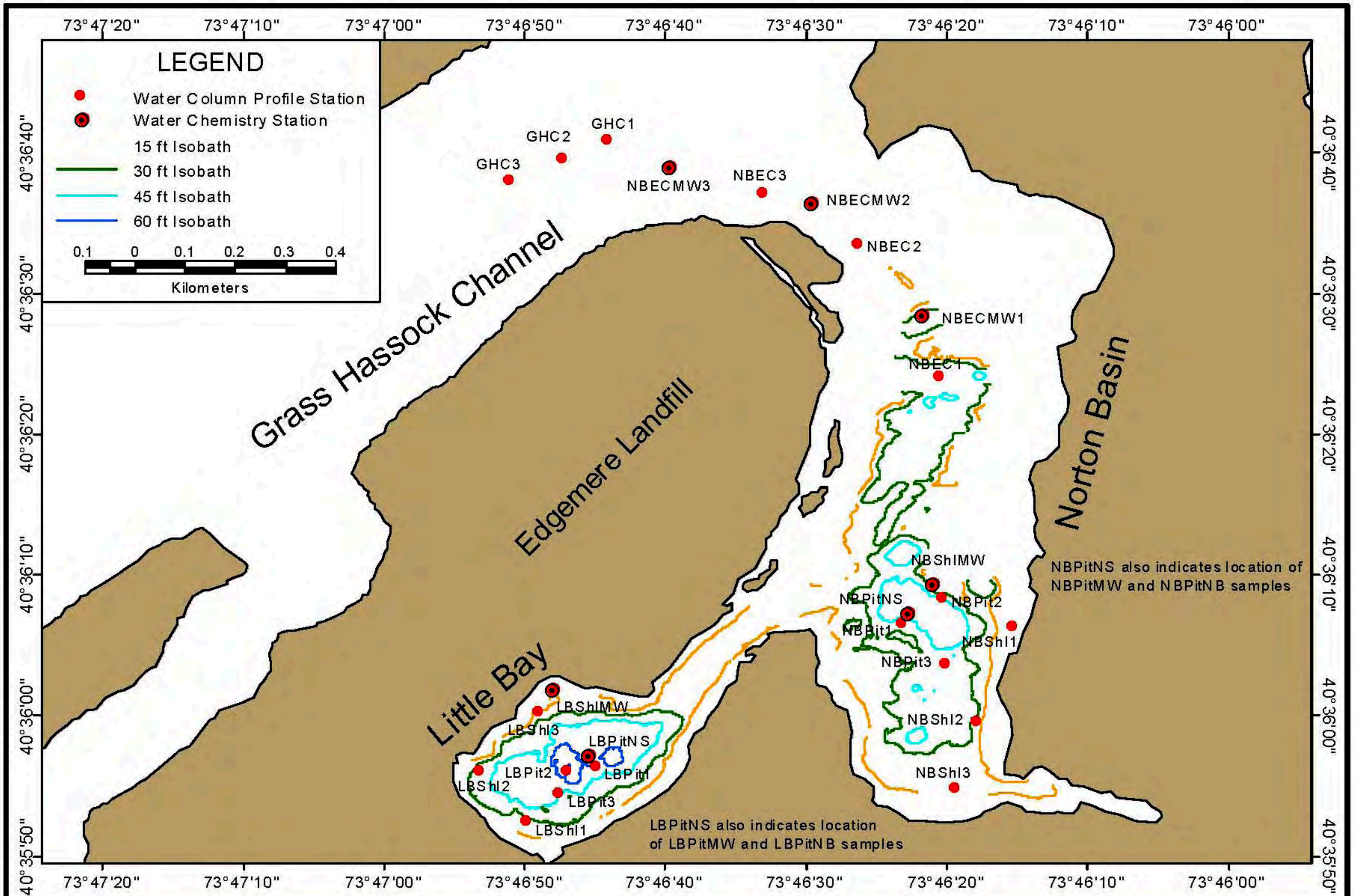

Figure 2. Water chemistry (6 May 2002) and water column profile stations (9 May 2002).

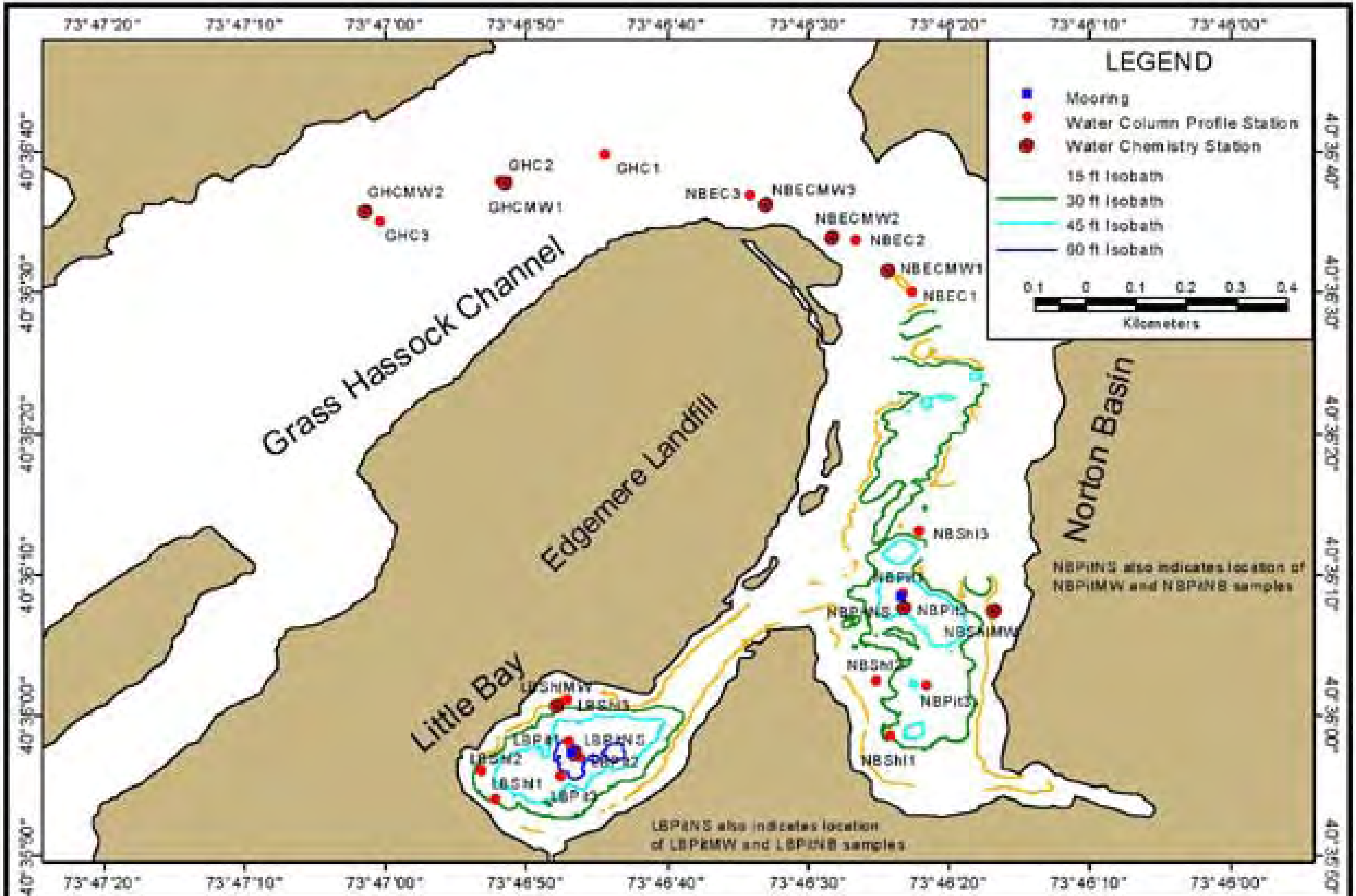

Figure 3. Water column profile, water chemistry, and current meter mooring stations during 19-20 June 2002 survey

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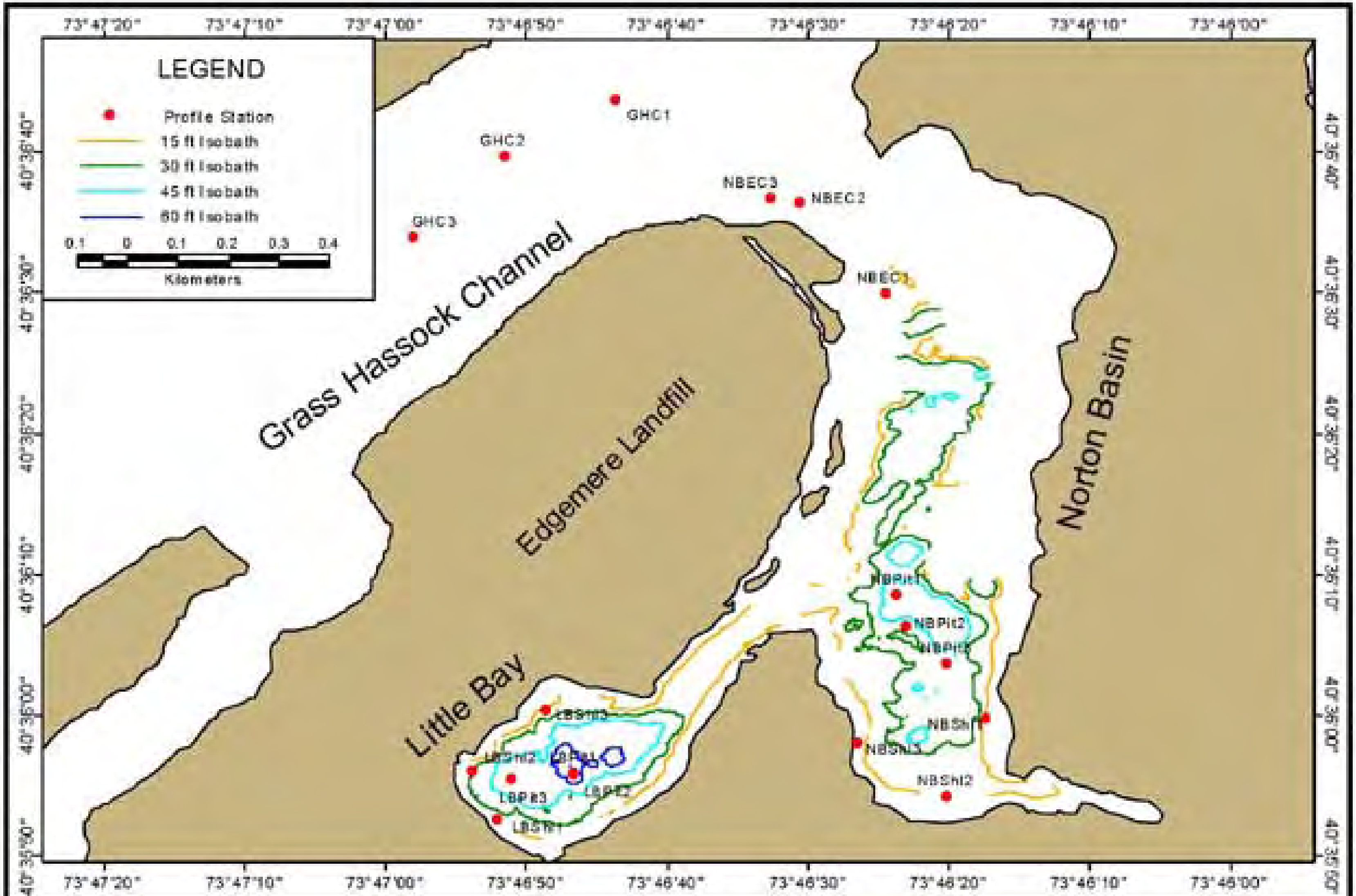

Figure 4. Water column profile stations during 25 June 2002 survey.

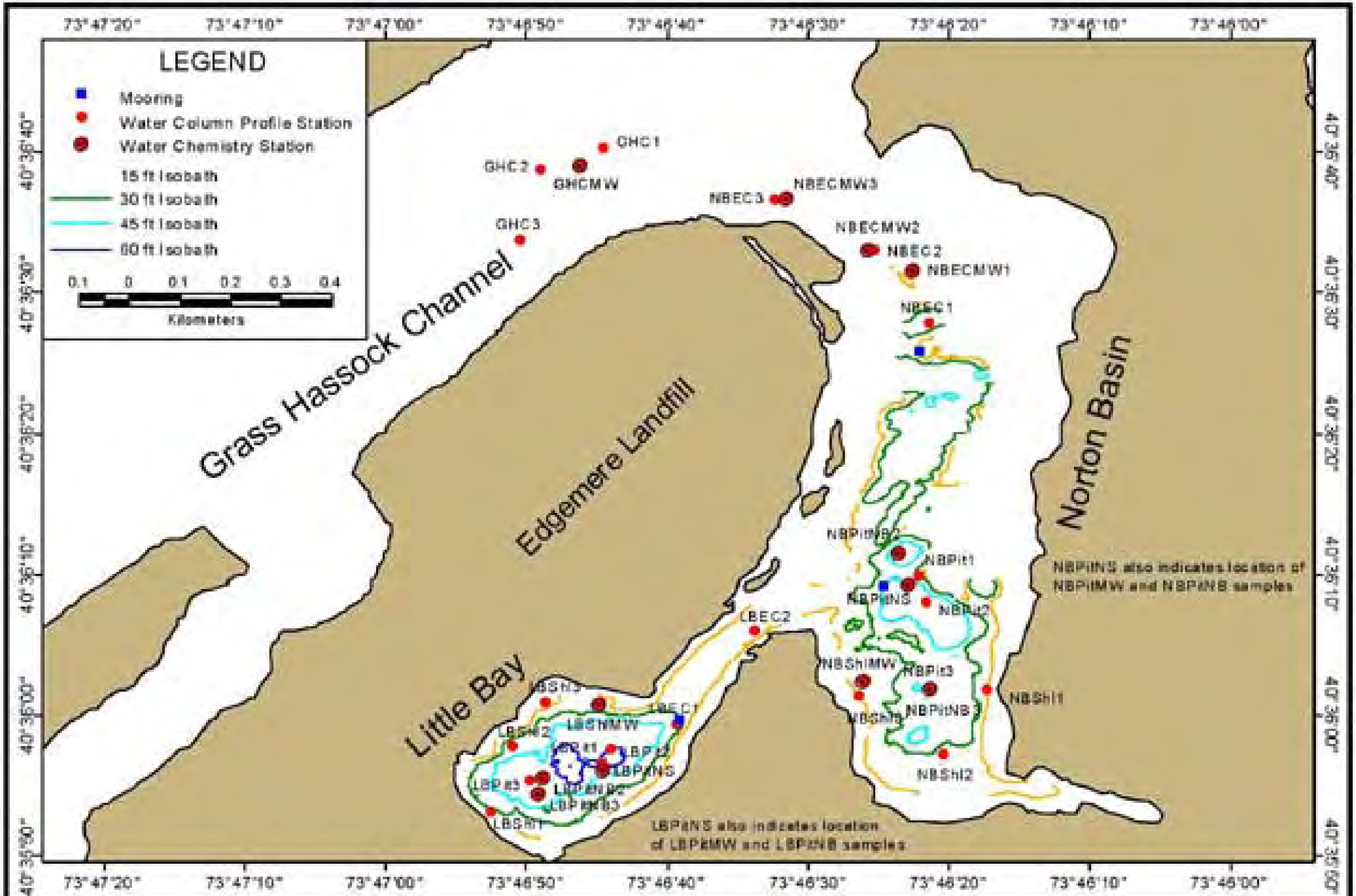

Figure 5. Water chemistry, water column profile, and current meter mooring stations during 30 July 2002 survey.

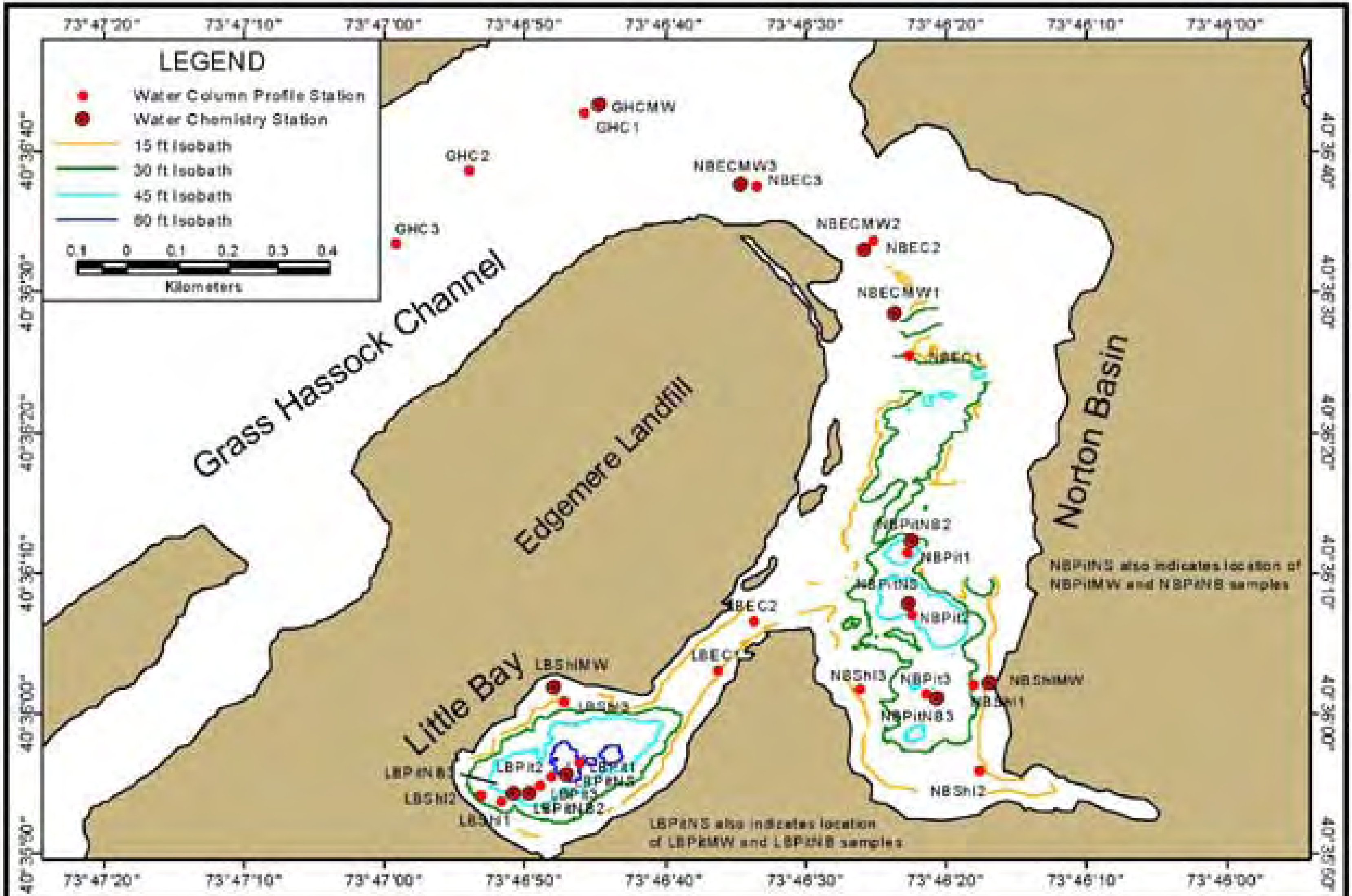

Figure 6. Water column profile and water chemistry stations during 30 August 2002 survey

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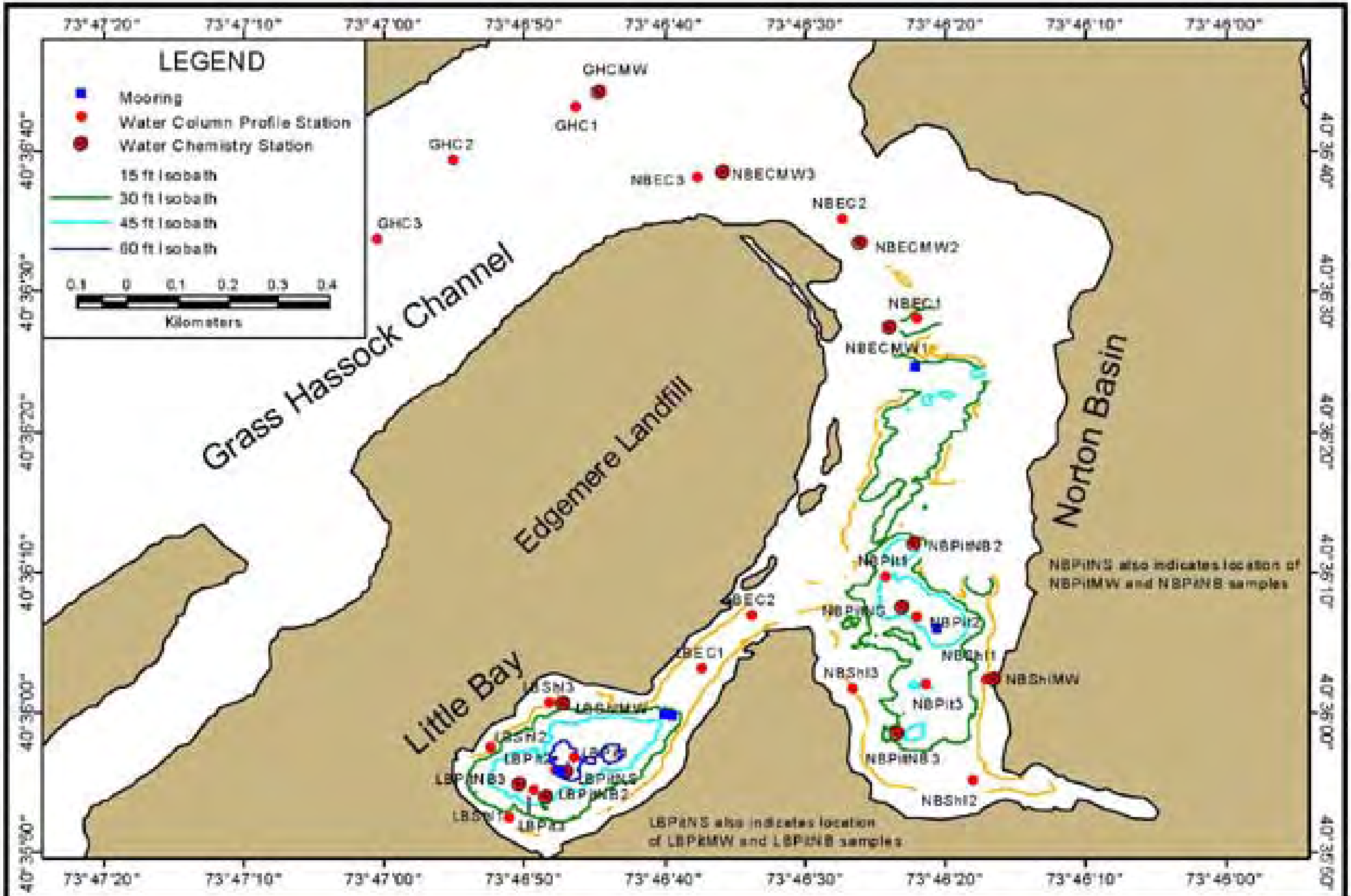

Figure 7. Water column profile, water chemistry, and current meter mooring stations during 24-25 September 2002 survey.

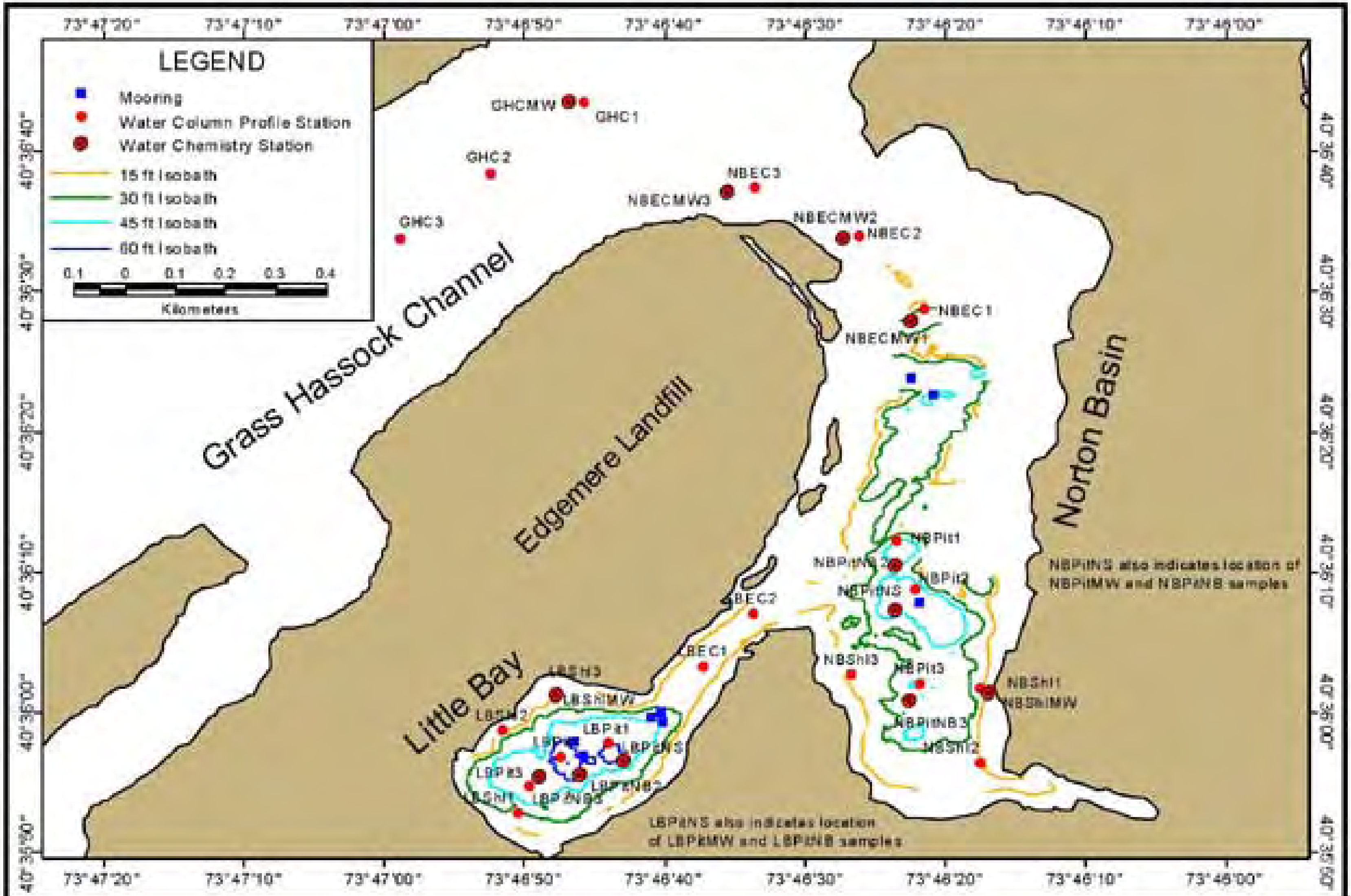

Figure 8. Water column profile, water chemistry, and current meter mooring stations during 22-23 October 2002 survey.

content in each sample was analyzed using a Chemetrics sulfide test kit immediately upon return to shore. The sulfide test is based on the methylene blue method for total soluble sulfide with a range of 0-3 ppm (mg/l) and a method detection limit of 0.15 ppm. Sulfides react with dimethyl-p-phenylenediamine in the presence of ferric chloride to produce methylene blue. The methylene blue concentration was measured on a portable colorimeter, and results are expressed as ppm (mg/l) S. Samples from the Little Bay pit near bottom required dilution in order to determine the sulfide concentration. High range sulfide samples were diluted with sulfide-free water from the site.

Table 2 summarizes the processing and analytical methods used for water chemistry. All labware used for nutrient analysis were acid washed and rinsed with deionized water (DI) prior to use. Samples were filtered through glass or plastic filter towers under a vacuum. Samples for dissolved nutrient analysis were filtered through glass fiber filters that were used for chlorophyll analysis also while the filtrate was transferred in polyethylene bottles and placed on ice. Particulate carbon and nitrogen samples were prepared from samples filtered through a glass fiber filter while biogenic silica samples were filtered through Nucleopore filters. TSS samples were prepared by filtering samples through a pre-weighed glass fiber filters. Filters containing particulate residues were folded in half to minimize sample loss, air-dried, and placed in aluminum pouches. All water samples and filters were shipped frozen in coolers to Chesapeake Bay Laboratory (CBL) in Solomons, MD for analysis.

As summarized in **Table 2**, automated wet chemistry techniques were used to analyze the water samples for the following parameters:

- Dissolved fraction – ammonium, phosphate, nitrate+nitrite, total dissolved nitrogen (TDN), total dissolved phosphorus (TDP), dissolved silica, and dissolved organic carbon (DOC).

- Particulate fraction – particulate nitrogen, particulate carbon, particulate phosphorus, biogenic silica, total and active chlorophyll, TSS, total volatile solids (TVS), and phaeophytin.

Ammonium, phosphate, and nitrate+nitrite were analyzed in a Bran and Luebbe TRAACS 800 autoanalyzer following methods by Solarzano (1969), Murphy and Riley (1962), and Wood et al. (1967), respectively. Nitrate+nitrite is reported because nitrite generally occurs in very low concentrations due to rapid oxidation to nitrate. TDN and TDP were analyzed using a Technicon Autoanalyzer II (D'Elia et al., 1977; Valderrama, 1981). Dissolved silica was analyzed using a Bran and Luebbe TrAAcs 800 autoanalyzer following the method by Armstrong et al. (1967). A Shimadzu 5000 autoanalyzer was used to determine DOC based on the method developed by Menzel and Vaccaro (1964). Particulate nitrogen and particulate carbon were determined using an Exeter Analyzer Model 240X-A analyzer according to EPA Method 440 while particulate phosphorus was analyzed using a Technicon Autoanalyzer II (Aspila et al., 1976). Biogenic silica was determined using a Technicon Autoanalyzer II according to the method of Paasche (1973). Sulfide was analyzed colorimetrically (APHA, 1979). Nutrient concentrations are expressed in mg/l of the corresponding atom, e.g., as mg N/l for ammonium, nitrate+nitrite, TDN, and particulate nitrogen; as mg P/l for phosphate, TDP, and particulate phosphorus; as mg C/l for DOC, particulate carbon; as mg Si/l for silica and biogenic silica, etc.

Table 2. Summary of processing and analytical methods for water chemistry parameters.

Variable	Sample Filtered Volume	Sample Container or Filter	Field Processing	Method/Instrument	Reference
Ammonium	250-300 ml	125-ml PE 47-mm GF/F glass fiber	Pass sample through filter under vacuum and freeze filtrate	Bran and Luebbe TrAAcs 800	Solarzano, 1969
Phosphate					Murphy and Riley, 1962
Nitrate+Nitrite					Wood et al., 1967
Total Dissolved Nitrogen				Technicon Autoanalyzer II	D'Elia et al., 1977 and Valderrama, 1981
Total Dissolved Phosphorus					
Dissolved Silica				Bran and Luebbe TrAAcs 800	Armstrong et al., 1967
Dissolved Organic Carbon				Shimadzu 5000	Menzel and Vaccaro, 1964
Particulate Nitrogen	100-150 ml	25-mm GF/F glass fiber	Pass sample through filter; fold, air-dry, and place filter in aluminum foil pouch, and freeze	Exeter Analyzer Model 240X-A	EPA Method 440
Particulate Carbon					
Particulate Phosphorus				Technicon Autoanalyzer II	Aspila et al., 1976
Biogenic Silica	50-100 ml	47-mm 0.4-µm Nucleopore	Pass sample through filter; fold and store filter in centrifuge tube, and freeze	Technicon Autoanalyzer II	Paasche, 1973
Chlorophyll and Phaeophytin	200-300 ml	47-mm GF/F glass fiber	Pass sample through filter; fold, air-dry, and place filter in aluminum foil pouch, and freeze	Model TD-700 Turner Fluorometer	Strickland and Parsons, 1972
Total Suspended Solids	300-400 ml	Pre-combusted pre-weighed 47-mm GF/F glass fiber	Pass sample through filter; fold, air-dry, and place filter in aluminum foil pouch, and freeze	Gravimetric (dry at 100°C)	APHA, 1975
Total Volatile Solids				Gravimetric (Ignite at 500°C)	APHA, 1975
Sulfide (MDL 0.3 mg S/l)	N/A	None	Colorimetric analysis	Chemetrics sulfide test kit	APHA, 1979

APHA = American Public Health Association.
EPA = Environmental Protection Agency.
PE = Polyethylene.

Total and active chlorophyll and phaeophytin were determined in acetone extracts using a Model TD-700 Turner Designs fluorometer (Strickland and Parsons, 1972). Total chlorophyll encompasses living and dead cells whereas active chlorophyll only takes the fluorescence from living cells into account. Total and active chlorophyll and phaeophytin are expressed in µg/l.

TSS was determined gravimetrically after oven-drying pre-weighed filters at 100°C and is expressed in mg/l. TVS was determined gravimetrically after ignition of pre-weighed filters at 500°C. Organic matter content was the difference between TSS and TVS and is expressed as a percentage (%) of the TSS.

3.3 CURRENTS

Current meter data was collected in stations located in Norton Basin and Little Bay in June, July, September, and October. The current meter deployment schedule is summarized in **Table 3**. In June, current meter measurements were made in pits in Little Bay and Norton Basin, while in July, current meters were deployed in the entrance channels to both embayments plus a single near bottom measurement in the Norton Basin pit. During September and October, current meter measurements were made in both pits and entrance channels in Norton Basin and Little Bay.

Current speed and direction were measured using factory-calibrated InterOceans Systems S4 current meters mounted on taut-wire moorings anchored to the bottom and suspended from fiberglass spheres. Calibration records can be found in **Appendix D**. In addition to current speed and direction, some of S4 meters were equipped with sensors for temperature, salinity, and depth also. Current meters were programmed for a 2-minute averaging period. A surface float attached to the anchor marked the position and allowed for retrieval of the moorings. The mooring configurations used in the study are shown in **Figures 9** and **10**. At the end of each deployment, the mooring was raised to the surface, and the mooring assembly moved to the next survey location or dismantled. After each survey, the mooring was dismantled, and data were downloaded from the current meters.

In June, current meter measurements were made in pit stations to compare currents in the deep areas of both embayments. A mooring equipped with three S4 current meters mounted at near surface, midwater, and near bottom was deployed in a pit in Little Bay on the morning of 19 June 2002 (**Figure 3**). The mooring was retrieved the next morning and redeployed in a pit in Norton Basin by mid-morning and retrieved mid-afternoon of the same day. The moorings were deployed at the water quality sampling stations located in deep pits in Little Bay and Norton Basin.

In July, two moorings equipped with two S4 current meters mounted at near surface and near bottom were deployed in the entrance channels to Little Bay and Norton Basin on the morning of 30 July 2002 (**Figure 5**). A third mooring with a single S4 current meter mounted at near bottom was deployed in a pit in Norton Basin. The moorings were retrieved after an approximately 6-hour deployment.

Figure 7 depicts the location of moorings deployed during the September survey. During the September survey, a mooring equipped with three S4 current meters mounted at near surface, midwater, and near bottom was deployed in a pit in Little Bay on the morning of 24 September 2002. A second mooring with two S4 current meters mounted near bottom and near surface was deployed at approximately the same time in the Little Bay Entrance

Table 3. Summary of current meter mooring deployments.

Survey	Survey Date	Norton Basin		Little Bay	
		Pit	Entrance Channel	Pit	Entrance Channel
2	19 June 2002	None	None	Twenty four hours at near surface, midwater, and near bottom	None
	20 June 2002	Six hours at near surface, midwater, and near bottom	None	None	None
3	30 July 2002	Six hours at near surface and near bottom	Six hours at midwater	Six hours at near surface and near bottom	None
5	24 September 2002	Eighteen hours at near surface, midwater, and near bottom	Eighteen hours at near surface and near bottom	Six hours at near surface, midwater, and near bottom	Six hours at near surface and near bottom
	25 September 2002	Six hours at midwater	Six hours at near surface and near bottom	None	Six hours at near surface and near bottom
6	22 October 2002	Six hours at near surface, midwater, and near bottom	Six hours at near surface and near bottom	Eighteen hours at near surface, midwater, and near bottom	Eighteen hours at near surface and near bottom
	23 October 2002	None	Six hours at near surface and near bottom	Six hours at midwater	Six hours at near surface and near bottom

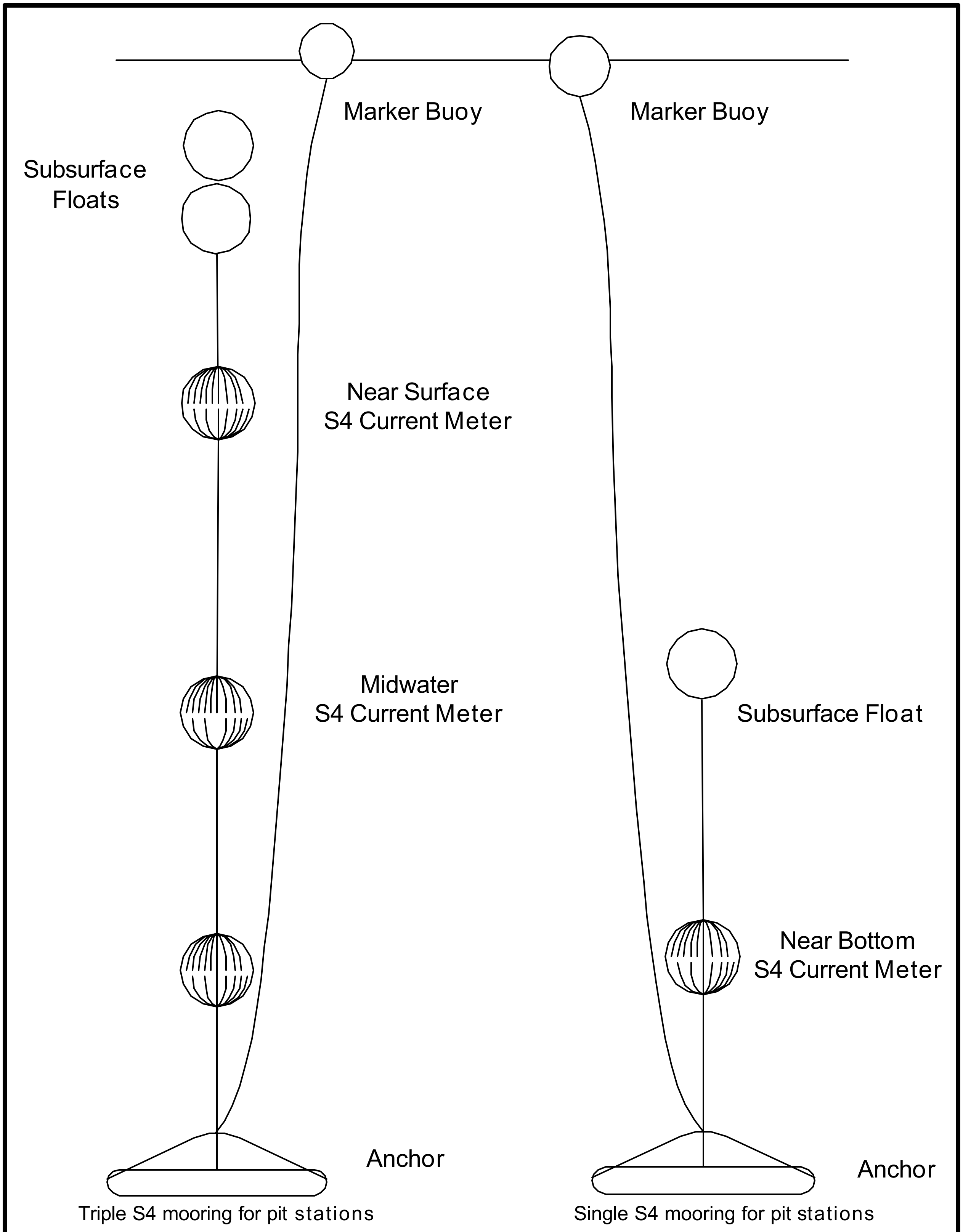

Figure 9. Configuration of current meter stations in Little Bay and Norton Basin pits with InterOceans Systems S4 current meter on a taut-wire mooring.

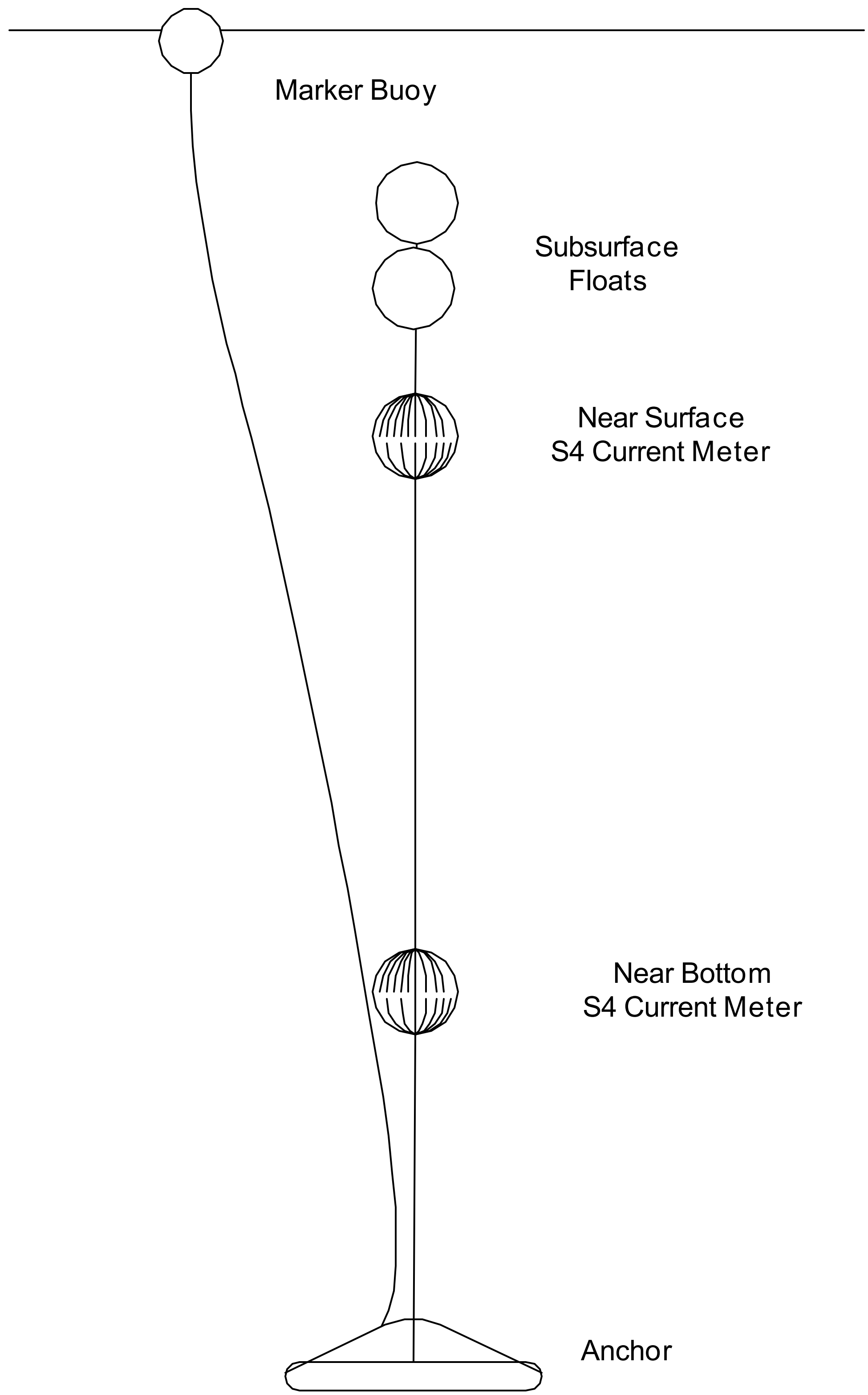

Figure 10. Configuration of current meter stations at Little Bay and Norton Basin entrance channels with two InterOceans Systems S4 current meters on a taut-wire mooring.

Channel. After a 6-hour deployment, the moorings were moved to a pit in Norton Basin and in the Norton Basin Entrance Channel in the mid-afternoon for an overnight deployment. The next morning, the mooring in the Norton Basin pit was retrieved, reconfigured into two moorings, and deployed as follows: a mooring with two S4 current meters mounted at near bottom and near surface was deployed in the Little Bay Entrance Channel and another mooring with a single S4 meter mounted at near bottom was deployed in the Little Bay pit. The mooring in the Norton Basin Entrance Channel was not moved and allowed to continue collecting data. These mooring deployments and those in October allowed comparison of simultaneous current patterns between the pits at three levels and the entrance channels at two levels.

In October, a mooring equipped with three S4 current meters mounted at near surface, midwater, and near bottom was deployed in a pit in Norton Basin on the morning of 22 October 2002 (**Figure 8**). A second mooring with two S4 current meters mounted near bottom and near surface was deployed in the Norton Basin Entrance Channel at the same time. After the 6-hour deployment in Norton Basin, the moorings were moved in the afternoon to a pit in Little Bay and the Little Bay Entrance Channel for an overnight deployment. The next morning, the mooring in the Little Bay pit was retrieved, reconfigured into two moorings, and deployed as follows: a mooring with two S4 current meters mounted at near bottom and near surface was deployed in the Norton Basin Entrance Channel and another mooring with a single S4 current meter mounted at near bottom was deployed in the Little Bay pit. The mooring in the Little Bay Entrance Channel was not moved and allowed to continue collecting data.

4.0 RESULTS

Tidal conditions, air temperature, wind speed and direction, and rainfall in the previous 72 hours in each of the surveys are summarized in **Table 4**. Only the August survey was preceded by significant rainfall.

4.1 WATER COLUMN PROFILES

Table 5 summarizes the qualitative results of the water column profiling surveys conducted from May to October. To facilitate the data presentation and focus on the most important information, only the presence of a thermocline, hypoxia (<3 mg/l O_2), and anoxia (<1 mg/l O_2) are shown in **Table 5**. Detailed information on water column parameters, e.g., temperature, salinity, DO, and turbidity by survey are provided in **Appendix A**.

A graphic summary of the qualitative results is presented in **Figure 11**, which depicts the locations of all water column profiles where a thermocline (i.e., stratified conditions), hypoxic conditions, and anoxic conditions were present. The results show definitive differences between the Little Bay pits compared with the Little Bay shallows, the Norton Basin pits and shallows, the Norton Basin Entrance Channel, Little Bay Entrance Channel, and Grass Hassock Channel. **Figure 11** shows that anoxia consistently occurred where a thermocline was present. Profiles and descriptions of the water column information by survey are provided in **Appendix A**.

4.1.1 Temperature

Temperature profiles showed that the Little Bay pits were different from other areas of the Norton Basin/Little Bay complex. While the upper water column of Little Bay showed similar temperature profiles as other areas, the lower water column had very different profiles. The differences in temperature profiles between Little Bay pits and other areas were evident in all the surveys. A thermocline and very low near bottom temperatures (less than 6°C) were persistent features of the three Little Bay pit profiles taken during each survey. There was no thermocline in Little Bay shallow stations and all stations in Norton Basin, the Norton Basin Entrance Channel, and Grass Hassock Channel through the course of the surveys.

In May, the temperature at the near surface in all profiles was about 15°C. In the upper water column of the Little Bay and Norton Basin pits and the shallow stations of both embayments, the Norton Basin Entrance Channel, and Grass Hassock Channel, temperature was constant with depth and generally comparable among the stations. Very low near bottom temperatures (less than 6°C) and a thermocline at a depth of 25 to 35 ft (i.e., stratified conditions) were observed in the Little Bay pit profiles.

During the surveys on 19 and 25 June, very low near bottom temperatures (less than 6°C) and a thermocline were present in the Little Bay pits also. Near surface temperatures were about 20°C on 19 June and 23°C to 24°C on 25 June. With the exception of the Little Bay pits, temperature was constant with depth generally in all profiles. A sharp thermocline occurred in the Little Bay pits at 25 to 30 ft, and temperature was less than 6°C near the bottom.

Table 4. Summary of conditions during water sampling, profiling, and current meter surveys.

Survey	Survey Date(s)	Time	Tide	Daily Avg. Air Temperature (°F)	Daily Avg. Wind Speed (mph)	Daily Avg. Wind Direction (degrees)	Previous 72 h Rainfall (in)
1	6 May 2002 Water Sampling	0800-1030	Ebb	58	14.7	190	0.00
1	9 May 2002 Profiling	1000-1200	Ebb	53	8.6	90	0.14
2	19 June 2002 Profiling/Currents	0900-1100	Ebb/Slack Low	70	7.1	200	0.07
2	19 June 2002 Water Sampling/Currents	1200-1300	Flood	70	7.1	200	0.07
2	20 June 2002 Currents	0900-1500	Ebb/Flood	69	5.6	140	0.07
2	25 June 2002 Profiling	0900-1100	Slack High/Ebb	77	8.3	140	0.00
3	30 July 2002 Profiling/Currents	1100-1200	Flood	87	13.5	200	0.00
3	30 July 2002 Water Sampling/Currents	1200-1330	Flood	87	13.5	200	0.00
4	30 August 2002 Profiling/Currents	1000-1200	Flood	65	7	360	2.90
4	30 August 2002 Water Sampling/Currents	1200-1400	Flood	65	7	360	2.90
5	24 September 2002 Profiling/Currents	1230-1430	Flood	68	8.5	360	0.00
5	25 September 2002 Water Sampling/Currents	0900-1030	Ebb	67	9.1	40	0.00
6	22 October 2002 Water Sampling/Currents	1130-1300	Ebb	47	6.5	130	0.00
6	23 October 2002 Profiling/Currents	0930-1130	Flood	46	10.2	340	0.00

Table 5. Summary of results from water column profiling surveys.

Survey	Area	Thermocline	Hypoxia (<3 mg/l O_2)	Anoxia (<1 mg/l O_2)
9 May	Little Bay Pit	Yes	Yes	No
	Little Bay Shallow	No	No	No
	Little Bay Entrance Channel	Not surveyed	Not surveyed	Not surveyed
	Norton Basin Pit	No	No	No
	Norton Basin Shallow	No	No	No
	Norton Basin Entrance Channel	No	No	No
	Grass Hassock Channel	No	No	No
19 June	Little Bay Pit	Yes	Yes	Yes
	Little Bay Shallow	No	Yes	Yes
	Little Bay Entrance Channel	Not surveyed	Not surveyed	Not surveyed
	Norton Basin Pit	No	Yes	Yes
	Norton Basin Shallow	No	Yes	No
	Norton Basin Entrance Channel	No	No	No
	Grass Hassock Channel	No	No	No
25 June	Little Bay Pit	Yes	Yes	Yes
	Little Bay Shallow	No	No	No
	Little Bay Entrance Channel	Not surveyed	Not surveyed	Not surveyed
	Norton Basin Pit	No	No	No
	Norton Basin Shallow	No	No	No
	Norton Basin Entrance Channel	No	No	No
	Grass Hassock Channel	No	No	No
30 July	Little Bay Pit	Yes	*	*
	Little Bay Shallow	No	*	*
	Little Bay Entrance Channel	Yes	*	*
	Norton Basin Pit	No	*	*
	Norton Basin Shallow	No	*	*
	Norton Basin Entrance Channel	No	*	*
	Grass Hassock Channel	No	*	*
30 August	Little Bay Pit	Yes	Yes	Yes
	Little Bay Shallow	No	Yes	Yes
	Little Bay Entrance Channel	No	No	No
	Norton Basin Pit	No	No	No
	Norton Basin Shallow	No	No	No
	Norton Basin Entrance Channel	No	No	No
	Grass Hassock Channel	No	No	No
24 September	Little Bay Pit	Yes	Yes	Yes
	Little Bay Shallow	No	No	No
	Little Bay Entrance Channel	No	No	No
	Norton Basin Pit	No	Yes	No
	Norton Basin Shallow	No	No	No
	Norton Basin Entrance Channel	No	Yes	No
	Grass Hassock Channel	No	No	No
23 October	Little Bay Pit	Yes	Yes	Yes
	Little Bay Shallow	No	No	No
	Little Bay Entrance Channel	No	No	No
	Norton Basin Pit	No	No	No
	Norton Basin Shallow	No	No	No
	Norton Basin Entrance Channel	No	No	No
	Grass Hassock Channel	No	No	No

* - data not available due to equipment problems.

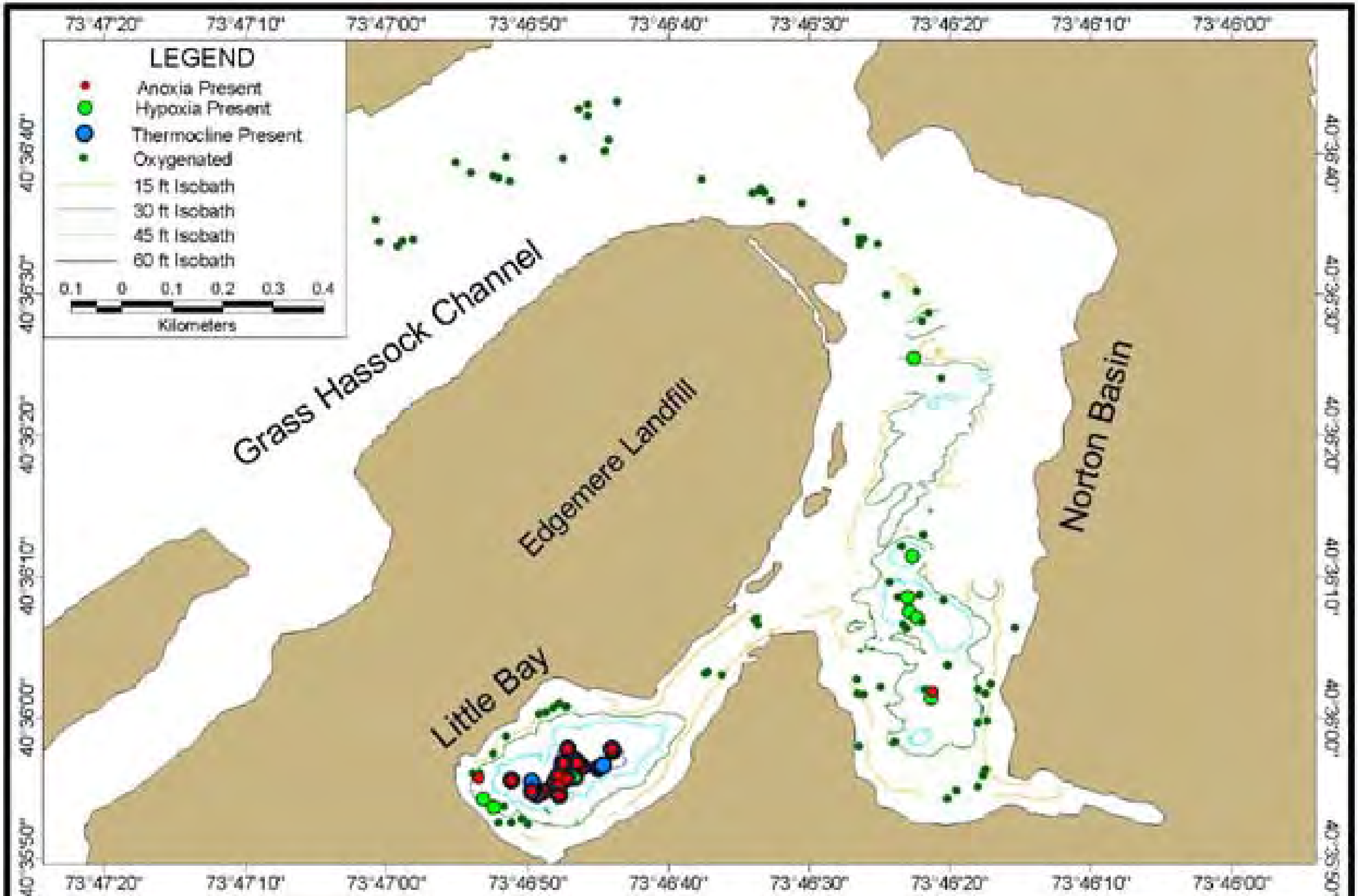

Figure 11. Summary of water column profile survey results from May to October 2002.

In July and August, very low near bottom temperatures (less than 6°C) and a thermocline were present in the Little Bay pits. Temperature at the near surface in all stations was about 25°C in July and only slightly decreased with depth. In August, there were slightly lower near surface temperatures, which were attributed to recent rains, although a few feet below the surface, the temperature was 25°C in most profiles and remained relatively unchanged with depth except in the Little Bay pits. Below the thermocline, temperature was about 6°C. There was no thermocline evident in other stations except in a profile from the Little Bay Entrance Channel located near Little Bay where there was cold water also on the bottom in August.

Temperatures were lower in September and October compared to the previous surveys. Near surface temperature was about 22°C in all profiles in September and 14°C to 16°C in October. Temperature remained constant with depth in general in all profiles except in the Little Bay pits. There was a sharp thermocline in the pits in Little Bay and below a depth of 45 ft, the temperature was about 6°C. In contrast, there was no thermocline evident in other stations. Conditions in the Little Bay Entrance Channel were similar among stations other than the Little Bay pits.

4.1.2 Dissolved Oxygen

DO profiles also showed that the three Little Bay pits greatly differed from other areas of the Norton Basin/Little Bay complex. Below the thermocline in the Little Bay pits, hypoxia and anoxia were persistent through the course of the surveys. Hypoxic conditions also occurred occasionally in the Little Bay shallows and in the Norton Basin pits. Anoxia was not observed in the Little Bay shallow stations except for a single station in June. Anoxic conditions did not occur in Norton Basin, the Norton Basin Entrance Channel, and in Grass Hassock Channel.

In May, while the upper water column was supersaturated with respect to oxygen in all stations (i.e., well oxygenated), there were nearly anoxic conditions in the Little Bay pit below the thermocline. In the Norton Basin pits, lower DO levels (4 to 5 mg/l) occurred near the bottom compared to the surface, but hypoxic (<3 mg/l DO) or anoxic conditions were not evident. Profiles from all other stations showed well oxygenated conditions from the surface to the bottom.

During the 19 June survey, the DO in the upper water column was 4 to 6 mg/l in all stations, while there were anoxic conditions in the Little Bay pits below the thermocline. One Little Bay shallow station showed anoxic conditions on the bottom. Hypoxic conditions also occurred in the Little Bay shallows and in the Norton Basin pit. On 25 June, DO at the near surface in all the profiles ranged from 5 to 8 mg/l, but below a depth of 25 ft, hypoxic and anoxic conditions were present in the pits in Little Bay. In contrast, profiles from the shallow stations in Little Bay, the shallow stations in Norton Basin, the Norton Basin Entrance Channel, and the Grass Hassock Channel revealed DO values that usually were greater than 4 mg/l. DO on the bottom of Norton Basin pits decreased to 3 mg/l, but hypoxic or anoxic conditions did not occur. DO data during the July survey are not presented due to equipment problems.

In August, the upper water column in the Little Bay and Norton Basin pits and the entire water column in the Little Bay and Norton Basin shallows, the Little Bay Entrance Channel, the Norton Basin Entrance Channel, and the Grass Hassock Channel were well oxygenated. DO at the near surface ranged between 5 to 7 mg/l in all the profiles. The pits in Little Bay showed anoxic conditions below a depth of 35 ft. DO also was lower at depth in the Norton Basin pits but remained greater than 2 mg/l.

The upper water column in the Norton Basin and Little Bay pits and much of the entire water column in the other areas in September and October were well oxygenated with DO ranging from 4 to 7 mg/l. The Little Bay pits were anoxic below the thermocline. In contrast, DO on the bottom of the Norton Basin pits remained above 4 mg/l.

4.1.3 Salinity

With respect to salinity, the Little Bay pits did not differ greatly from all other areas in the Norton Basin/Little Bay complex but showed slightly higher salinity in the near bottom. Salinity patterns were unremarkable in general. Over the course of the surveys, salinity at the surface in all stations generally was 25 ppt to 27 ppt and varied with depth by only a few ppt through the water column. Salinity remained unchanged with depth in general except for a slight increase with depth in the pits. Salinity increased slightly in the Little Bay pit stations at the level of the thermocline. In August, salinity was lower near the surface (24 ppt to 25 ppt) due to recent rains and then increased to 28 ppt at depth in deeper profiles from the pits in both embayments.

4.1.4 Turbidity

Although turbidity in the upper water column of the Little Bay pits was similar to all other areas, turbidity profiles at depth from the Little Bay pits differed with profiles from all other stations. While turbidity generally remained constant with depth in all other stations, there was a peak in turbidity at the thermocline and above the anoxic layer in the Little Bay pits. There were slight variations in turbidity over the course of the surveys.

In May, turbidity in all stations ranged from 5 to 8 NTUs and was relatively constant with depth except in the Little Bay pits where profiles showed slightly higher values (10 to 14 NTUs) near the thermocline or anoxic layer. On 19 June, turbidity was lower in all profiles (1.4 to 4.2 NTUs) except for slightly higher values in the turbidity peak (7 to 13 NTUs) above the thermocline in the Little Bay pits. On 25 June and in the July and August surveys, there was similar turbidity as on 19 June and relatively constant turbidity also through the water column in most of the profiles. The peak in turbidity associated with the thermocline in the Little Bay pits also occurred.

In September, turbidity generally was higher (3.7 to 18.1 NTUs) in all stations than in previous surveys and showed little variability with depth except in the Little Bay pits. Turbidity profiles in the Little Bay pits showed peaks of 34 to 75 NTUs near the thermocline. Turbidity in October ranged from 4.8 to 15.1 NTUs among all stations except in the Little Bay pits, which showed turbidity peaks of 44 to 48 NTUs.

4.1.5 pH

In June and August when a Hydrolab H2O Multiprobe was used for the profiles, measurements of pH were made. Although the pH decreased with depth in the Little Bay and Norton Basin pits, the difference between the near surface and near bottom pH was minimal. In June, the differences between the average near surface and near bottom pH were similar in both pits. In August, the previous rain decreased salinity and pH at the near surface and obscured the differences in pH between the near surface and near bottom.

4.2 WATER CHEMISTRY

Table 6 provides a qualitative summary of the results of the water chemistry analyses conducted each month from May to October. Only summary information regarding ammonium, phosphate, nitrate+nitrite, TDN, TDP, dissolved silica, biogenic silica, sulfide, total chlorophyll, and phaeophytin are provided in **Table 6**. These parameters show marked differences between Little Bay pit near bottom samples and samples from the upper water column of Little Bay and other areas of the Norton Basin/Little Bay Complex. The remaining water chemistry parameters (particulate nitrogen, particulate phosphorus, particulate carbon, organic matter content, and TSS) showed no definitive differences and are not summarized in **Table 6**, although a brief qualitative summary is provided on the results of analyses for these parameters in the text. Active chlorophyll is not discussed because it is a component of total chlorophyll and followed the same trends.

The qualitative summary of the water chemistry data is presented in **Table 6** to facilitate examination and interpretation of the data. The terms low, medium, and high listed in **Table 6** are comparisons of data for each parameter for a sample **relative to other samples collected during the same monthly survey**, i.e., “low” means that the concentration of the parameter in this sample was low relative to other samples collected during the survey; “intermediate” means that the concentration of the parameter in this sample was intermediate (between low and high values) relative to other samples collected during the survey; and “high” means that the concentration of the parameter in this sample was high relative to other samples collected during the survey.

A graphic summary of the results of the water chemistry analyses from all surveys is presented in **Figure 12**. Near bottom stations with high ammonium, phosphate, TDN, TDP, and silica and low nitrate+nitrite, biogenic silica, total chlorophyll, and phaeophytin are shown. Near surface, midwater, and near bottom stations characterized by low ammonium, phosphate, TDN, TDP, and silica and high nitrate+nitrite, biogenic silica, total chlorophyll, and phaeophytin are depicted also. For clarity, samples showing intermediate parameter values are not included. The results show marked differences between the Little Bay pits compared with the Little Bay shallows, the Norton Basin pits and shallows, the Norton Basin Entrance, and Grass Hassock Channel. Descriptive summaries and detailed information on all water chemistry parameters by survey are provided in **Appendix B**.

4.2.1 Nutrients

Ammonium and phosphate showed a marked difference between Little Bay pit near bottom samples compared to all other samples throughout all the surveys. In all surveys, near bottom samples from the Little Bay pit consistently had high ammonium and phosphate compared to all other samples collected. In contrast, ammonium and phosphate were low consistently in the Norton Basin pit near bottom samples in all surveys. Ammonium and phosphate in the Norton Basin pit and shallow samples were similar in general to those of the Norton Basin Entrance Channel and Grass Hassock Channel samples. All additional Little Bay pit near bottom samples collected in July, August, September, and October also showed high ammonium and phosphate, while additional Norton Basin pit near bottom samples showed low ammonium and phosphate. Ammonium in the near bottom Little Bay pit samples ranged from 4 mg N/l to 10 mg N/l, while all other samples had 1 mg N/l or less of ammonium. Phosphate ranged from 1 mg P/l to 2.7 mg P/l in Little Bay pit near bottom samples, while all other samples were less than 0.5 mg P/l. From May to August,

Table 6. Summary of results of water sample analyses for selected parameters.

Parameter	Area	Survey					
		05-May	19-Jun	30-Jul	30-Aug	24-Sep	23-Oct
Ammonium/Phosphate	Little Bay Pit Near Surface	Low	Low	Low	Low	Low	Low
	Little Bay Pit Midwater	Interm.	Interm.	Interm.	Interm.	Low	Low
	Little Bay Pit Near Bottom	High	High	High	High	High	High
	Little Bay Shallow Midwater	Low	Low	Low	Low	Low	Low
	Norton Basin Pit Near Surface	Low	Low	Low	Low	Low	Low
	Norton Basin Pit Midwater	Low	Low	Low	Low	Low	Low
	Norton Basin Pit Near Bottom	Low	Low	Low	Low	Low	Low
	Norton Basin Shallow Midwater	Low	Low	Low	Low	Low	Low
	Norton Basin Entrance Channel Midwater (3)	Low	Low	Low	Low	Low	Low
	Grass Hassock Channel Midwater	NS	Low	Low	Low	Low	Low
Nitrate+ Nitrite	Little Bay Pit Near Surface	Interm.	High	High	High	High	High
	Little Bay Pit Midwater	Interm.	High	Low	Low	High	High
	Little Bay Pit Near Bottom	Low	Low	Low	Low	Low	Low
	Little Bay Shallow Midwater	High	High	High	High	High	High
	Norton Basin Pit Near Surface	High	High	High	High	High	High
	Norton Basin Pit Midwater	High	Interm.	High	High	High	High
	Norton Basin Pit Near Bottom	High	Interm.	High	High	High	High
	Norton Basin Shallow Midwater	High	High	High	High	High	High
	Norton Basin Entrance Channel Midwater (3)	High	High	High	High	High	High
	Grass Hassock Channel Midwater	NS	High	High	High	High	High
TDN/TDP	Little Bay Pit Near Surface	Low	Low	Low	Low	Low	Low
	Little Bay Pit Midwater	Interm.	Interm.	Low	Low	Low	Low
	Little Bay Pit Near Bottom	High	High	High	High	High	High
	Little Bay Shallow Midwater	Low	Low	Low	Low	Low	Low
	Norton Basin Pit Near Surface	Low	Low	Low	Low	Low	Low
	Norton Basin Pit Midwater	Interm.	Low	Low	Low	Low	Low
	Norton Basin Pit Near Bottom	Interm	Interm.	Low	Low	Low	Low
	Norton Basin Shallow Midwater	Interm.	Interm.	Low	Low	Low	Low
	Norton Basin Entrance Channel Midwater (3)	Low	Low	Low	Low	Low	Low
	Grass Hassock Channel Midwater	NS	Low	Low	Low	Low	Low*

Table 6. (Continued).

Parameter	Area	Survey					
		05-May	19-Jun	30-Jul	30-Aug	24-Sep	23-Oct
Silica	Little Bay Pit Near Surface	Low	Low	Low	Low	Low	Low
	Little Bay Pit Midwater	Interm.	Interm.	Low	Low	Low	Low
	Little Bay Pit Near Bottom	High	High	High	High	High	High
	Little Bay Shallow Midwater	Interm.	Low	Low	Low	Low	Low
	Norton Basin Pit Near Surface	Low	Low	Low	Low	Low	Low
	Norton Basin Pit Midwater	Interm.	Low	Low	Low	Low	Low
	Norton Basin Pit Near Bottom	Interm.	High	Low	Low	Low	Low
	Norton Basin Shallow Midwater	Low	Low	Low	Low	Low	Low
	Norton Basin Entrance Channel Midwater (3)	Low	Low	Low	Low	Low	Low
	Grass Hassock Channel Midwater	NS	Low	Low	Low	Low	NA
Biogenic Silica	Little Bay Pit Near Surface	High	High	Interm.	Interm.	High	High
	Little Bay Pit Midwater	Interm.	Interm.	Interm.	Interm.	High	High
	Little Bay Pit Near Bottom	Low	Low	Low	Low	Low	Low
	Little Bay Shallow Midwater	High	High	High	Interm.	High	High
	Norton Basin Pit Near Surface	High	High	High	High	High	High
	Norton Basin Pit Midwater	High	Interm.	Interm.	Interm.	High	High
	Norton Basin Pit Near Bottom	High	High	High	Interm.	High	High
	Norton Basin Shallow Midwater	High	High	High	High	High	High
	Norton Basin Entrance Channel Midwater (3)	High	High	High	High	High	High
	Grass Hassock Channel Midwater	NS	High	High	High	High	NA
Sulfide	Little Bay Pit Near Surface	None	None	None	None	None	None
	Little Bay Pit Midwater	None	None	None	Low	Low	None
	Little Bay Pit Near Bottom	High	High	High	High	High	High
	Little Bay Shallow Midwater	None	None	None	None	None	None
	Norton Basin Pit Near Surface	None	None	None	None	None	None
	Norton Basin Pit Midwater	None	None	None	None	None	None
	Norton Basin Pit Near Bottom	None	None	None	None	None	None
	Norton Basin Shallow Midwater	None	None	None	None	None	None
	Norton Basin Entrance Channel Midwater (3)	None	None	None	None	None	None
	Grass Hassock Channel Midwater	NS	None	None	None	None	None

Table 6. (Continued).

Parameter	Area	Survey					
		05-May	19-Jun	30-Jul	30-Aug	24-Sep	23-Oct
Total Chlorophyll	Little Bay Pit Near Surface	High	High	Interm.	High	High	High
	Little Bay Pit Midwater	Low	Low	Low	Interm.	Interm.	High
	Little Bay Pit Near Bottom	Low	Low	Low	Low	Low	Low
	Little Bay Shallow Midwater	High	High	Interm.	High	High	High
	Norton Basin Pit Near Surface	High	High	High	High	High	High
	Norton Basin Pit Midwater	High	Low	Low	Interm.	High	High
	Norton Basin Pit Near Bottom	High	Low	Low	Interm.	High	High
	Norton Basin Shallow Midwater	High	High	Interm.	High	High	High
	Norton Basin Entrance Channel Midwater (3)	High	High	High	High	High	High
	Grass Hassock Channel Midwater	NS	High	Interm.	High	High	NA
Phaeophytin	Little Bay Pit Near Surface	High	High	High	High	High	High
	Little Bay Pit Midwater	High	Interm.	Interm.	Interm.	High	High
	Little Bay Pit Near Bottom	Low	Low	Low	Low	Low	Low
	Little Bay Shallow Midwater	High	Interm.	High	High	High	High
	Norton Basin Pit Near Surface	High	High	High	High	High	High
	Norton Basin Pit Midwater	High	Interm.	High	High	High	High
	Norton Basin Pit Near Bottom	High	High	High	High	High	High
	Norton Basin Shallow Midwater	High	High	High	High	High	High
	Norton Basin Entrance Channel Midwater (3)	High	High	High	High	High	High
	Grass Hassock Channel Midwater	NS	High	High	High	High	NA

* - TDN not measured
NA – not analyzed
NS – not sampled
Interm. – Intermediate

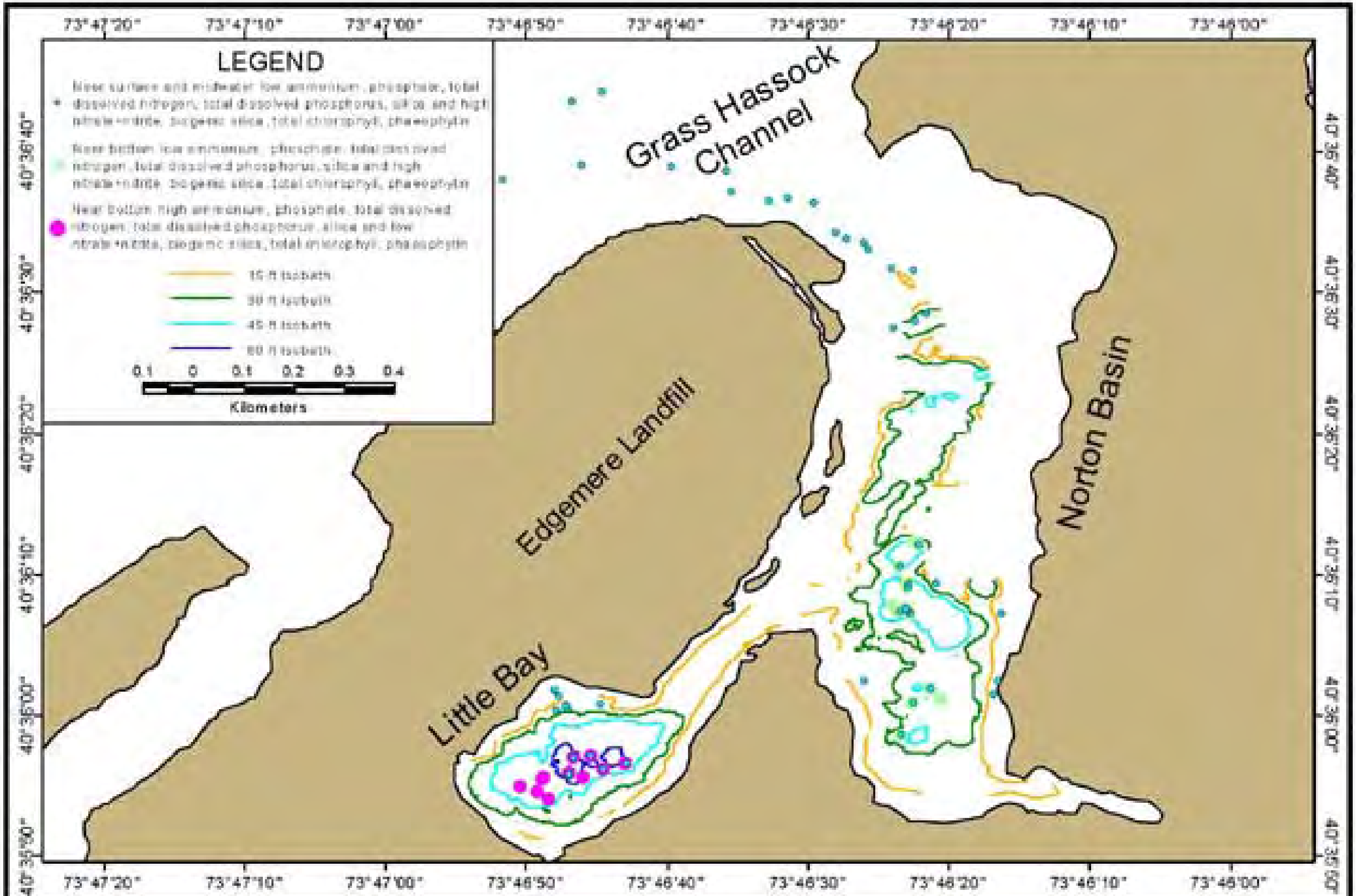

Figure 12. Summary of water chemistry survey results from May to October 2002. Samples showing "intermediate" values are not depicted.

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ammonium and phosphate were intermediate in the Little Bay pit midwater sample but low in September and October. Samples from the near surface in the Little Bay and Norton Basin pits, the Little Bay and Norton Basin shallows, and the Norton Basin Entrance Channel showed low ammonium and phosphate in all surveys. **Figure 13** shows ammonium and phosphate in Little Bay pit near bottom samples relative to other samples through the course of the surveys (for clarity, Norton Basin pit midwater and near surface and shallow midwater samples are not included in **Figure 13**). Ammonium in Little Bay pit near bottom was higher in samples collected in June through October (8 to 10 mg N/l) compared to May (4 mg N/l), while there were slightly higher phosphate levels in the later surveys (e.g., 1 mg P/l in May versus 2.5 mg P/l in October). In contrast, there were no evident trends in the Norton Basin pit near bottom and Norton Basin Entrance Channel samples over time.

The lower water column in Little Bay also showed an evident and consistent difference in nitrate+nitrite compared to other areas, i.e., nitrate+nitrite was low in Little Bay pit near bottom samples compared to all other samples. The near bottom samples from the Little Bay pit ranged from 0.001 mg N/l to 0.05 mg N/l and showed a decreasing trend over the course of the surveys. Except for the Little Bay pit near bottom samples, all other samples showed similar nitrate+nitrite (0.04 mg N/l to 0.56 mg N/l). In samples other than the Little Bay pit near bottom samples, higher nitrate+nitrite values generally occurred in May, September, and October compared to June, July, and August. All additional Little Bay pit near bottom samples collected in July, August, September, and October also showed low nitrate+nitrite, while additional Norton Basin pit near bottom samples showed high nitrate+nitrite. Nitrate+nitrite in the Norton Basin pit and shallow samples were similar in general to those of the Norton Basin Entrance Channel and Grass Hassock Channel samples. **Figure 13** shows nitrate+nitrite in Little Bay pit near bottom samples relative to other samples through the course of the surveys. Nitrate+nitrite levels in Little Bay pit near bottom samples remained low through the course of the surveys compared to other samples. In October, nitrate+nitrite was almost absent in the Little Bay pit near bottom samples, while nitrate+nitrite almost doubled in other samples compared to May.

TDN and TDP in the Little Bay pit near bottom samples were very different from all other samples. The high ammonium and phosphate in the Little Bay pit near bottom samples were reflected also in their markedly higher TDN and TDP compared to other samples. Intermediate TDN and TDP occurred in the midwater samples from the Little Bay pit and Norton Basin pit near bottom and midwater samples during May and June. TDN in the Little Bay pit near bottom samples ranged from 3.8 mg N/l to 7.7 mg N/l compared to 0.4 mg N/l to 1.8 mg N/l in all other samples, while TDP ranged from 1.0 mg P/l to 2.7 mg P/l in the Little Bay pit near bottom samples and 0.04 mg P/l to 0.5 mg P/l in all other samples. TDN and TDP in the Little Bay pit near bottom samples increased through the course of the surveys, while there was little change in other samples (**Figure 14**). There was good agreement in the additional Little Bay pit near bottom samples collected in July, August, September, and October. The additional samples had high TDN (TDN was not analyzed in additional October samples) and TDP, while additional Norton Basin pit near bottom samples showed low TDN and TDP. The Norton Basin pit and shallow samples were similar in terms of TDN and TDP to samples from the Norton Basin Entrance Channel and Grass Hassock Channel.

There were no evident differences in particulate nitrogen among samples. Particulate nitrogen ranged from 0.1 mg N/l to 0.4 mg N/l among all samples in all surveys. Except for the Little Bay pit near bottom sample, particulate nitrogen in all samples was in similar concentrations as dissolved inorganic nitrogen (i.e., ammonium and nitrate+nitrite). There

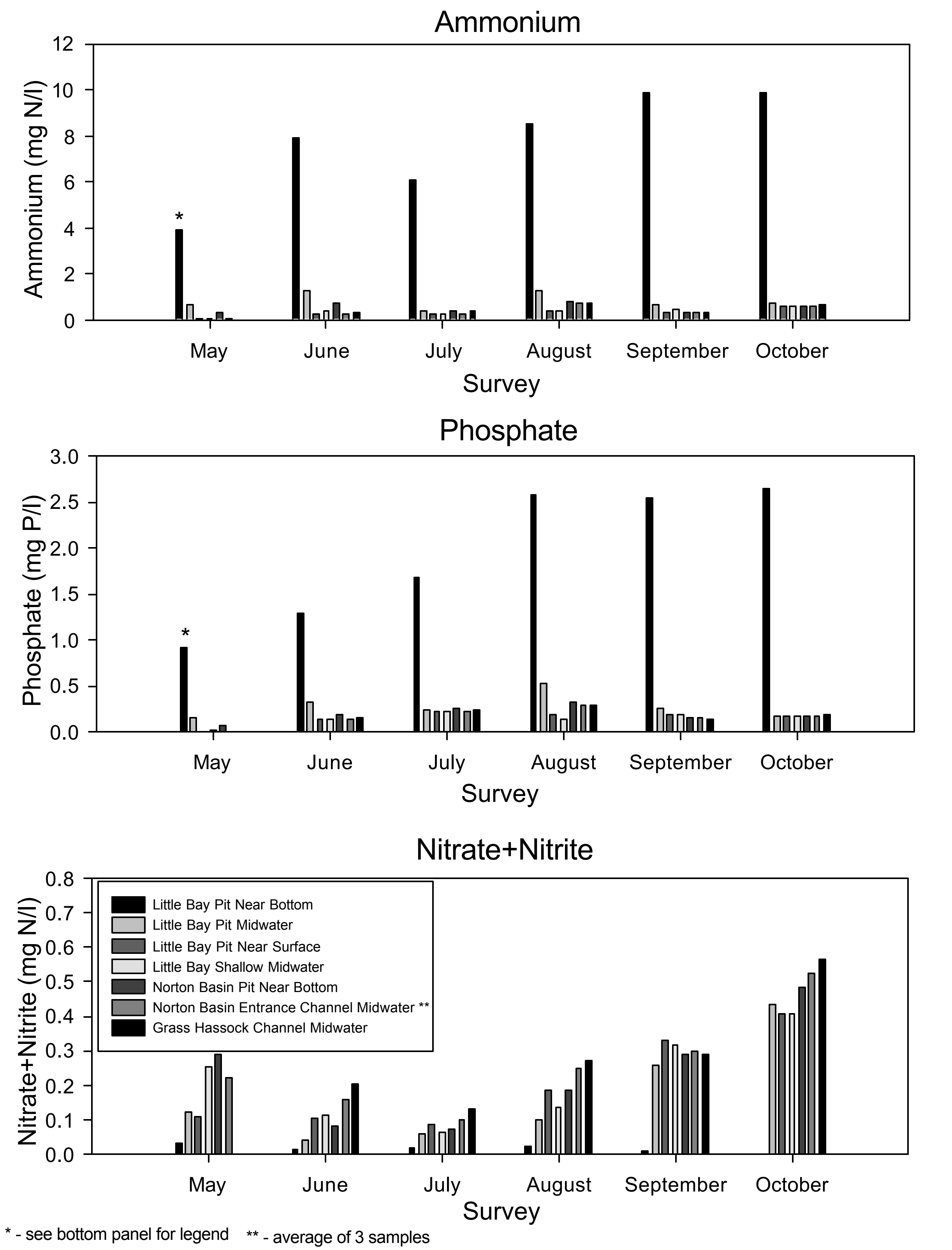
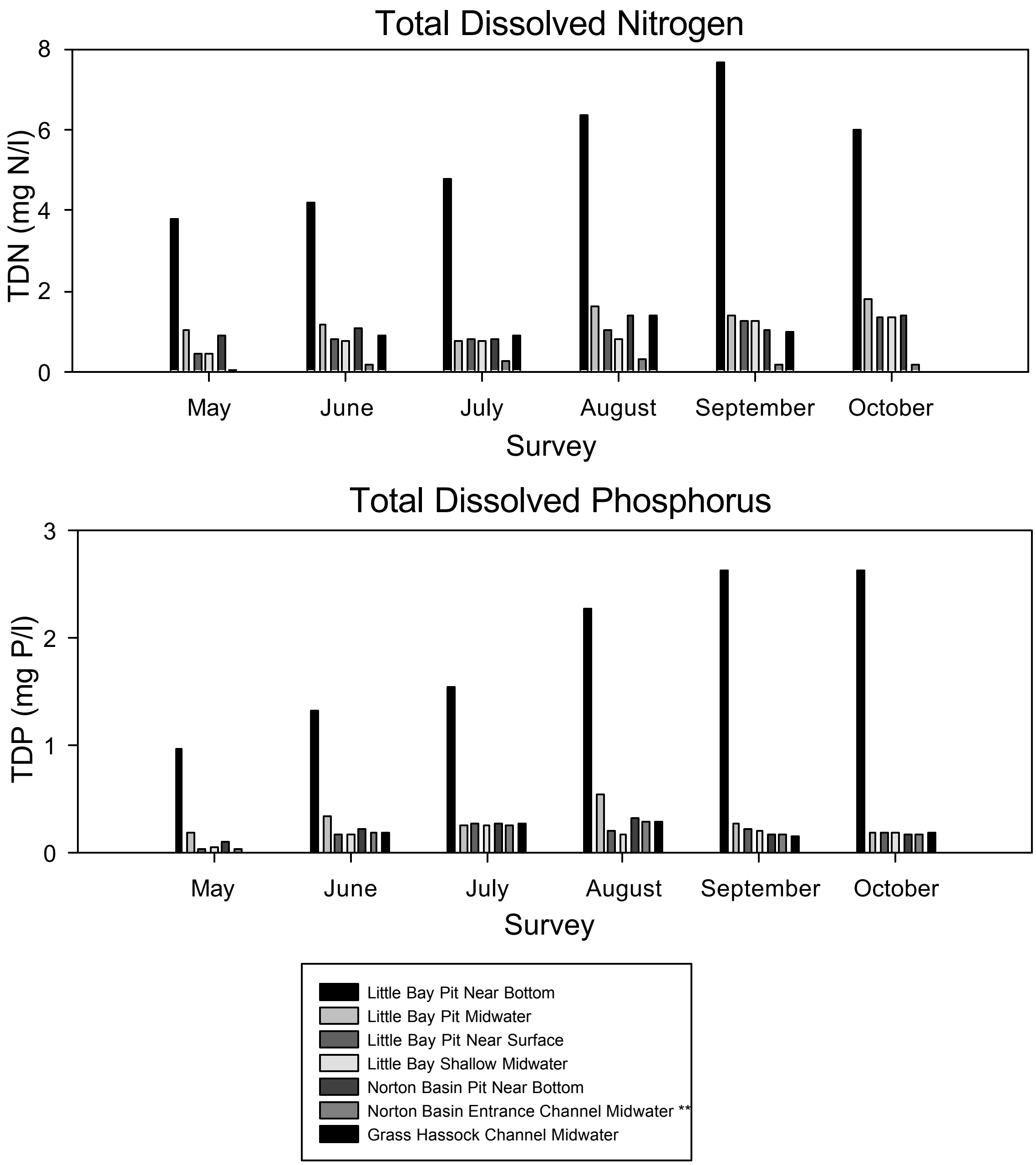


Figure 13. Ammonium, phosphate, and nitrate+nitrite in Little Bay pit near bottom, midwater, and near surface, Little Bay shallow midwater, Norton Basin pit near bottom, Norton Basin Entrance Channel midwater, and Grass Hassock Channel midwater samples.



** - average of 3 samples

Figure 14. Total dissolved nitrogen and total dissolved phosphorus in Little Bay pit near bottom, midwater, and near surface, Little Bay shallow midwater, Norton Basin pit near bottom, Norton Basin Entrance Channel midwater, and Grass Hassock Channel midwater samples.

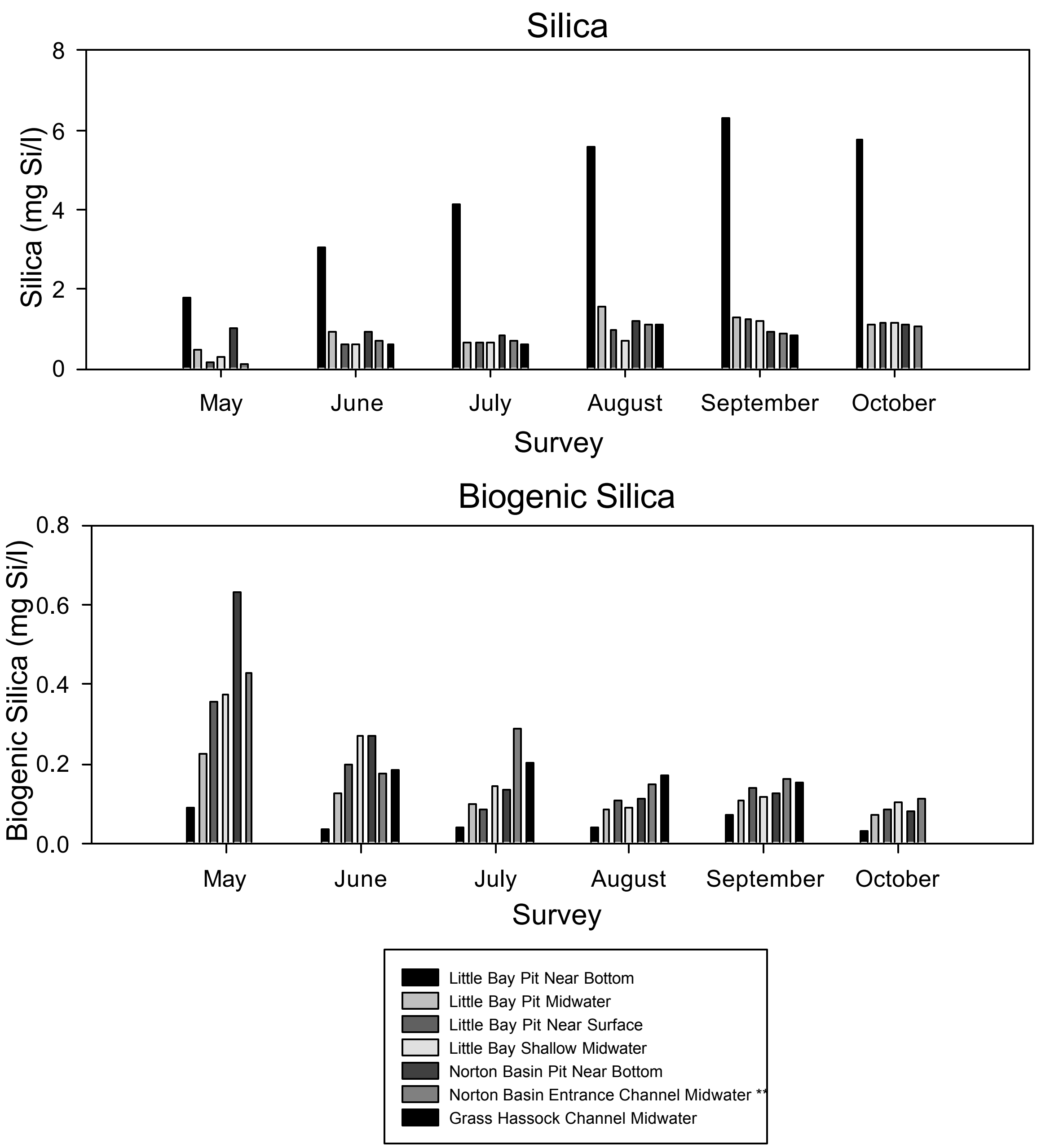
were no evident trends in particulate nitrogen between surveys. The range in particulate phosphorus among all samples in all surveys was 0.02 mg P/l to 0.09 mg P/l. Although particulate phosphorus was low in the Little Bay pit near bottom sample compared to other samples during some surveys, the differences were not consistent.

Dissolved silica showed a marked difference between Little Bay pit near bottom samples compared to all other samples through all the surveys. Dissolved silica in the near surface samples in the Little Bay and Norton Basin pits, in the Little Bay and Norton Basin shallow stations, and the Norton Basin Entrance Channel stations were low consistently. During some surveys, intermediate dissolved silica occurred in the Little Bay pit and Norton Basin pit midwater samples, while all other samples showed low levels. With the exception of the May survey, when dissolved silica in the near bottom Little Bay and Norton Basin pit samples were comparable (e.g., 1.0 mg Si/l in Norton Basin versus 1.8 mg Si/l in Little Bay), dissolved silica was higher consistently and markedly in the Little Bay pit near bottom samples compared to all other samples. There was good agreement in dissolved silica in the additional Little Bay and Norton Basin pit near bottom samples collected in July, August, September, and October. Dissolved silica in the Norton Basin pit and shallow samples was similar in general to those of the Norton Basin Entrance Channel and Grass Hassock Channel samples. Dissolved silica in the Little Bay pit near bottom samples ranged from 1.9 mg Si/l to 6.3 mg Si/l, while other samples had less than 1.5 mg Si/l. As shown in **Figure 15**, dissolved silica in the Little Bay pit near bottom samples increased through the course of the surveys (e.g., 1.8 mg Si/l in May and 3 mg Si/l in June versus 6.3 mg Si/l in September and 5.8 mg Si/l in October). Also, there was generally lower dissolved silica in all other samples in May compared to October.

Little Bay pit near bottom samples were markedly different in biogenic silica compared to other samples. Biogenic silica is present in the siliceous skeletons of diatoms and are an indicator of diatom populations. Biogenic silica was low in the Little Bay pit near bottom samples, while biogenic silica was high in all other samples including the Norton Basin pit near bottom samples. Biogenic silica in the additional Little Bay and Norton Basin pit near bottom samples collected in July, August, and September was consistent also. Biogenic silica in the Norton Basin pit and shallow samples was similar in general to those of the Norton Basin Entrance Channel and Grass Hassock Channel samples. Biogenic silica in the Little Bay pit near bottom sample ranged from 0.05 mg Si/l to 0.1 mg Si/l, while in all other samples the range was 0.1 mg Si/l to 0.6 mg Si/l in all surveys. Biogenic silica was intermediate in the Little Bay pit midwater sample in some surveys. Except for the Little Bay pit near bottom samples, which showed little consistent trends over time, biogenic silica in most samples was higher in general during May, June, and July (0.1 mg Si/l to 0.6 mg Si/l) compared to August, September, and October (0.09 mg Si/l to 0.18 mg Si/l), indicating higher diatom populations in earlier surveys (i.e., spring phytoplankton bloom). **Figure 15** shows the low biogenic silica in Little Bay pit near bottom samples changing little over time compared to other samples.

4.2.2 Chlorophyll and Phaeophytin

Little Bay pit near bottom samples consistently differed in chlorophyll and phaeophytin from all other samples, while the Norton Basin pit and shallow samples were similar in general to those of the Norton Basin Entrance Channel and Grass Hassock Channel. Total chlorophyll was low in the Little Bay pit near bottom samples through the course of the surveys (0.7 to 3.4 μg/l), while other samples had much higher total chlorophyll (2.4 to 50 μg/l). There were also low total chlorophyll values in the Little Bay pit midwater



** - average of 3 samples

Figure 15. Dissolved silica and biogenic silica in Little Bay pit near bottom, midwater, and near surface, Little Bay shallow midwater, Norton Basin pit near bottom, Norton Basin Entrance Channel midwater, and Grass Hassock Channel midwater samples.

samples and the Norton Basin pit near bottom and midwater samples during June, July, and August. When the Little Bay pit near bottom and midwater samples are not considered, chlorophyll values were highest during May (approximately 35 to 50 µg/l) compared to any other months. The lowest total chlorophyll values occurred in October when the range was 4.9 to 7.8 µg/l in samples other than the Little Bay pit near bottom sample. From June to September, total chlorophyll values generally ranged between 10 and 20 µg/l in samples other than those with low total chlorophyll mentioned previously. **Figure 16** shows low total chlorophyll in Little Bay pit near bottom samples changing little over time compared with other samples.

Similar differences were noted in phaeophytin concentrations with Little Bay pit near bottom samples (0.9 to 4.1 µg/l) showing markedly lower concentrations compared to all other samples (approximately 2 to 24 µg/l). The low phaeophytin in Little Bay pit near bottom samples over the course of the surveys is shown relative to other samples in **Figure 16**.

4.2.3 Dissolved Organic Carbon, Particulate Carbon, and Organic Matter

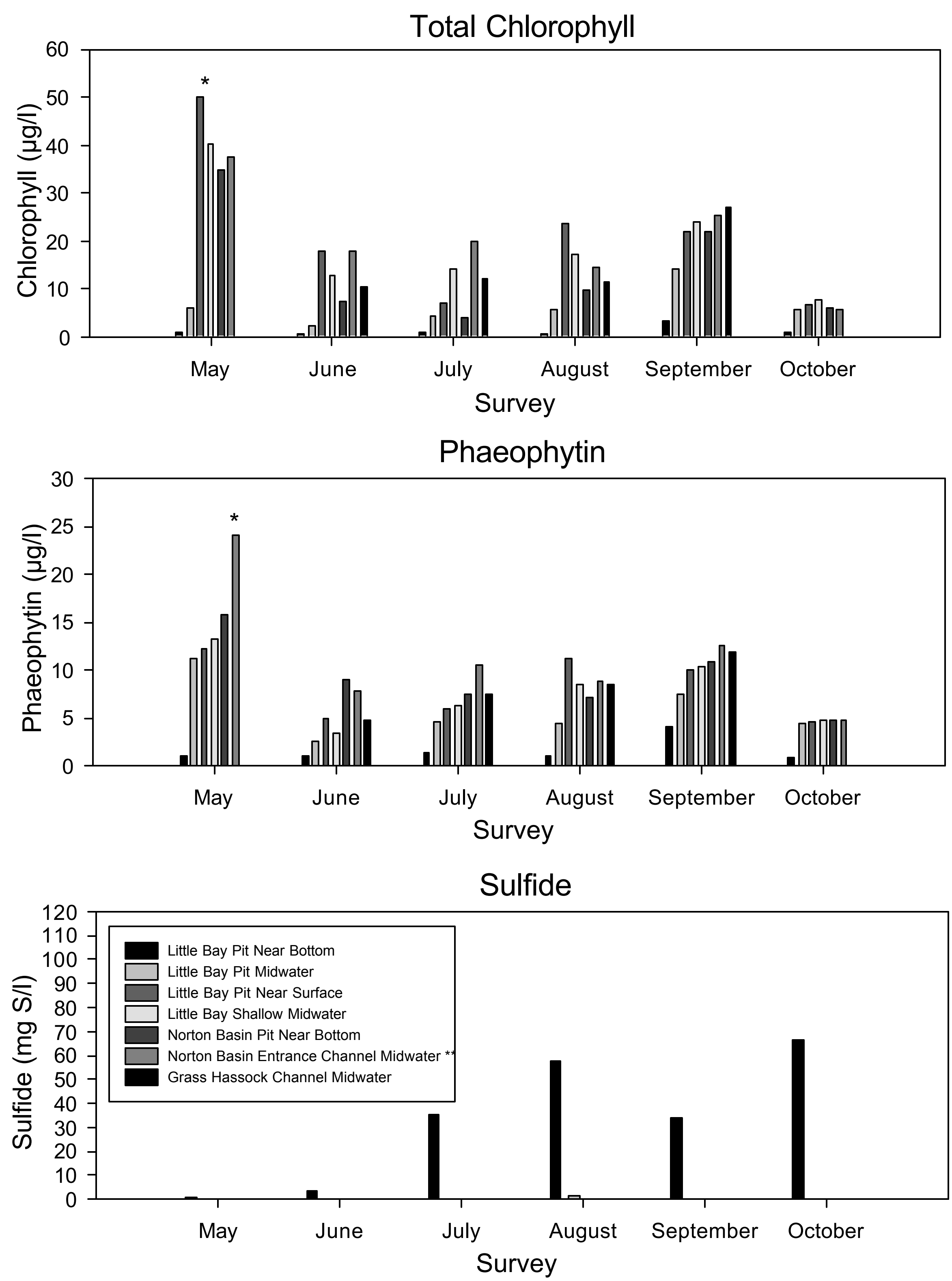
There were no evident trends in DOC. DOC ranged from 2.3 mg C/l to 5.4 mg C/l among samples in all surveys. Similarly, there were no apparent differences in particulate carbon among samples in all surveys. Particulate carbon ranged from 0.5 mg C/l to 2.7 mg C/l. The Little Bay pit near bottom samples did not show consistent differences in DOC and particulate carbon with other samples through the survey. DOC and particulate carbon varied little also through the course of the surveys. Organic matter content did not show evident differences also among all samples and ranged from 63% to 90% among samples in all surveys, with no apparent trends over time.

4.2.4 Sulfide

There were dramatic differences in sulfide between the Little Bay pit near bottom samples compared to all other samples. The high sulfide in Little Bay pit near bottom samples over the course of the surveys is shown relative to other samples in **Figure 16**. Sulfide was present at high concentrations in the Little Bay pit near bottom samples in all surveys. Sulfide was not detected in all other samples except for low levels in the Little Bay pit midwater sample in August and in trace concentrations (0.1 mg S/l) in Norton Basin pit near bottom and midwater samples during some months. Sulfide increased markedly in Little Bay pit near bottom samples through the course of the surveys from 0.7 mg S/l in May to 35 mg S/l in July, and to 70 mg S/l in October.

4.2.5 TSS

There were no evident differences in TSS found among samples during the surveys. Except for the May survey when TSS was lower in a few samples including the Little Bay pit near bottom sample compared to other samples, TSS was similar generally in most samples through the course of the surveys. This agrees with the similar turbidity values among all stations observed in the profiles. There were no evident differences in TSS among samples collected in May, June, and July when TSS ranged from 9 to 83 mg/l. TSS was lower during August, September, and October when TSS ranged from 17 to 68 mg/l (when possible outliers are not included, the range is 17 to 25 mg/l).



* - see bottom panel for legend. ** - average of 3 samples

Figure 16. Total chlorophyll, phaeophytin, and sulfide in Little Bay pit near bottom, midwater, and near surface, Little Bay shallow midwater, Norton Basin pit near bottom, Norton Basin Entrance Channel midwater, and Grass Hassock Channel midwater samples.

4.2.6 Relationships Between Water Chemistry Parameters

Relationships between water chemistry parameters can reveal contributory factors leading to observed conditions. Evident and significant relationships between selected water chemistry parameters are shown in **Figures 17** to **22**, where data from all surveys and all stations are plotted. There were significant correlations (r^2>0.80, p<0.05) between ammonium and phosphate, TDN, TDP, dissolved silica, and sulfide (**Figures 17** to **19**). Ammonium had a negative relationship with nitrate+nitrite, biogenic silica, and total chlorophyll. **Figures 20** and **21** show that phosphate had a significant correlation (r^2>0.80, p<0.05) with TDP, TDN, silica, and sulfide and a negative correlation with nitrate+nitrite (r^2=0.24, p<0.05), biogenic silica (r^2=0.16, p<0.05), and total chlorophyll (r^2=0.44, p<0.05). The evident relationships between the water chemistry parameters would be expected from a highly stratified waterbody with limited circulation and low temperatures dominated by anaerobic decomposition producing high concentrations of mineralized nutrients. The large differences in nutrient concentrations between the Little Bay pit near bottom samples compared to all other samples can be seen in the clustering of points encircled in **Figures 17** to **22**.

As common products of organic matter decomposition, ammonium and phosphate would be expected to be highly correlated, and since ammonium and phosphate make up almost all of the dissolved nitrogen and phosphorus in the Little Bay pits, they also would be highly correlated with TDN and TDP, respectively (**Figures 17** to **20**). **Figures 18** and **20** show that nitrate+nitrite is low when high concentrations of ammonium and phosphate are present (e.g., in the Little Bay pit near bottom samples) and that nitrate+nitrite is high when ammonia and phosphate are low (e.g., in the pit midwater and near surface samples, the shallow midwater samples, and the Norton Basin Entrance Channel samples).

Ammonium and phosphate would be expected also to be highly correlated with dissolved silica (**Figure 18**) if the organic matter being decomposed were derived from diatoms and/or if the dissolved silica was not being actively assimilated by diatom production. There is a negative relationship between ammonium and biogenic silica (**Figure 18**). It is likely that dissolved silica is high because there is decomposition of organic matter, and there are no diatom populations (as indicated by low biogenic silica) to assimilate the dissolved silica in the Little Bay pit near bottom station. Except for the unlikely possibility of a flux of silica from the Little Bay pit near bottom sediments, there is no other likely explanation for the high silica levels in the Little Bay pits.

The significant correlation between sulfide and ammonium (**Figure 19**; r^2=0.84, p<0.05) and phosphate (**Figure 22**; r^2=0.91, p<0.05) in the Little Bay pit near bottom samples (i.e., sulfide increased when ammonium and phosphate increased) suggests a relationship between processes that generate ammonium and phosphate with processes generating sulfide. The data indicate that the Little Bay pits are dominated by anaerobic decomposition processes that produce high concentrations of ammonium, phosphate, and sulfide.

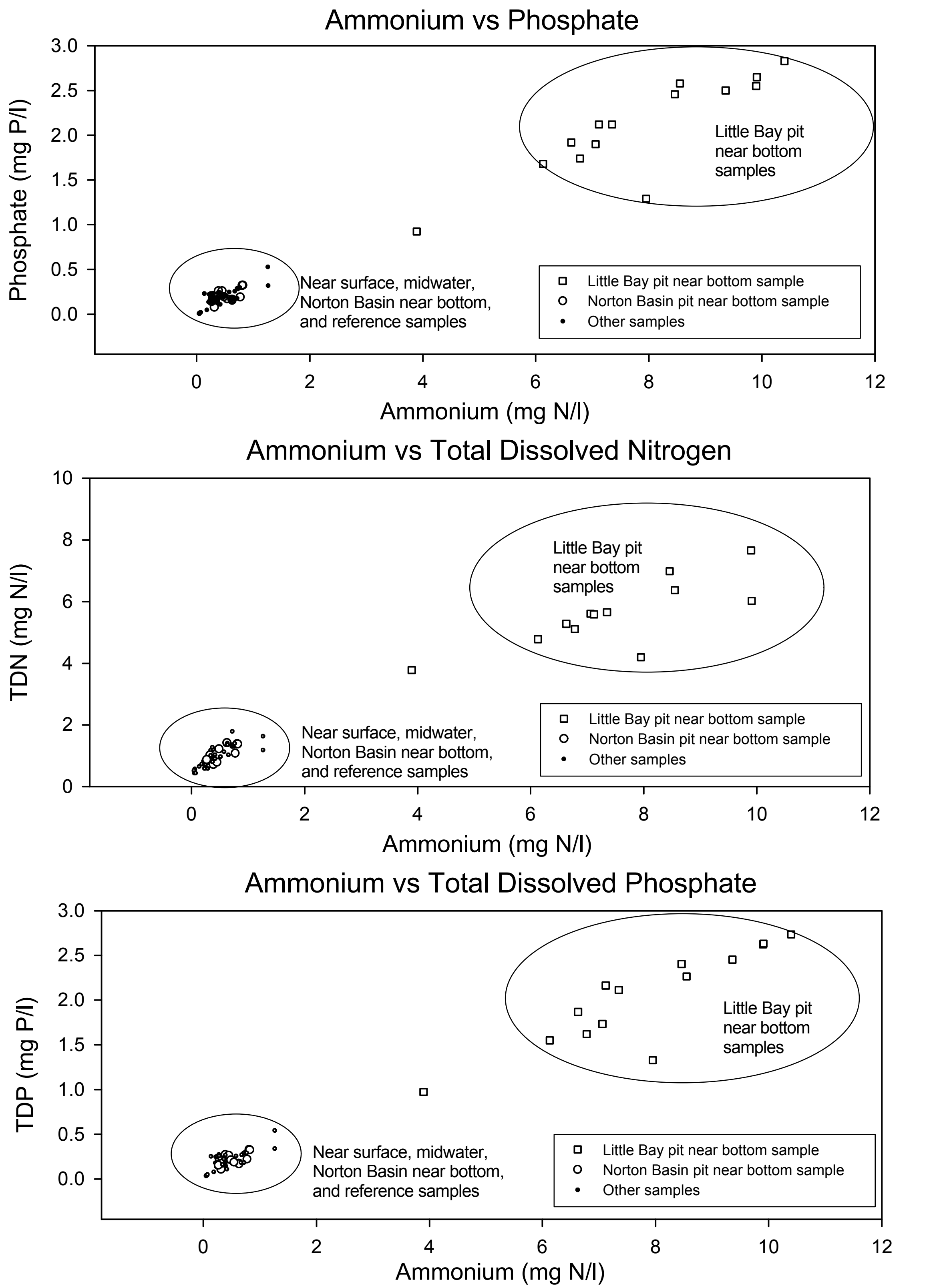


Figure 17. Relationships between ammonium and phosphate, total dissolved nitrogen, and total dissolved phosphate. Data from all surveys and stations are plotted.

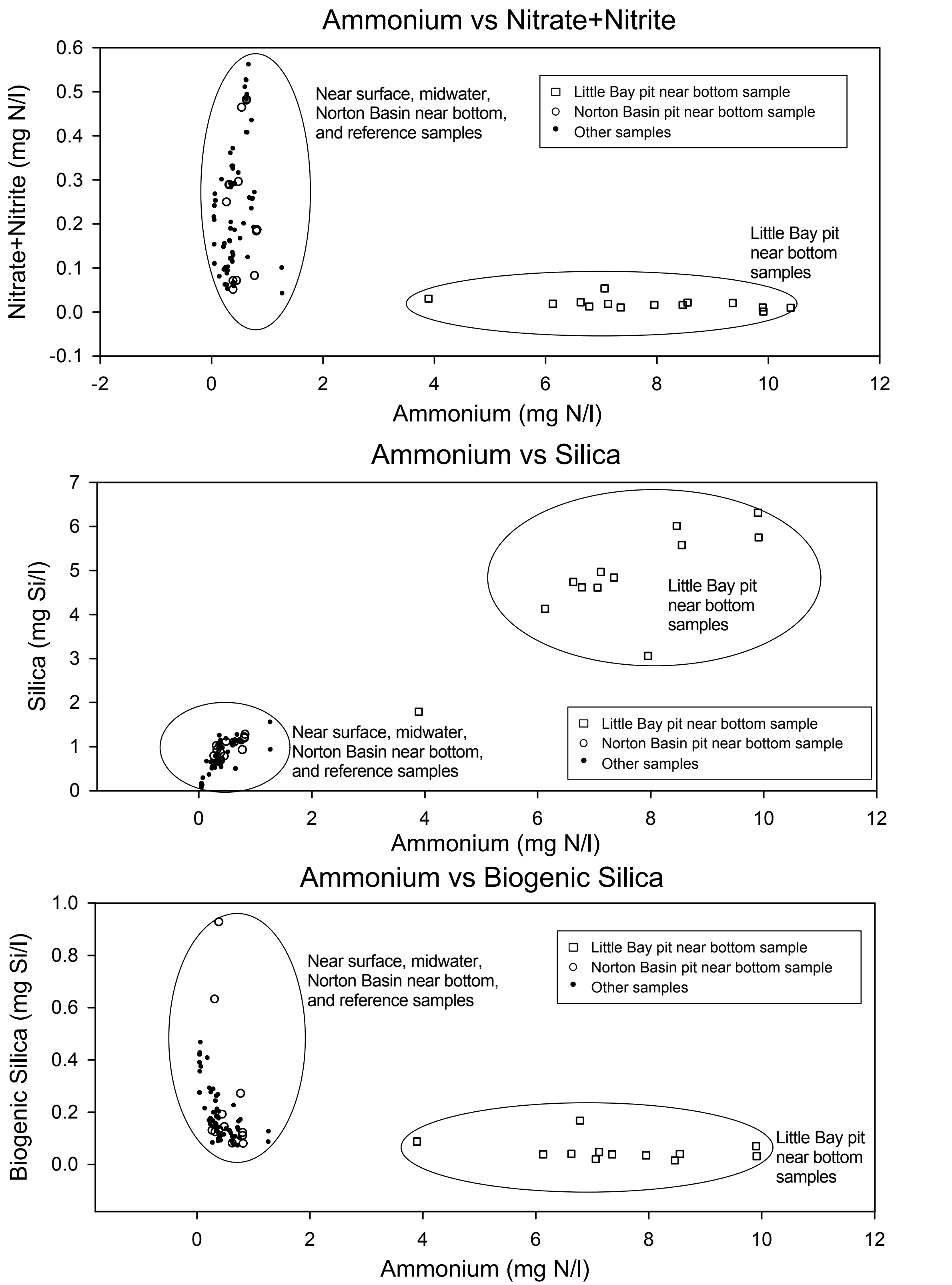


Figure 18. Relationships between ammonium and nitrate+nitrite, silica, and biogenic silica. Data from all surveys and stations are plotted.

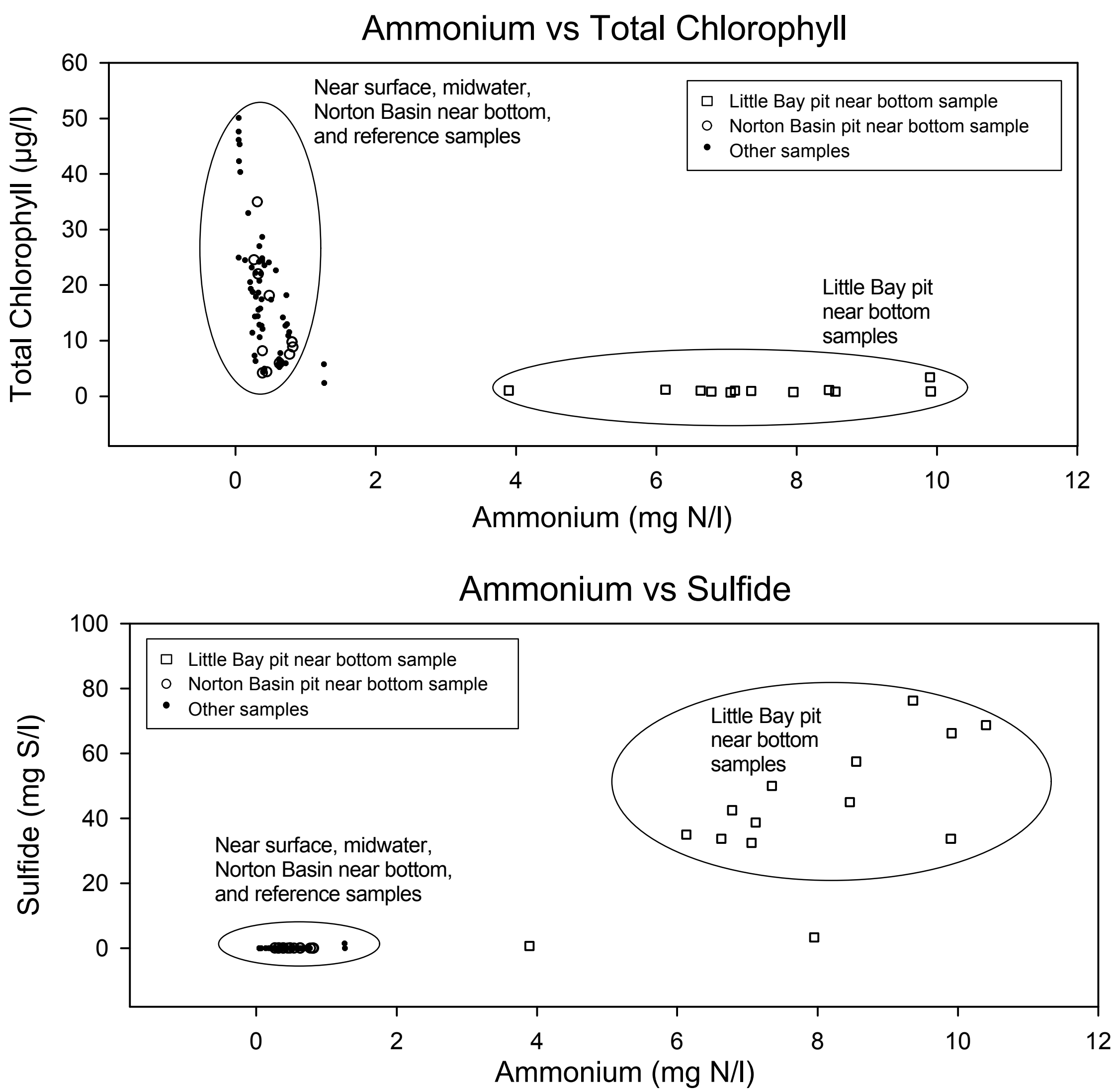


Figure 19. Relationships between ammonium and total chlorophyll and sulfide. Data from all surveys and stations are plotted.

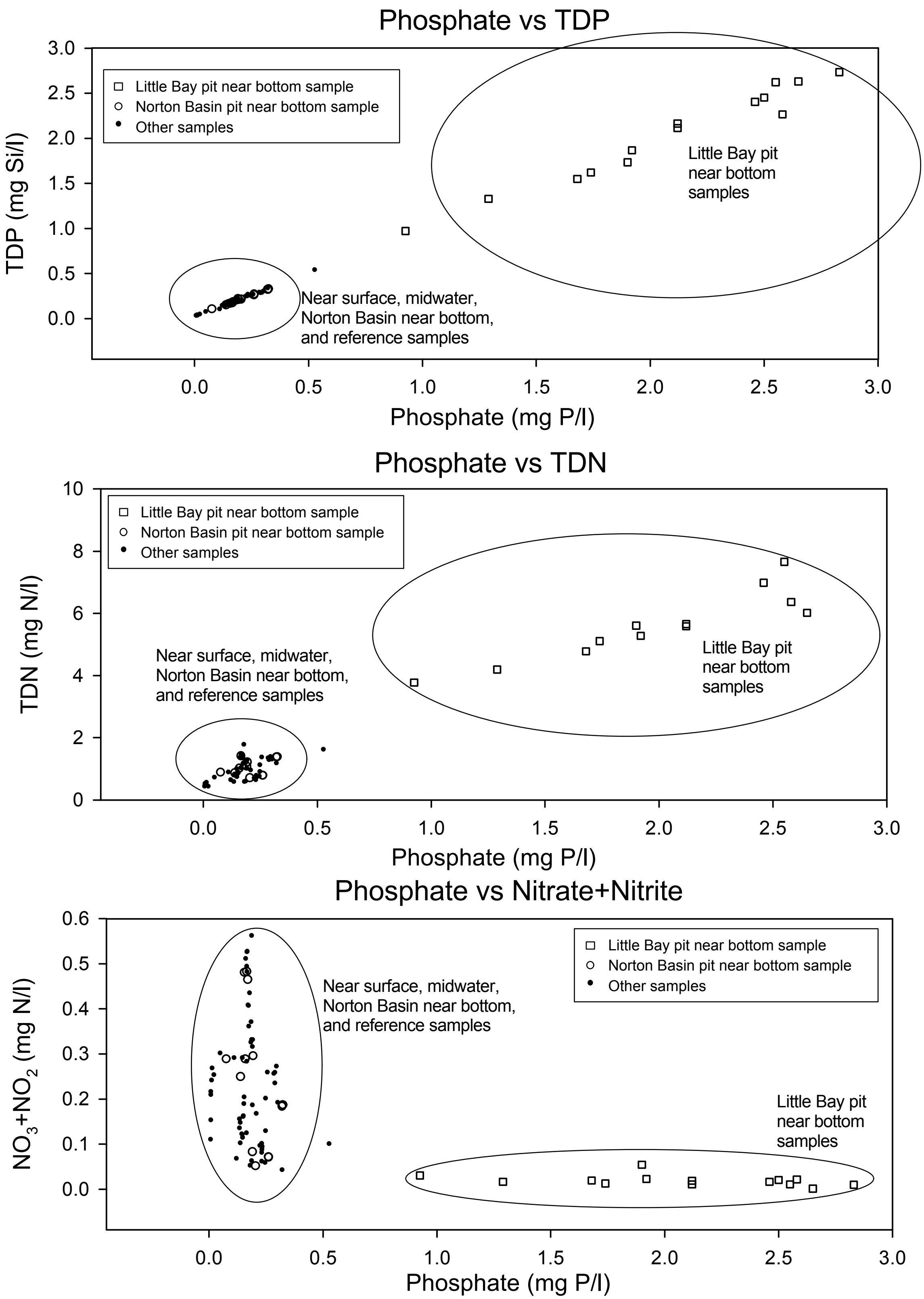


Figure 20. Relationships between phosphate and total dissolved phosphorus, total dissolved nitrogen, and nitrate+nitrite. Data from all surveys and stations are plotted.

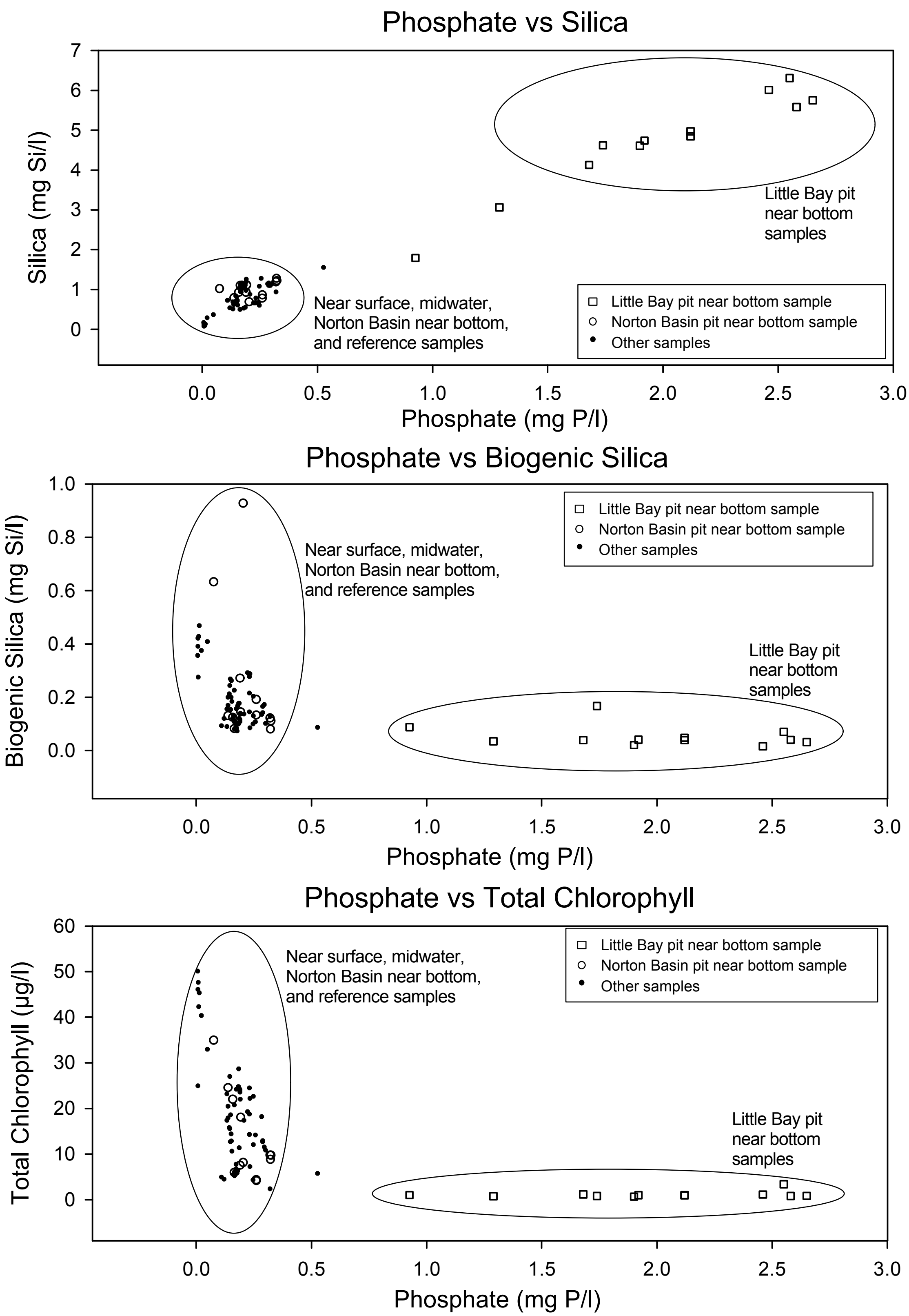


Figure 21. Relationships between ammonium and silica, biogenic silica, and total chlorophyll. Data from all surveys and stations are plotted.

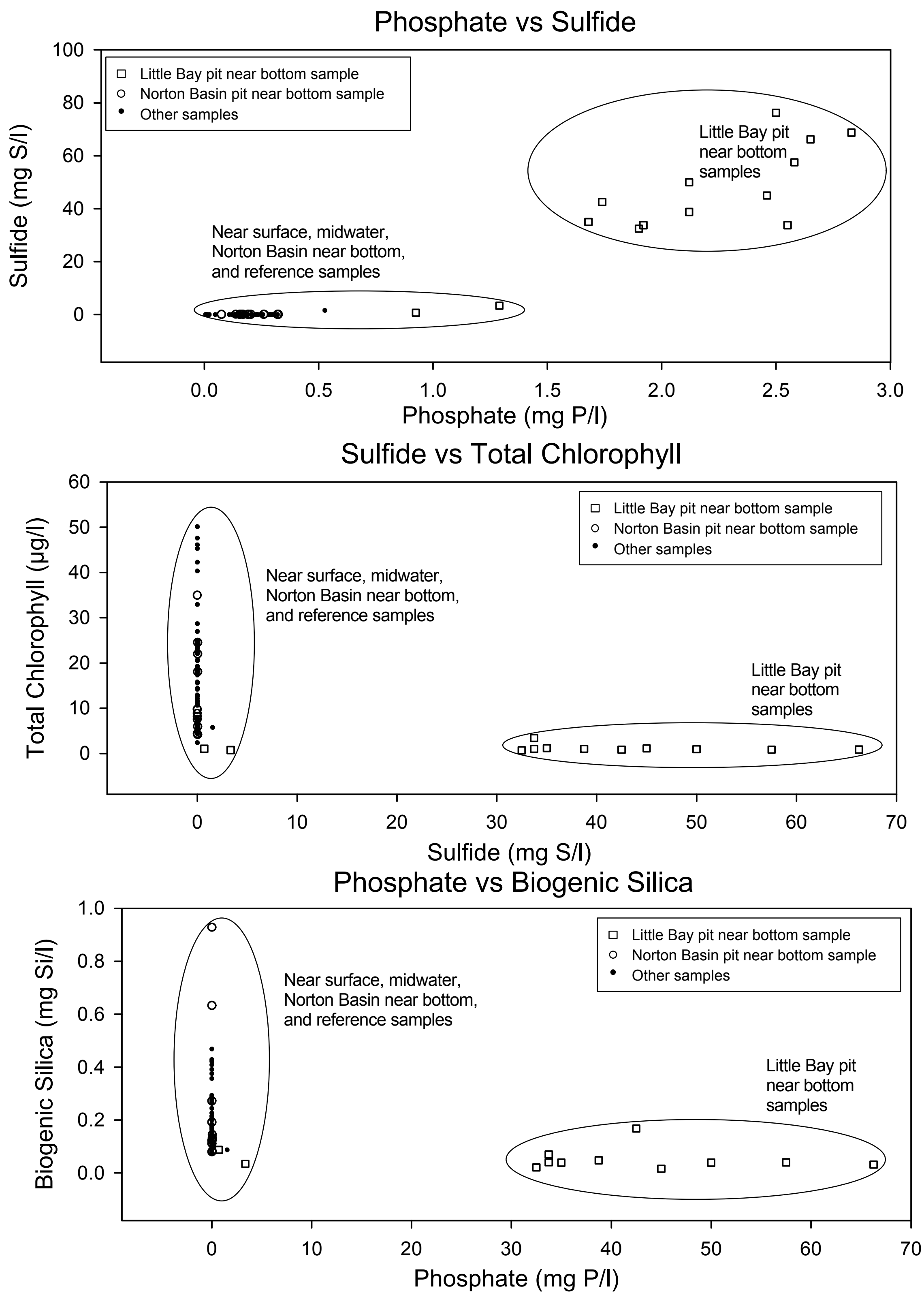


Figure 22. Relationships between phosphate and sulfide, sulfide and total chlorophyll, and sulfide and biogenic silica. Data from all surveys and stations are plotted.

4.3 CURRENTS

Deployment conditions and a summary of the current meter surveys conducted in June, July, September, and October are presented in **Table 7**. The start and end times are provided for current data recovered for each deployment, although actual soak time may be slightly longer. Average current speed and direction for the duration of the current meter deployments, along with average temperature, salinity, and depth for current meters that were equipped with corresponding sensors are provided. Differences in the deployment duration (i.e., tidal phases) were not taken into account in the calculation of current speed and direction averages. Average current speed and direction at the phases of the tide that allow comparisons between the pits and entrance channels are shown in **Figures 23** to **28**. A graphic of the current vectors for and frequency distributions of current speeds in 1 cm/s intervals for each survey are provided in **Appendix C**.

In June, current meters were deployed in the Little Bay and Norton Basin pits at near surface, midwater, and near bottom and showed very low current speeds (generally less than 8 cm/s) in all levels of both pits. Currents in the Little Bay pit were measured through two tidal cycles, while in Norton Basin, measurements were made the next day during a slack low and flood tide (**Table 7**). Average current speed in the Little Bay pit was higher at near bottom than at near surface or midwater. In Little Bay, the average current direction was different at midwater compared to the near surface and near bottom, while in Norton Basin, average current direction varied at all levels. Average current speed was highest at midwater in Norton Basin. Average currents speeds in the three levels generally were higher in Norton Basin than in Little Bay. While there was a very large difference in average temperature between the near surface and near bottom in Little Bay where it was almost 15°C colder in the near bottom, there was little temperature difference in Norton Basin between the near surface and near bottom. Average salinity was slightly higher in the Little Bay pit near bottom than the near surface, while in Norton Basin pit, the near bottom salinity was lower than the near surface. Although there were differences in current speeds between Norton Basin and Little Bay, both embayments showed low currents and complex flow patterns. **Figure 23** shows average current speed and direction during flood tide in the Little Bay and Norton Basin pits in June. There were higher current speeds in the Norton Basin pit, particularly at midwater compared to Little Bay. Current directions differed at the three levels in the Little Bay pit and did not correspond to expected tidal direction. In the Norton Basin pit, the current direction in the near surface and midwater corresponded generally to the direction of tidal flow but not near bottom. A southerly wind averaging 7 knots blowing counter to the tidal direction may have dampened tidal flow in the near surface in Little Bay and Norton Basin.

In the July survey, current meters mounted on moorings for the near surface and near bottom were deployed in the Little Bay and Norton Basin Entrance Channels for approximately 6 hours through a flood and ebb tide. A single current meter was placed also at near bottom in the Norton Basin pit during the same period. The data indicated slow currents (generally less than10 cm/s) in the Little Bay and Norton Basin entrance channels and in the Norton Basin pit near bottom. In the Little Bay Entrance Channel, the average current speed was higher in the near bottom than the near surface while in the Norton Basin Entrance Channel the near bottom speed was lower than the near surface (**Table 7**). The average near surface current speed was slightly higher in the Norton Basin Entrance Channel compared to the Little Bay Entrance Channel. Average temperature and salinity in the near bottom of both channels were similar. **Figure 24** shows average current speed and direction at flood tide in the entrance channels and the Norton Basin pit near bottom during

Table 7. Summary of current speed and direction. Temperature, salinity, and depth are provided also for meters that had corresponding sensors.

Date	Location/Current Meter	Start Time (h)	End Time (h)	Tide	Average Speed (cm/s)	Average Direction (°)	Average Temp. (°C)	Average Salinity (ppt)	Average Depth (ft)
19 to 20Jun	Little Bay Pit Near Surface	9:30	7:30	Flood-Ebb-Flood-Ebb	1.74	46	20.6	25.8	18
	Little Bay Pit Midwater	9:30	7:30	Flood-Ebb-Flood-Ebb	1.87	318			
	Little Bay Pit Near Bottom	9:30	7:30	Flood-Ebb-Flood-Ebb	4.75	46	5.9	27.0	48
20-Jun	Norton Basin Pit Near Surface	9:30	14:30	Slack Low-Flood	0.98	117	21.7	25.7	8
	Norton Basin Pit Midwater	9:30	14:30	Slack Low-Flood	5.64	157			
	Norton Basin Pit Near Bottom	9:30	14:30	Slack Low-Flood	3.01	20	20.3	24.7	34
30-Jul	Little Bay Entrance Channel Near Surface	9:30	16:00	Flood-Ebb	4.63	164			
	Little Bay Entrance Channel Near Bottom	9:30	16:00	Flood-Ebb	9.54	59	24.2	27.5	25
	Norton Basin Entrance Channel Near Surface	11:00	16:00	Flood-Ebb	5.22	50			
	Norton Basin Entrance Channel Near Bottom	11:00	16:00	Flood-Ebb	3.35	232	24.8	28.6	26
	Norton Basin Pit Near Bottom	11:30	16:30	Flood-Ebb	3.39	49			
24-Sep	Little Bay Pit Near Surface	10:00	15:30	Slack High-Ebb	8.78	236	22.4	26.2	18
	Little Bay Pit Midwater	10:00	15:30	Slack High-Ebb	4.83	349			
	Little Bay Pit Near Bottom	10:00	15:30	Slack High-Ebb	2.68	86	7.0	27.6	57
24 to 25-Sep	Norton Basin Pit Near Surface	16:30	8:00	Slack Low-Flood-Ebb-Flood	7.00	230	22.9	26.2	7
	Norton Basin Pit Midwater	16:30	8:00	Slack Low-Flood-Ebb-Flood	2.84	349			
	Norton Basin Pit Near Bottom	16:30	8:00	Slack Low-Flood-Ebb-Flood	1.04	237	22.5	26.9	37
24-Sep	Little Bay Entrance Channel Near Surface	10:30	16:30	Slack High-Ebb	0.97	213	22.5		
	Little Bay Entrance Channel Near Bottom	10:30	16:30	Slack High-Ebb	2.93	207	22.3		
24-Sep	Norton Basin Entrance Channel Near Surface	17:00	8:00	Flood-Ebb-Flood	2.88	289	22.7		
	Norton Basin Entrance Channel Near Bottom	17:00	8:00	Flood-Ebb-Flood	1.02	170	22.6		
25-Sep	Little Bay Entrance Channel Near Surface	9:00	15:30	Slack High-Ebb	5.52	140			
	Little Bay Entrance Channel Near Bottom	9:00	15:30	Slack High-Ebb	4.54	236	22.3	26.1	27

Table 7. (Continued).

Date	Location/Current Meter	Start Time (h)	End Time (h)	Tide	Average Speed (cm/s)	Average Direction (°)	Average Temp. (°C)	Average Salinity (ppt)	Average Depth (ft)
25-Sep	Little Bay Pit Near Bottom	9:30	15:30	Slack High-Ebb	3.74	286	7.00	27.5	
25-Sep	Norton Basin Entrance Channel Near Surface	8:00	16:00	Slack High-Ebb	1.82	307	22.3		
	Norton Basin Entrance Channel Near Bottom	8:00	16:00	Slack High-Ebb	1.49	14	22.4		
22 to 23-Oct	Little Bay Pit Near Surface	18:30	8:30	Flood-Ebb-Flood	1.48	18	15.4		
	Little Bay Pit Midwater	18:30	8:30	Flood-Ebb-Flood	0.70	305	15.7		
	Little Bay Pit Near Bottom	18:30	8:30	Flood-Ebb-Flood	5.65	251	8.4	26.3	42
22-Oct	Norton Basin Pit Near Surface	11:30	16:30	Ebb-Slack Low	4.98	348	15.0		
	Norton Basin Pit Midwater	11:30	16:30	Ebb-Slack Low	0.71	211	15.0		
	Norton Basin Pit Near Bottom	11:30	16:30	Ebb-Slack Low	6.33	230	14.9	25.3	35
22-Oct	Little Bay Entrance Channel Near Surface	17:00	8:30	Flood-Ebb-Flood	2.77	267	15.3		
	Little Bay Entrance Channel Near Bottom	17:00	8:30	Flood-Ebb-Flood	0.05	177	15.6	26.5	34
22-Oct	Norton Basin Entrance Channel Near Surface	11:00	16:00	Ebb	3.17	295	14.8		
	Norton Basin Entrance Channel Near Bottom	11:00	16:00	Ebb	0.45	304	14.7	26.3	
23-Oct	Little Bay Entrance Channel Near Surface	9:30	15:30	Slack High-Ebb	0.87	348	15.2		
	Little Bay Entrance Channel Near Bottom	9:30	15:30	Slack High-Ebb	1.84	25	15.3	26.3	31
23-Oct	Little Bay Pit Near Bottom	9:30	15:30	Slack High-Ebb	5.60	348	13.4		
23-Oct	Norton Basin Entrance Channel Near Surface	10:00	16:00	Slack High-Ebb	4.98	19	14.6		
	Norton Basin Entrance Channel Near Bottom	10:00	16:00	Slack High-Ebb	9.07	36	14.7	25.3	33

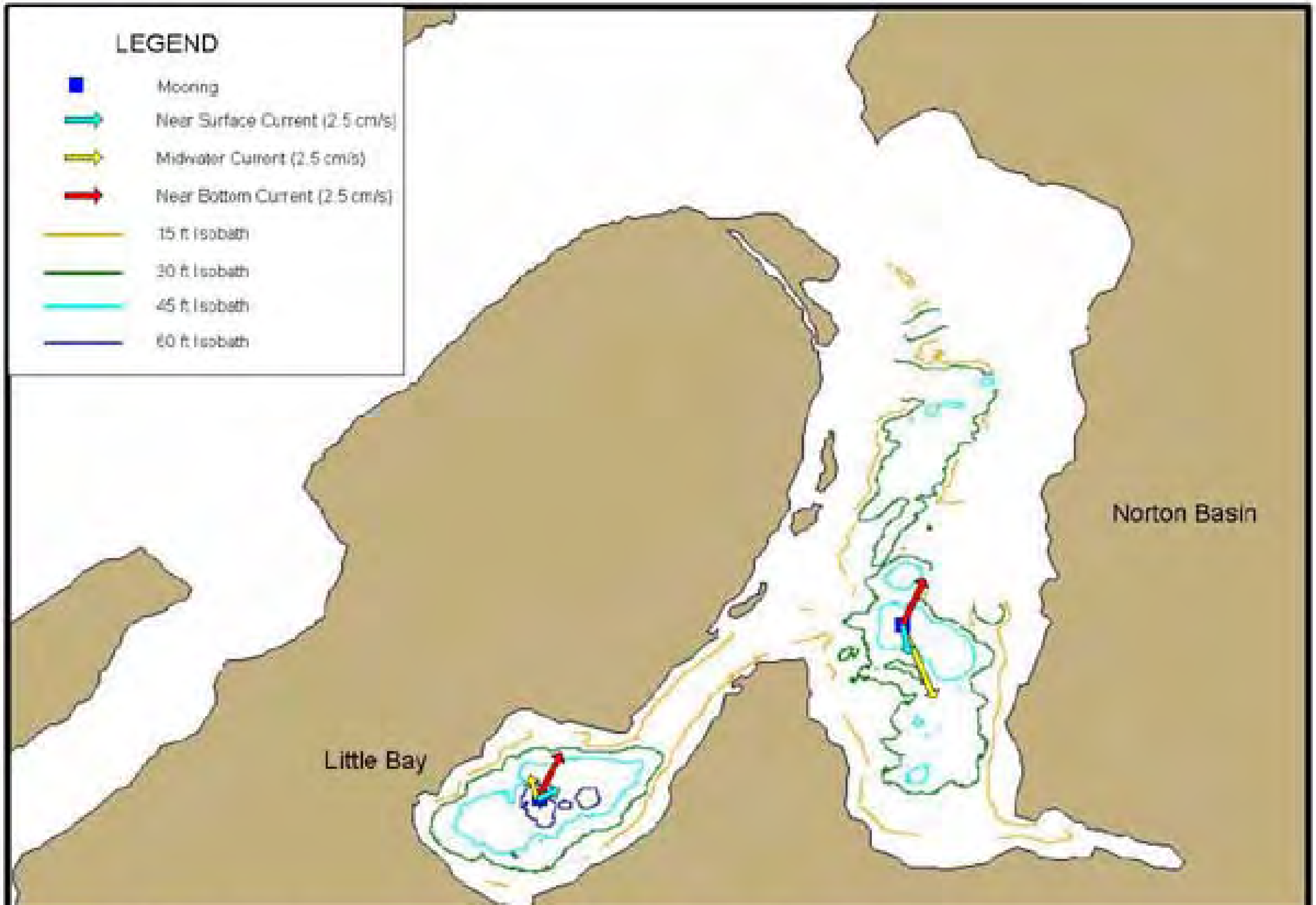


Figure 23. Average current speed and direction at flood tide on 19 June in Little Bay and on 20 June in Norton Basin.

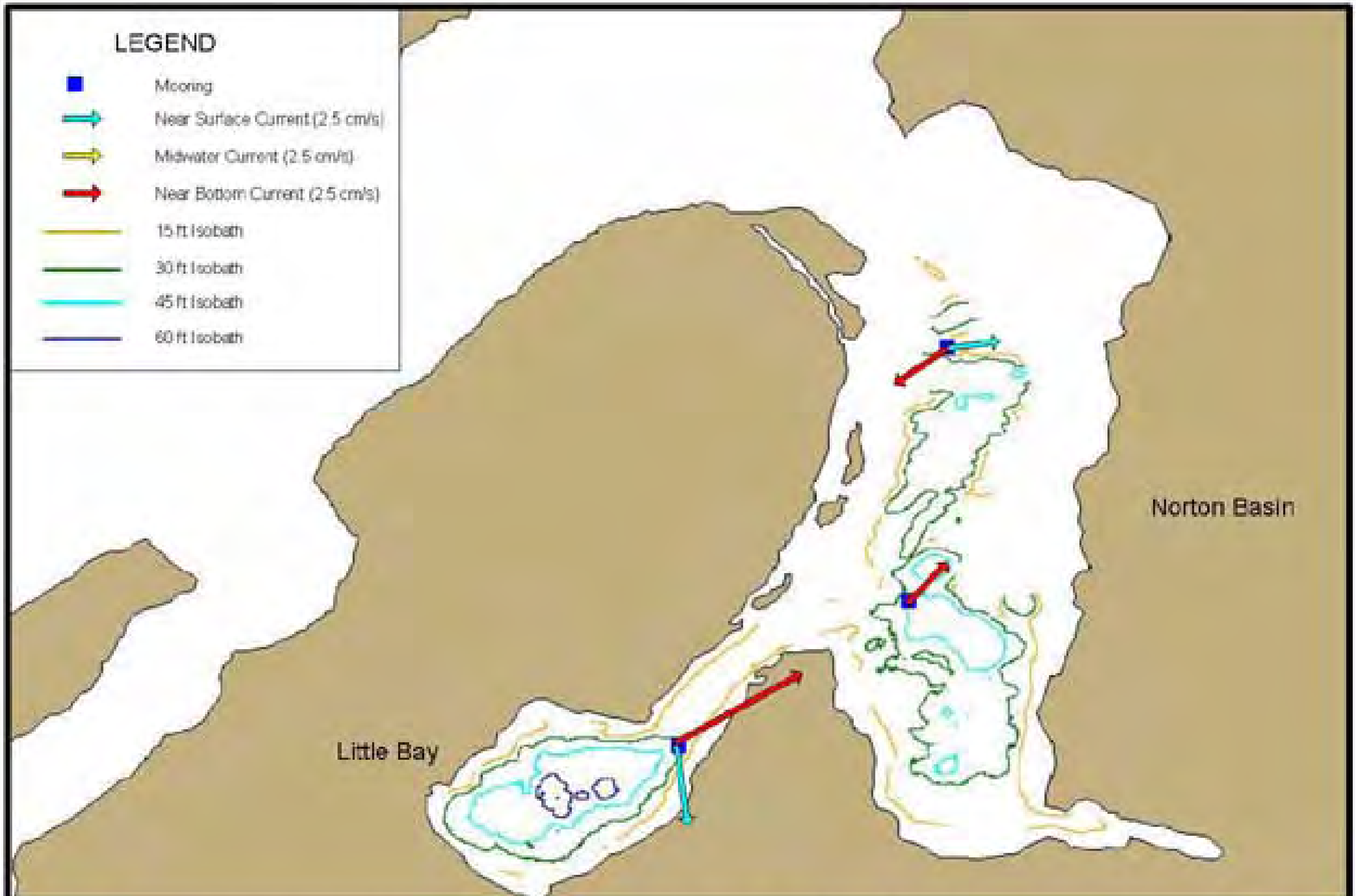


Figure 24. Average current speed and direction at flood tide on 30 July in Little Bay and Norton Basin Entrance Channels and Norton Basin pit.

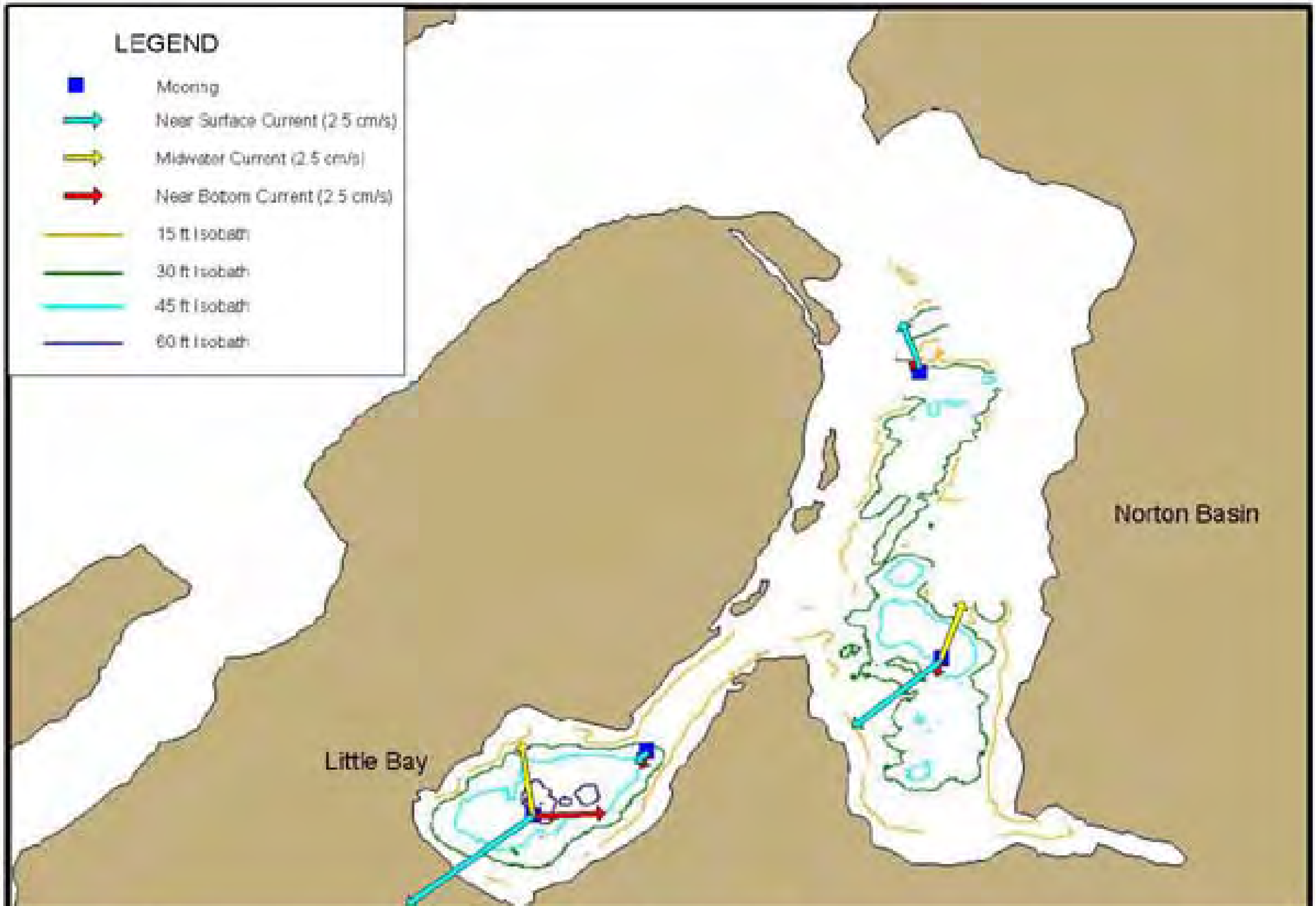


Figure 25. Average current speed and direction at ebb tide on 24 September in Little Bay and Norton Basin pits and entrance channels.

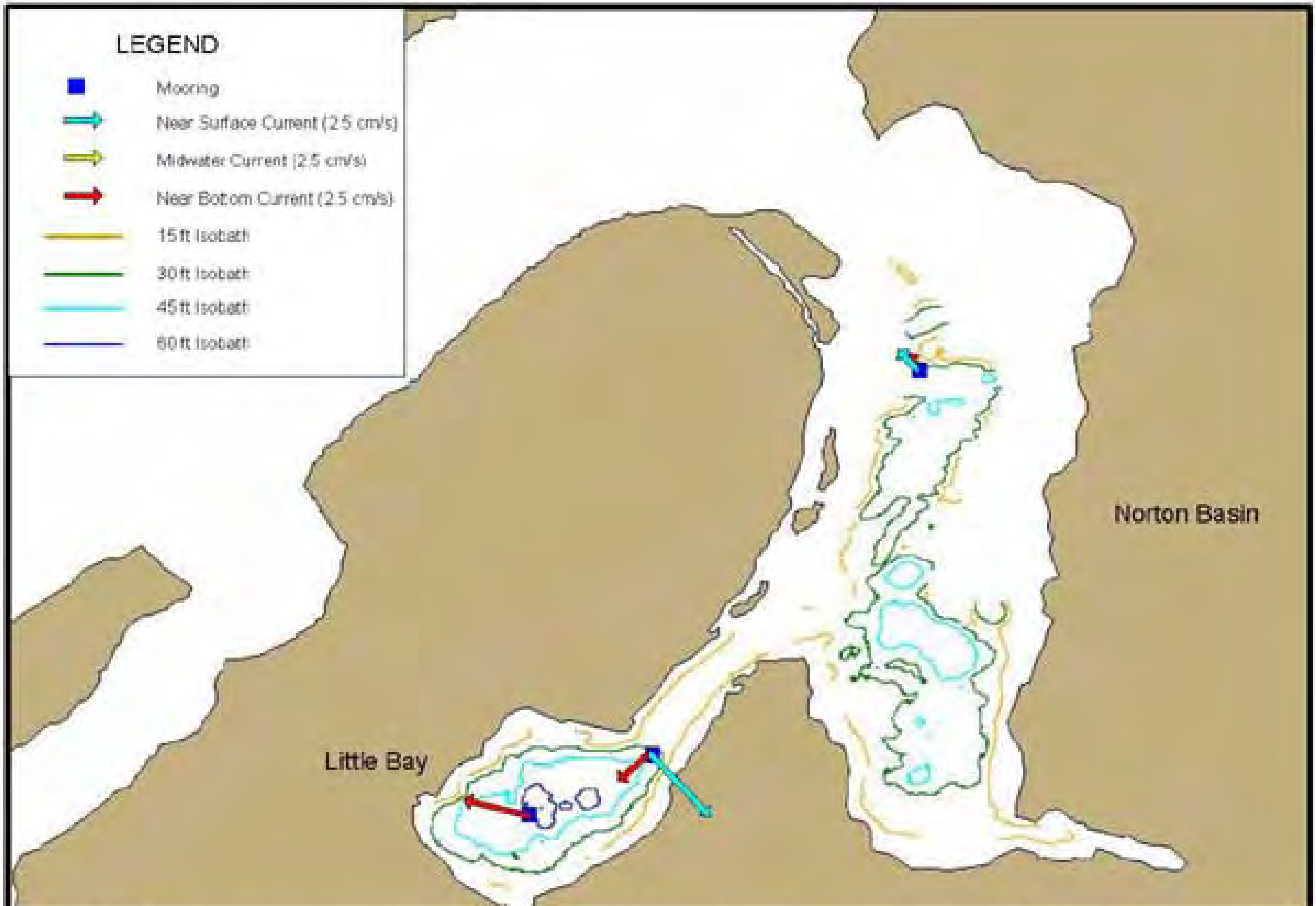


Figure 26. Average current speed and direction at ebb tide on 25 September in Little Bay and Norton Basin Entrance Channels and Little Bay Pit.

Figure 27. Average current speed and direction at ebb tide on 22 October in Little Bay and Norton Basin pits and entrance channels.

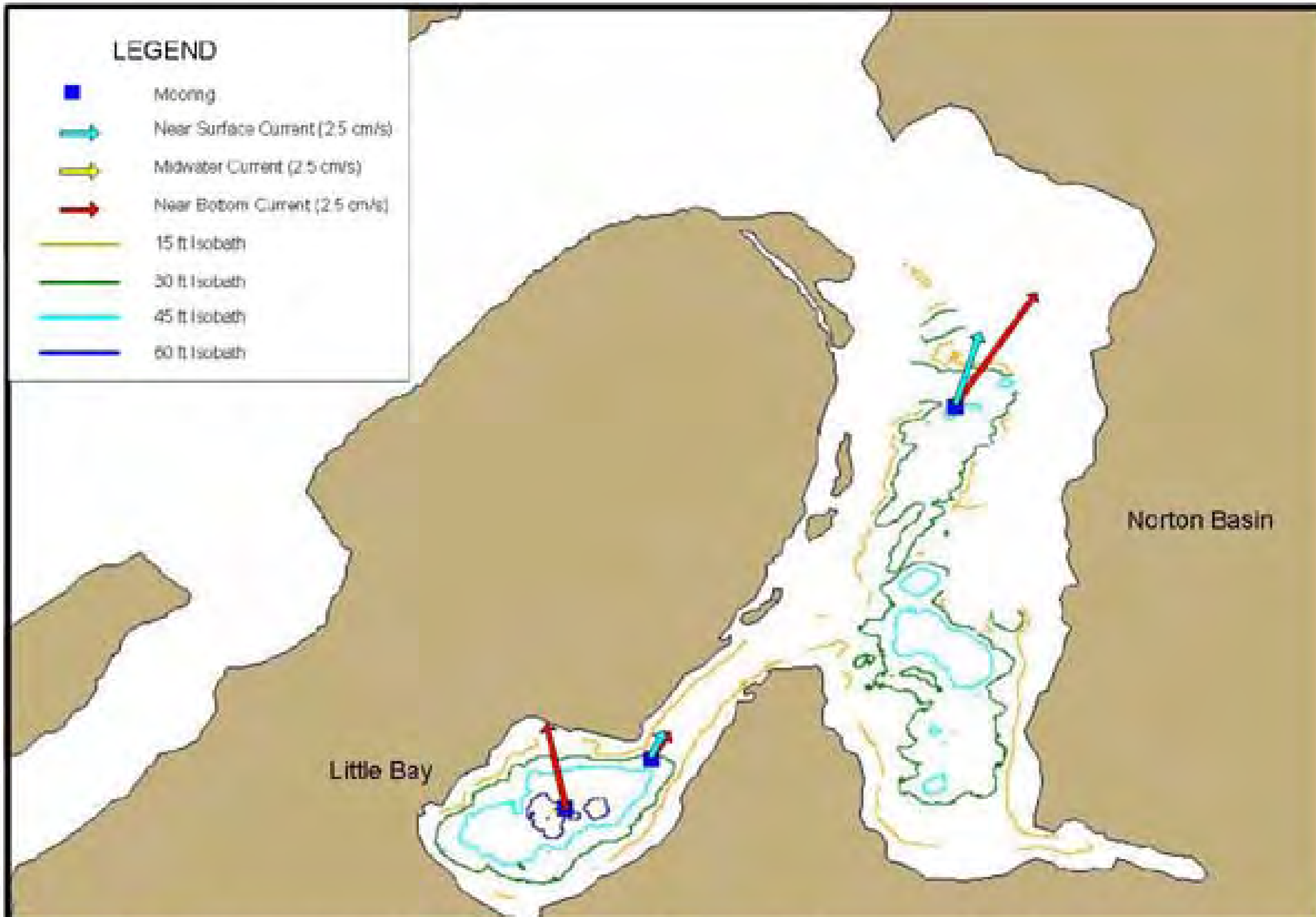


Figure 28. Average current speed and direction at ebb tide on 23 October in Little Bay and Norton Basin Entrance Channels and Little Bay pit.

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the July survey. Current speeds were similar in both channels, but direction differed between levels and channels. Current directions diverged between the near surface and near bottom in both entrance channels. In the Little Bay Entrance Channel, the near bottom current ran counter to the near surface tidal flood. Current direction at the near surface in both channels corresponded to the expected tidal direction. Flow in the near bottom in the Little Bay Entrance Channel and Norton Basin pit near bottom was opposite to the expected tidal direction. A 13 knot wind from the west-northwest would likely deflect the near surface currents in both channels. The near surface current in the Norton Basin Channel would be further deflected by the prevailing wind due to its orientation and wider channel compared to the near surface flow in the Little Bay Entrance Channel, where the narrow channel would constrain deflection.

In September, current meters were deployed at three levels in the Little Bay and Norton Basin pits and at two levels in the entrance channels (**Table 7**). Currents were measured in the entrance channels in separate deployments on 24 and 25 September. The data indicated slow currents (generally less than 10 cm/s) in the Little Bay and Norton Basin pits and entrance channels. Average current speed in the midwater and near bottom in both pits were similar, while near surface speeds were greater. The average current speed in the Norton Basin pit near bottom was lower compared to the near bottom current in the Little Bay pit. Average current direction differed among the three levels in both pits. Current directions in the near surface and midwater were similar in both embayments, while the near bottom current directions differed. While the temperature in the near surface and near bottom in the Norton Basin pit was about the same, the near bottom temperature in the Little Bay pit was 15°C colder than the near surface temperature. Average salinity in the Norton Basin pit near surface and near bottom were also similar, while salinity in the Little Bay pit near bottom was higher than in the near surface. **Figure 25** shows average current speed and direction at ebb tide on 24 September in the Little Bay and Norton Basin pits and entrance channels. Current speeds and directions differed between pits and between channels. Current directions diverged between the three levels in both pits. Current direction at both levels in the Norton Basin Entrance Channel and at midwater in the Norton Basin pit corresponded to the expected tidal direction but not in the Little Bay pit or Entrance Channel. A 8.5-knot northerly wind blowing counter to the ebb tide direction could cause the southwesterly directed near surface current, while the currents at midwater would be less influenced.

Currents were measured in the Little Bay Entrance Channel through a slack high and ebb tide on 24 September, while currents were measured overnight in the Norton Basin Entrance Channel from a slack low tide on 24 September to the middle of the flood tide on 25 September (**Table 7**). Average current speeds in the Little Bay and Norton Basin entrance channels during these deployments were similar. There were higher average current speeds in the near surface compared to near bottom in the entrance channels. Average temperatures were also similar at both levels in both entrance channels. On 25 September, average current speed was higher in the Little Bay Entrance Channel and Little Bay pit near bottom compared to the Norton Basin Entrance Channel. **Figure 26** shows average current speed and direction at ebb tide in the entrance channels on 25 September indicating higher current speeds in the Little Bay Entrance Channel and Little Bay pit near bottom compared to the Norton Basin Entrance channel. Current direction in the Little Bay Entrance Channel diverged between near surface and near bottom while the current in both levels in the Norton Basin Entrance Channel ran generally in the same direction as the ebb tide. A 9-knot northeasterly wind blowing counter to the ebb tide direction would be expected to dampen the near surface current in the Norton Basin

Entrance Channel, while the channel orientation may deflect the near surface ebb current in the Little Bay Entrance Channel.

Currents were measured at three levels in the Little Bay and Norton Basin pits on 22 October and at two levels in the Little Bay and Norton Basin entrance channels on 22 and 23 October (**Table 7**). On 23 October, currents were measured also in the Little Bay pit near bottom. Currents were measured in the Little Bay pit over a full tidal cycle, while currents in the Norton Basin pit were measured during an ebb and slack low tide. There were slow currents (generally less than 9 cm/s) in the Little Bay and Norton Basin pit and entrance channels. Currents at the near surface and near bottom were faster than in the midwater in the Little Bay and Norton Basin pits. Current direction in the near surface and midwater differed from the near bottom in the Little Bay pit. In the Norton Basin pit, current direction also differed between the three levels. Average current speeds at the near bottom were slightly higher in the Norton Basin pit compared to the Little Bay pit. There were very little differences in temperature between the three levels in the Norton Basin pit, while there was a 7°C difference between the near surface and near bottom (colder) in the Little Bay pit. Average salinity in the Little Bay pit near bottom was higher than in the Norton Basin pit near bottom. **Figure 27** shows average current speed and direction at ebb tide on 22 October in the Little Bay and Norton Basin pits and entrance channels. There were higher current speeds in the pits compared to their corresponding entrance channels. Current directions diverged between the near surface and near bottom in both embayments. The near surface currents in the North Basin generally were directed down its axis corresponding to direction of tidal flow. There was a 6.5 knot wind from the east-southeast that could have caused deflections in the near surface currents.

Average current speeds at the Little Bay and Norton Basin entrance channels on 23 October were faster at the near bottom than at near surface (**Table 7**). Near surface and near bottom current speeds in the Norton Basin Entrance Channel were higher compared to the Little Bay Entrance Channel. On 23 October, average current speed in the Little Bay Entrance Channel near surface was less compared to the previous day, while higher currents were measured in the Little Bay Entrance Channel near bottom. Near surface currents in both entrance channels and the near bottom current in the Little Bay Entrance Channel were slower than the current in the near bottom in the Little Bay pit. Average current direction in the near surface and near bottom were similar in both entrance channels on both days. There were very little differences in temperature and salinity between the two levels in both entrance channels. **Figure 28** shows the average current speed and direction at ebb tide in the entrance channels and Little Bay pit near bottom on 23 October. There were higher current speeds in the Norton Basin Entrance Channel where the near surface and near bottom currents corresponded to direction of tidal flow. The current direction also corresponded to the direction of tidal flow in the Little Bay Entrance Channel. The wind had shifted to a north-northwest direction at 10 knots compared to the previous day. This may be responsible for the slower near surface current in the Norton Basin Entrance Channel.

5.0 DISCUSSION

5.1 WATER COLUMN PROFILES

The water column profiles showed that conditions in the lower water column of the Little Bay pits were very different from other areas of the Norton Basin/Little Bay complex. A strong thermocline, low temperature, and anoxia were persistent features of the Little Bay pits in all surveys. A thermocline was present in the Little Bay pit profiles during all surveys but was absent in profiles from all other areas. Temperature profiles indicate that while the thermocline moves deeper, it becomes even more pronounced through the summer. There must be minimal circulation or vertical exchange between the upper and lower water column in Little Bay to explain the low temperature in the near bottom through the summer even when the temperature in the near surface is 15°C higher.

The persistent occurrence of anoxia in the Little Bay pit stands out compared to other areas of the Norton Basin/Little Bay complex. Although DO data in July were not available due to equipment problems, the presence of a thermocline in the Little Bay pits would suggest that there were anoxic conditions also at the time. Hypoxia occurred in a limited number of profiles from the Little Bay shallows and in the Norton Basin pits, suggesting while oxygen demand may be high, that in these areas there was adequate exchange with surface waters to prevent anoxic conditions from occurring in the near bottom. Profiles from other areas of the Norton Basin/Little Bay complex and Grass Hassock Channel showed adequately oxygenated conditions throughout the water column, although lower DO concentrations between 3 mg/l to 5 mg/l may be present near the bottom.

While there were no evident differences in salinity among most stations in the Norton Basin/Little Bay complex, there was higher salinity in the Little Bay pits below the thermocline. The higher salinity below the thermocline in the Little Bay pits also indicates minimal exchange with the upper water column.

The Little Bay pits also showed a peak in turbidity associated with the thermocline. The peak in turbidity just above the thermocline indicates that suspended matter is being trapped at or above the interface between the warmer, less saline, and less dense upper water column and the colder, more saline, and denser water at the near bottom of the Little Bay pits. The persistence of the turbidity layer through all the surveys would further indicate that there is minimal circulation and exchange between the upper water column and the near bottom waters of Little Bay. This indicates that tidal currents do not reach and affect the turbidity layer above the thermocline in Little Bay or are not strong enough to disrupt it.

The thermocline, low temperature, higher salinity, and the persistence of a turbidity layer above the thermocline in the Little Bay pits in spite of diurnal tides with a large tidal amplitude are indications that the near bottom waters are largely unaffected by daily tidal flow and have minimal exchange with the upper water column. The daily tidal flow through an embayment would be expected to disrupt formation of a thermocline and allow interchange of water between the upper and lower water column, thus warming the cold bottom waters and reducing the occurrence of anoxia in the Little Bay pits. Compared to Little Bay, tidal flow into Norton Basin or the shape of its basin apparently is adequate to prevent the formation of a thermocline and the onset of anoxic conditions. The presence of a thermocline in a tidal system and very cold bottom waters throughout the summer indicates that the lower water column in the Little Bay pits is separated or decoupled from daily tidal influence. Cold water is denser than warm water and promotes stability in the water column, thus allowing stratified conditions to persist.

Little Bay is a small dead-end embayment where tidal flow may be expected to be slower than in Norton Basin. The basin shape and reduced current speed may be inadequate to disrupt the thermocline or stratified conditions in Little Bay, thus allowing anoxia to persist in the near bottom. Disrupting the thermocline could enhance water exchange between the upper and lower water column in Little Bay. The shallow Norton Basin Entrance Channel acts as a sill that dampens tidal energy entering the Norton Basin/Little Bay complex. The shallow Little Bay Entrance Channel acts as a second sill that would further minimize the tidal energy entering Little Bay. Along with basin morphology, the reduced tidal flow may only act on circulation in the upper water column in Little Bay and have minimal effect on the lower water column because of the pronounced thermocline that separates the warmer, less saline, and less dense upper water column from the colder, more saline, and denser lower water column.

5.2 WATER CHEMISTRY

The water chemistry data differentiate the Little Bay pits from other areas of the Norton Basin/Little Bay complex, while documenting how similar the water column in Norton Basin is to the entrance channel and Grass Hassock. The lower water column (near bottom water) of the Little Bay pits was markedly different from other areas of the Norton Basin/Little Bay complex through the course of the surveys as follows:

- ammonium and phosphate was higher;
- nitrate+nitrite was lower;
- dissolved silica was higher;
- biogenic silica was lower;
- total chlorophyll was lower;
- phaeophytin was lower, and
- sulfide was present in very high concentrations.

In contrast, the upper water column in Little Bay pits and shallows, and the Norton Basin pits and shallows were similar in terms of most water chemistry parameters to the Norton Basin Entrance Channel and Grass Hassock Channel. The similarity in water chemistry parameters in addition to temperature, salinity, DO, and turbidity in areas other than the near bottom in the Little Bay pits suggests that there is a common water mass being exchanged in these areas. Each of the water chemistry parameters alone could serve to differentiate the near bottom waters of the Little Bay pits from the other areas. The distinctiveness of the near bottom waters of the Little Bay pits suggests there is minimal exchange with other areas of the Norton Basin/Little Bay complex. Taken together, the water chemistry parameters indicate that conditions in the near bottom waters of the Little Bay pits are highly anomalous relative to other areas and are more reminiscent of conditions usually found in the sediment below the typical sediment-water interface in estuarine areas.

The water chemistry data, particularly sulfide, indicate that the lower water column of Little Bay is dominated by high rates of anaerobic decomposition. During microbial decomposition of organic matter, organic nitrogen is broken down by putrefying bacteria and fungi into inorganic ammonium through ammonification. Organic phosphorus is decomposed by bacterial and fungal mineralization of organic matter and released in the form of inorganic phosphate typically. If autotrophs such as phytoplankton were not present to assimilate the mineralized (inorganic) nitrogen and phosphorus for photosynthesis, and there were no processes for their transport or removal from the water body (diffusion, advection, or precipitation), the ammonium and phosphate concentrations would increase as microbial decomposition continues. The high ammonium and phosphate concentrations in the Little Bay near bottom relative to other areas and the increasing ammonium and phosphate concentrations through the summer indicate that there are high rates of organic matter decomposition, and there is minimal transport, uptake, or transformation of ammonium and phosphate.

If oxygen is not available (e.g., below a thermocline, which restricts exchange between the oxygenated upper water column and the lower water column), anaerobic microbial decomposition proceeds by utilizing alternate hydrogen ion acceptors, e.g., nitrate, sulfate, for decomposition of organic matter. In aerobic systems, normally ammonium would be oxidized through nitrification to nitrate, a bacterial process that requires oxygen. The bacterial conversion of ammonium to nitrate (nitrification) is inhibited by oxygen depletion and by low temperatures. Low nitrate+nitrite concentrations even when ammonium is high, i.e., when oxygen is absent, suggest that nitrification is suppressed in the Little Bay pits, likely due to the lack of oxygen. Further, nitrification is temperature dependent. The anoxic conditions and low temperatures in the Little Bay pits would inhibit nitrification, and this would further increase ammonium concentrations. Another process that can reduce nitrate in aquatic systems is denitrification, the conversion of nitrates to dinitrogen gas under anaerobic conditions. Denitrification is temperature dependent also. Although low nitrate in Little Bay pit near bottom could be due to denitrification, the low temperature is likely to suppress it.

Most aquatic systems, particularly the open oceans, are nutrient limited (i.e., the availability of nitrogen, phosphorus, and silica limits phytoplankton production). In coastal systems, the nutrient flux from the sediment is one of the main sources of nitrogen and phosphorus for phytoplankton growth in addition to upstream and atmospheric sources. Eutrophic conditions in estuaries occur when there are excessive inputs of nutrients that lead to algal blooms, high turbidity/reduced light penetration, and increased oxygen demand, which leads to hypoxic conditions and even anoxia. The excess nutrients are usually from sources such as riverine discharge, surface runoff, and municipal discharges (sewage treatment plants) that maintain eutrophic conditions. The high concentrations of ammonium and phosphate in the Little Bay pit near bottom represents a large pool of nitrogen and phosphorus that could fuel continually phytoplankton growth and maintain eutrophic conditions in the upper water columns in Little Bay. Due to the steep gradient in TDP and TDN concentrations between upper and lower water columns, transport to the upper column by diffusion is possible. Algal blooms (brown tides) were observed during the surveys in the Norton Basin/Little Bay complex and other areas of Jamaica Bay in the summer, especially in June. If the water from the Little Bay pits reached the upper water column during the summer, it would likely cause an algal bloom (Assuming a surface area of the Little Bay pits of 74,000 m^2, a layer depth of 7 m (21 ft), and ammonium concentration of 5 mg N/l, the Little Bay pits represent a store of 2,500 kg of nitrogen that is readily available to phytoplankton production. At a phosphate concentration of 1 mg P/l, the Little Bay pits represent a store of 500 kg of phosphorus.

The high mineralization observed in the Little Bay near bottom requires a source of organic matter that could come from phytoplankton or macroalgae among others, e.g., zooplankton or other macrobiota. The high decomposition may be in the water column, in the sediment, or in the thick layer of suspended material (nepheloid layer) above the sediment. The Little Bay pits have very soft bottom sediments where it is difficult to determine where the actual bottom/sediment starts. The lack of differences in dissolved and particulate organic carbon in water samples from the near bottom of the Little Bay pits compared to other areas of the Norton Basin/Little Bay complex despite the presumably high decomposition rates suggests that the source of organic matter for decomposition is not in the water column as dissolved or particulate organic matter. The source of organic matter for decomposition could more likely be material such as dead macroalgae or other macroscopic organic matter such as zooplankton, fish, shellfish, and their fecal products. During the summer, large, thick mats of sea lettuce (*Ulva*) are present in Norton Basin and Little Bay, particularly in its shallows in the summer. Extensive mats of macroalgae growing on the shallows or brought into Little Bay by the tides could sink into the deep pits where they would die, and decompose. Bottom trawls for fish taken in the pits in Norton Basin invariably brought up thick mats of macroalgae that made sampling very difficult. The increasing concentrations of mineralized nutrients and sulfide throughout the summer and into fall may be due to increased inputs of organic matter into the Little Bay near bottom later in the summer season as spring and summer growths of macroalgae senesce and die, fueling higher rates of anaerobic decomposition.

In addition to low total chlorophyll and low biogenic silica, the Little Bay pit near bottom was very well differentiated also by the ratio of active chlorophyll to total chlorophyll (aChl:tChla) and phaeophytin to total chlorophyll (Phaeo:tChl) distinct from other samples. Active chlorophyll takes into account chlorophyll inside living cells, while phaeophytin is a breakdown product of chlorophyll. In an actively growing phytoplankton population, active chlorophyll takes up a larger proportion of the total chlorophyll (i.e., aChl:tChla is closer to 1), while phaeophytin will be in lower proportions to total chlorophyll. A senescing phytoplankton population would have a lower aChl:tChla ratio and a higher Phaeo:tChl ratio. The average aChl:tChla ratio of the Little Bay near bottom samples (0.41) was significantly different ($p<0.05$) from the average aChl:tChla ratio of all other samples (0.68). The higher aChl:tChla means that the phytoplankton in samples other than those from the Little Bay pit near bottom are actively growing. Also, the average Phaeo:tChl ratio of the Little Bay near bottom samples (1.19) was significantly different ($p<0.05$) from the average Phaeo:tChl ratio of all other samples (0.65). The higher Phaeo:tChl ratio in the Little Bay pit near bottom samples indicates that there are more chlorophyll breakdown products than chlorophyll, i.e., more of the phytoplankton are decomposing rather than active or alive.

The ratios indicate that the minimal phytoplankton found in the Little Bay near bottom is senescent unlike the large populations of actively growing phytoplankton found in the upper water column of Little Bay and other areas. Due to the lack of light necessary for photosynthesis in the Little Bay near bottom, it is unlikely that the chlorophyll and phaeophytin that was present came from phytoplankton that originated there. Also, the biogenic silica values indicate that the diatom population in the Little Bay near bottom is small, and the phytoplankton more likely originated from the upper water column. The chlorophyll and phaeophytin found in the Little Bay near bottom was probably deposited from the upper water column, where light is available for phytoplankton growth. Large masses of phytoplankton produced during the spring bloom evident in the high total chlorophyll values in May and phytoplankton growth throughout the summer and fall are the likely sources of phytoplankton detected in the Little Bay pit near bottom.

Based on the chlorophyll data, the peak in phytoplankton production occurred in May and June, when the blooms where observed. If the spring phytoplankton blooms died off and were deposited and decomposed in the Little Bay pit lower water column in May and June, there should have been a peak in ammonium, phosphate, dissolved silica, and sulfide at that time or soon after. However, the peak in ammonium, phosphate, dissolved silica, and sulfide occurred in the fall, some time after the peak in phytoplankton growth. This may suggest that either the spring phytoplankton production does not reach the near bottom to be decomposed until later in the summer, or the source of organic matter for decomposition is something other than phytoplankton, e.g., macroalgae.

It is possible that the turbidity layer found just above the thermocline in the Little Bay pits is minimal in spring, and increasing throughout the summer may represent phytoplankton or other organic matter from the upper water column accumulating just above the thermocline. The difference in density of the water at the thermocline could be trapping phytoplankton, other organic detritus, and sediment, thus creating the distinct turbidity layer. The turbidity layer becomes more pronounced later in the summer and could signify increasing concentrations of phytoplankton from the summer growth being deposited. If the turbidity layer does represent phytoplankton from the upper water column, it is possible that it may still reach the near bottom. As the strong thermocline becomes less pronounced with the onset of winter temperatures, density differences at the turbidity layer could also dissipate as organic matter sinks into the Little Bay near bottom. This could explain why the turbidity layer above the thermocline is minimal in May.

In a stagnant, stratified water body, aerobic organic matter decomposition rapidly depletes oxygen unless it is replenished from the atmosphere or from photosynthesis. In estuarine systems, sulfate is readily available as an alternate hydrogen ion acceptor for respiration. Sulfate reduction is a common and dominant process in eutrophic estuarine systems. If oxygen is present, aerobic decomposition predominates. However, when oxygen is depleted by aerobic processes (respiration), sulfate reducing bacteria can decompose organic matter by using sulfate as the hydrogen ion acceptor and in the process produce sulfides. Sulfides can inhibit nitrification and further increase ammonium concentrations. In the presence of iron, iron monosulfides (FeS) are formed, and sulfides may be further removed from solution by precipitation of iron sulfide or pyrite (FeS_2), common in black mud in coastal areas. The high sulfide concentrations in the water column in the Little Bay pits suggest the rates of sulfide generation exceeds the flux of metals that precipitate sulfide to the system.

The presence of sulfides in high concentrations in the water column through the course of the surveys is strong evidence of persistent anoxic conditions in the Little Bay pit near bottom, and minimal exchange with the upper water column where sulfide is absent. Along with the other water chemistry parameters, the presence of sulfides in the lower water column of Little Bay is further evidence of minimal exchange between the upper water column and the near bottom waters of Little Bay. Normally, if the oxygenated water of the upper water column could mix with the near bottom waters, the sulfide would be rapidly oxidized and disappear.

Unlike the Norton Basin pit near bottom samples and the near surface and midwater Little Bay pit samples, total chlorophyll and biogenic silica (present in diatoms) were low in the Little Bay pit near bottom samples. Sulfide is toxic to most aerobic organisms. The anoxic conditions and presence of toxic sulfides would preclude the survival of phytoplankton and other organisms in the Little Bay pit near bottom. Low chlorophyll, phaeophytin, and biogenic silica in Little Bay pit near bottom samples suggest that living phytoplankton or recently dead phytoplankton do not reach the near bottom waters of the Little Bay pits, although the high dissolved silica may indicate the products of the decomposition of diatoms do reach the bottom of the Little Bay pits.

The water chemistry results suggest that there are high rates of organic matter decomposition even at low temperatures, and anaerobic conditions in the Little Bay pits that result in release of high concentrations of ammonium, phosphate, and silica. Minimal exchange with the upper water column due to stratification promotes anaerobic decomposition that results in and is maintained by bacterial sulfate reduction, which produces high sulfide. High sulfide and low temperature inhibits nitrification, which would result in low nitrate concentrations.

5.3 CURRENTS

The current meter surveys documented generally slow and complex water flow in the Little Bay and Norton Basin pits and their entrance channels. The majority of the current speeds recorded in the surveys were less than 5 cm/s, and there were very few instances of currents greater than 10 cm/s. The data indicate that there are slow currents in the Little Bay pit near bottom that do not respond to daily tidal changes. Current speeds in the Little Bay pit near bottom were comparable in general with current speeds in the Little Bay pit midwater and near surface, along with currents in the Norton Basin pit and the two entrance channels. There was generally greater variability in current speed and direction in the near surface and midwater levels in Little Bay, and in the three levels in the Norton Basin pit compared to currents in the Little Bay pit near bottom.

In both Little Bay and Norton Basin pits, flow patterns were complex and differed between the near surface, midwater, and near bottom at different stages of the tide and under differing wind conditions. Current speed and direction differed between the three levels in the Little Bay and Norton Basin pits during the June, September, and October surveys. The differences in current speed and direction between the three levels were not consistent over the surveys. For example, during June in the Little Bay and Norton Basin pits, current speeds in the near surface and midwater were generally comparable, but in the September and October surveys, the current speed in midwater was much slower than in the near surface. There was an apparent increase in current speed in the Little Bay pit near bottom in October that may be due to spring tide conditions, which could set up stronger currents in the Little Bay pit near bottom.

While currents in the near surface and midwater in the Little Bay pit show apparent response to the tide, flow in the Little Bay pit near bottom did not respond to tidal changes as evidenced in the June surveys, covering almost two tidal cycles and in October with one tidal cycle. In the June survey, flow in the near bottom in the Little Bay pit shifted direction and appeared to slow down near slack high tide, but there was no evident change in flow with the next slack low tide or the following slack high. During the September survey in an ebb tide, there also were very little changes in current speed and direction in the Little Bay pit near bottom, although only small changes in current speed and direction in the near surface and midwater were evident also. During the October survey through a tidal cycle, there were only small changes in current speed and direction in the Little Bay pit near bottom, while there were more evident changes in current speed and direction in the near surface and midwater. Current speeds in the Little Bay pit near bottom were slightly higher also on 22 and 23 October than in June.

The currents at three levels in the Norton Basin pit also showed greater variability than currents in the Little Bay pit near bottom, although it is difficult to relate the variability directly to the tides. There were evident changes in current speed and direction in the near surface, while there were lesser changes in current speed and direction in the midwater and near bottom in the Norton Basin pit during a flood tide in the June survey. The September survey covering a tidal cycle in the Norton Basin pit showed changes in current speed and direction with changes in the tide. During the October survey in the Norton Basin pit, there was less variability observed in the currents at all levels with an ebb tide.

Current speeds in the Little Bay and Norton Basin entrance channels were low and comparable with those in the Little Bay and Norton Basin pits and also showed complex flow patterns (i.e., current speed and direction differed between the near surface and near bottom). Flow directions differed between the near surface and near bottom in the Little Bay and Norton Basin entrance channels during the surveys in July, September, and October. Currents were variable in both levels in the entrance channels and indicate a response to change in tide, particularly in the Norton Basin Entrance Channel. Differences in current speed and directions between the Little Bay and Norton Basin entrance channels appear to be attributed to wind conditions and differences in channel characteristics.

Temperature and salinity recorded in the current meters show that the near bottom in Little Bay remains consistently at a markedly lower temperature and higher salinity. In contrast, the temperature and salinity in the upper water column in Little Bay and other areas of the Norton Basin/Little Bay complex (i.e., all levels of the Norton Basin pit and the entrance channels) were very similar. The low temperature and higher salinity sharply differentiates the Little Bay pit near bottom from other areas of the Norton Basin/Little Bay complex that have very similar temperature and salinity. The similar temperature and salinity in other areas of Norton Basin/Little Bay complex indicate that there is good flow and exchange through changes in the tide except for the Little Bay pit near bottom.

The current meter data suggest that the Little Bay pit near bottom is not as influenced by daily tidal changes as the near surface and midwater levels in Little Bay and the Norton Basin pits and entrance channels. Coupled with the temperature and salinity data recorded in the current meters, circulation in the Little Bay pit near bottom is evidently separate from the circulation in the midwater and near surface and the rest of the Norton Basin/Little Bay complex.

The consistently low water temperature and higher salinity in the near bottom of the Little Bay pit compared with conditions in the upper water column of Little Bay and in the Norton Basin and the entrance channels through the course of the surveys are strong indications that there is little exchange between the near bottom and upper water column in Little Bay, and that near bottom circulation is separate. The lack of exchange between the near bottom and upper water column would result in stagnant conditions that maintain the persistent anoxia in the near bottom waters of the Little Bay pits.

In addition to proximity to Grass Hassock Channel, differences in the basin shape or morphology between Little Bay and Norton Basin may explain also the differences in water quality conditions. One sill separates Norton Basin from Grass Hassock Channel, while two sills separate Little Bay. The presence of two shallow sills between the Little Bay pits and energetic tidal currents in Grass Hassock Channel may be partly responsible for differences in water quality conditions between Little Bay and Norton Basin. Also, the pits in Little Bay are deeper than in Norton Basin. In addition, although smaller in total area, the deep pits in Little Bay make up a much larger proportion of the total area of Little Bay compared to deep pits in Norton Basin relative to its total area. In Little Bay, the surface area of the embayment representing depths greater than 30 ft is 56%, while in Norton Basin, the deep pits represent only 17% of the total basin surface area. At depths below 30 ft, oxygen consumption exceeds oxygen production.

The differences in relative surface areas (i.e., deep areas versus total basin area) would suggest that in Norton Basin there is much more total surface area to reoxygenate its deep pits compared to Little Bay. In Little Bay, the deep pits where oxygen consumption exceeds oxygen supply make up a larger proportion of the basin.

The differences in basin morphology alone could help explain why anoxia occurs in Little Bay but not in Norton Basin. Differences in water quality conditions may be further explained when differences in decomposition rates, i.e., oxygen consumption rates, and circulation are considered. There are likely higher oxygen consumption rates in the water column and sediment in Little Bay compared to Norton Basin given the ammonium and sulfide concentrations in the near bottom. The ammonium and sulfide are reduced ions that would consume oxygen also. The lack of exchange between the upper and lower water column in Little Bay due to the contributory factors discussed previously would further exacerbate the poor water quality conditions.

6.0 SUMMARY AND CONCLUSIONS

Water column profiles sharply differentiated the lower water column of the Little Bay pits from other areas of the Norton Basin/Little Bay complex. In contrast, water quality in the upper water column of the Little Bay pits were very similar to other areas. The near bottom water of the Little Bay pits was cold and anoxic during all surveys. A thermocline, low temperature, and anoxic conditions were persistent features of the Little Bay pits in all surveys but were not present in profiles from all other areas. A persistent turbidity layer above the thermocline and higher salinity further differentiate the lower water column of the Little Bay pits. The profiles indicated that the water column in the Little Bay pits remains highly stratified even throughout the summer and into early fall. The permanent stratification would minimize exchange between the upper and lower water column. Anoxia below a strong thermocline was a persistent condition that was unique to the near bottom waters of the Little Bay pits. The thermocline and low temperatures that promote stratified conditions in the near bottom waters of the Little Bay pits were likely to be among the major factors contributing to its persistent anoxia.

The water chemistry parameters that differentiated the near bottom waters of the Little Bay pits from other areas of the Norton Basin/Little Bay complex also indicated that conditions are highly anomalous for a tidally influenced estuarine environment. Near bottom waters in Little Bay pits were characterized by very high sulfide, high ammonium, phosphate, and dissolved silica, and low nitrate+nitrite, biogenic silica, total chlorophyll, and phaeophytin. The water chemistry of the Little Bay near bottom was more similar to conditions in the sediment rather than in the water column. In contrast, the upper water column in the Little Bay pits and shallows, and the Norton Basin pits and shallows were similar in terms of most water chemistry parameters, along with the reference stations in the Norton Basin Entrance Channel and Grass Hassock Channel. The uniqueness of the water chemistry of the near bottom waters of the Little Bay pits despite diurnal tides with a large amplitude suggests there was minimal exchange with the upper water column of Little Bay and other areas of the Norton Basin/Little Bay complex. The water chemistry data indicate that the lower water column of Little Bay is dominated by high rates of anaerobic decomposition, which is likely a major contributory factor to persistent anoxia in the Little Bay pits. Anaerobic decomposition renders the near bottom in Little Bay pits inhospitable to aerobic organisms due to toxic sulfides in addition to anoxia.

The current meter surveys documented generally slow and complex flow patterns in the Little Bay and Norton Basin pits and their entrance channels. Near bottom current speeds in the Little Bay pit were comparable in general with current speeds in the Little Bay pit midwater and near surface, along with currents in the Norton Basin pits and the two entrance channels. The majority of the current speeds in the Little Bay pit near bottom recorded in the surveys were less than 5 cm/s. The current meter data indicate that the slow near bottom currents in the Little Bay pit do not respond to daily tidal changes as much as the near surface and midwater levels in Little Bay and the Norton Basin pits and entrance channels. The consistently low water temperature and higher salinity in the near bottom of the Little Bay pit recorded in current meters compared with conditions in the upper water column of Little Bay and in the Norton Basin pits and the entrance channels strongly indicate that there is little exchange between the near bottom and upper water columns in Little Bay, and that near bottom circulation is separated from the more tidally influenced upper water column. The slow tidal currents entering Little Bay appear to be inadequate to disrupt the stratified conditions and significantly advect or entrain water from the Little Bay near bottom to allow adequate exchange between the upper and lower water columns in Little Bay. Reduced tidal currents that can only affect the upper water column would allow anoxia in the near bottom of the Little Bay pits to persist.

In addition to high rates of anaerobic decomposition in the near bottom, the anoxia in the lower water column of the Little Bay pits is likely due to and maintained by the lack of exchange or minimal circulation between the upper and lower water column. The evidence that there is minimal circulation between the upper and lower water columns in Little Bay pits in spite of the tidal conditions includes the following:

- presence of a strong thermocline;
- persistent anoxia;
- lower temperature and higher salinity in the near bottom;
- presence of a turbidity layer above the thermocline;
- unique water chemistry, particularly very high sulfide, high ammonium, phosphate, and dissolved silica, and low nitrate+nitrite, low biogenic silica, total chlorophyll, and phaeophytin; and
- slow bottom currents that do not respond to daily tides.

The study showed that the Little Bay pit near bottom waters:

- were highly stratified, cold, and anoxic throughout the late spring, summer, and fall;
- had very high sulfide, high ammonium, phosphate, and dissolved silica, and low nitrate+nitrite, biogenic silica, total chlorophyll, and phaeophytin, which indicate high rates of anaerobic decomposition; and
- had slow currents and minimal exchange with the upper water column and other areas of the Norton Basin/Little Bay complex.

The water column profile, water chemistry, and current data provide complementary information that document the very poor water quality conditions in the Little Bay pits. The data also help explain the persistent anoxia in the Little Bay near bottom. The basin morphology (i.e., basin shape, deep pits, and shallow sills), strong thermocline, and slow currents, along with high rates of anaerobic decomposition are likely the main contributory factors that promote anoxic conditions in the near bottom waters of the Little Bay pits. In contrast to the lower water column of the Little Bay pits, the upper water column and other areas of the Norton Basin/Little Bay complex showed water quality conditions that were typical of temperate estuarine areas that were unimpaired by anoxia and sulfide.

The poor water quality of the Little Bay near bottom waters, particularly anoxia and the presence of high levels of sulfide, indicate conditions that are inhospitable to the aerobic organisms that would be desirable in an estuarine environment, e.g., fish and shellfish. The presence of high levels of poisonous sulfide, along with persistent anoxic conditions in Little Bay pits is compelling evidence that water quality conditions are very poor, and the poor water quality conditions would preclude use of the Little Bay pits as a habitat for desirable estuarine organisms for at least the late spring through the early fall. Given that anaerobic decomposition occurs in the Little Bay near bottom even at temperatures less than 7°C, it is possible that anoxic conditions and sulfides may still be present even during the winter, further precluding the use of the lower water column in the Little Bay pits by aerobic estuarine organisms.

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