THE OCEANOGRAPHIC CIRCULATION OF THE PORT OF SAINT JOHN OVER SEASONAL AND TIDAL TIME SCALES

by

Reenu Toodesh

BSc. Surveying and Land Information, University of the West Indies, St. Augustine, 2007

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Supervisor: John Hughes Clarke, PhD., Geodesy and Geomatics Engineering

Examining Board: Susan Nichols, PhD., Geodesy and Geomatics Engineering

Susan Haigh, PhD., Geodesy and Geomatics Engineering
Katy Haralampides, PhD., Civil Engineering

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ABSTRACT

As part of the sustainable management of the Port of Saint John there is a critical need to maintain sufficient under keel clearance for the various container and cruise ship traffic in and out of the harbour. Because of high and variable sedimentation rates, annual maintenance dredging is necessary and causes economic concerns for the Port. Therefore to better predict future dredging volumes and hence improve the budgeting process for the Port of Saint John, the estuarine circulation of the harbour has been analysed to better quantify the relative importance of the offshore sediments that contribute to the high dredging volumes in the Saint John harbour.

The Port of Saint John lies at the mouth of the Saint John River on the north side of the macrotidal Bay of Fundy. Because of this, the harbour sedimentation is influenced by two major sources of siltation: the Saint John River and the Bay of Fundy. The sediment flux from the river is strongly modulated by the seasonal variations in river discharge. In the Bay of Fundy, there is significant resuspension of offshore marine sediments.

To better understand this complex interaction between the fresh water flow and the tidal inflow of salt water, high density oceanographic surveys have been conducted at four different river discharge periods. In order to quantitatively analyse the mixing of the fresh and salt water in the harbour channels, high density ADCP currents and CTD measurements were acquired along main longitudinal axis of the Main Harbour channel and Courtenay Bay over four tidal cycles. By imaging the 200kHz acoustic volume backscatter within the water column, the appearance of interfacial waves at the

pycnocline can be examined. The optical backscatter sensor provided observations used to estimate suspended sediment concentrations.

A cross-sectional analysis of the flow at a location 700m south and seaward of the Rodney bay terminal in the Main Channel revealed that regardless of the river discharge rate, the interfacial waves are best developed on the rising tide. However, during the Spring freshet the interfacial waves are also developed at high tide, low tide and falling tide. Examination of the timing and location of the interfacial waves are important because they influence the nature of sediment transport in the Main Harbour Channel.

During high river discharge periods, the sediment concentration and volume flux estimates indicate that the river is the main source of sediments. For the low river discharge periods, the observations suggest that the possible source of suspended sediments observed in the lower saline layer are either from outside of the harbour or bottom sediments being resuspended on the rising tide.

ACKNOWLEDGEMENTS

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Last and most importantly I would like to thank my family, Toodesh Ramesar and Nina Toodesh, for your encouragement, financial assistance and love. To my sisters, Vida and Simi I hope I can now join you on your travels. Hamid, you are my joy, thanks for your continuous encouragement.

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Chapter 1: INTRODUCTION – RESEARCH INTEREST

This thesis is part of a greater collaborative research project between the Port of Saint John and the University of New Brunswick aimed at understanding the processes controlling the siltation in the harbour. The single most import process is the oceanographic circulation which is also the main focus of this thesis project.

This information is of great importance to the Port of Saint John because of the need to keep the channels at particular depths for safe navigation of the vessels and cargo ships in and out of the Main Channel and Courtenay Bay. Much of the sedimentation that causes an economic concern for the Port of Saint John occurs in Courtenay Bay. The port normally dredges twice per year, removing relatively large quantities of sediment material from these channels to designated offshore locations such as Black Point. Costs related to investment and maintenance dredging are often critical to the economic functioning of ports. Understanding the physical system of the circulation of the port can contribute to a more sustainable development plan to keep sedimentation rates to a minimum.

This thesis seeks therefore, to understand mainly the oceanographic processes taking place in the harbour, in both the Main Channel and Courtenay Bay. A particular concern of this research is the mixing of two water masses. The nature of this interaction is not limited only to the geometry of the channel, but other factors such as currents, tides and differences in density of the water masses impacting circulation patterns. The main characteristics of Saint John Harbour that affect the salinity and hence density distributions are the climate, the tides, the river discharge and the bathymetry of the area.

Understanding the influences these physical factors have on estuarine circulation of the Saint John Harbour provides a better understanding of oceanographic processes which can be integrated with other studies to help solve sedimentation issues in the harbour. Therefore, the oceanographic processes which affect the source and movement of the sediments should be better understood before attempting any other engineering solutions.

Hence, to assess these influences and patterns, detailed oceanographic tidal cycle surveys were conducted in March 2009, April 2008, June 2009 and November 2008 (approximately 12.42hours) to capture the seasonal variability of the circulation in the Saint John Harbour as influenced by the annual variation of freshwater discharge rates from the Saint John River. This thesis involved the design of the oceanographic surveys, implementation and detailed analyses of these four tidal cycle surveys requiring repetitive steaming of the vessel used along the Main Harbour Channel and Courtenay Bay.

Extensive field data were collected to show how estuarine velocity, salinity, density, optical backscatter and 200kHz acoustic imagery can be analysed to yield a qualitative and quantitative picture of the Saint Harbour circulation patterns.

1.1 Research Objectives

1. To describe the seasonal and tidal variations of the estuarine circulation of the Main Harbour channel and Courtenay Bay of the Port of Saint John.

2. Quantify the net volume fluxes in the Main harbour channel, seasonally (March, April, June and November) over their respective tidal cycles.

3. Examine the relationship between the optical backscatter observations and the suspended sediments as the first step in assessing the relative importance of river derived versus marine sediments.

4. To describe the oceanographic processes and main influences that contribute to the high sedimentation rates in Courtenay Bay.

Sub-Objectives

1. To determine the differences in estuarine circulation over seasonal and tidal timescales.

2. To calculate the fluxes in the upper and lower layers of the flow at instantaneous times of the tide and tidally averaged.

3. Estimate the mixing between the fresh water and the salt water in the Main Harbour Channel. To quantify the mixing that occurs along the high shear zone in the Main Harbour Channel?

Chapter 2: STUDY AREA

2.1. Description of the Study area –Location and description of Saint John Harbour

The study area being addressed is Saint John Harbour which represents the seaward limit of the Saint John estuary system. The Saint John Harbour, Saint John, New Brunswick, is located at the mouth of the Saint John River and lies on the north side of the Bay of Fundy (see Figure 2.1). The river widens near the mouth, then passes through a constriction with a sill called the Reversing Falls to enter into Saint John Harbour [Godin, 1991]. The Saint John Harbour therefore, is the main passage for the freshwater outflow from the Saint John River towards the Bay of Fundy. This study will also make relevant reference to research conducted upstream of the Reversing Falls including Long Reach [Delpeche, 2004], Grand Bay [Hughes Clarke and Haigh, 2005] and the Kennebacasis (Trites, [1959]; Hachey [1939]) estuarine systems.

The upper limits of the Saint John Harbour section of the estuary can be defined as the section through the Reversing Falls where the river discharge outflow competes with the tidal inflow from the Bay of Fundy. As the Saint John Harbour section of the estuary broadens into the Bay of Fundy the seaward limits of the Main Harbour channel can be defined as being the seaward extent out towards Patridge Island. Courtenay Bay experiences insignificant freshwater inflows except from the Main Channel cross flows which occur over the tidal flat between the two channels and a small amount of freshwater flux from Marsh Creek at the head of Courtenay Bay. According to the Port's manager "there's a very low current coming through the Marsh Creek area".

[Somerville, 2011] which confirms the observations in Courtenay Bay. Courtenay Bay can be considered a side basin which lies to the east side of the Main Channel. There is a breakwater structure to the east side of Courtenay Bay which separates it from another mud flat (which is visible at low tide) on the eastern side of Courtenay Bay's breakwater structure. The seaward limit of the Saint John Harbour estuary was defined by Neu (1960) to be between Lorneville and Cape Spencer (see Figure 2.1).

To give a clearer description of the entire Saint John estuary in relation to the Saint John Harbour, present study area, the Saint John Harbour, the topography and the salinity structure of the upper parts of the estuary are described in Chapter 3. The Saint John River flows into the upper end of Long Reach and is abruptly diverted by 90 degrees at the lower end into the Westfield Channel. Downstream, the Westfield Channel opens up into Grand Bay, which, in turn, drains out through a narrow gorge, over the Reversing Falls and through the Main Harbour channel into the Bay of Fundy (see Figure 2.2).

The bottom topography of these sections of the Saint John River estuary is irregular, with depths varying from greater than 60m in the Kennebecasis Bay to 5m at the Reversing Falls (Trites, 1959). The Main Harbour channel is 4500m with a maximum depth of 40m in the inner harbour and a minimum depth of 7.4m at the entrance of the channel. The Main harbour channel is maintained to regular navigable depths of 9m through annual dredging. Courtenay Bay however, is approximately 3000m in length for which the depths are maintained at 5m at low tide for safe navigation. Figures 2.3 shows the bathymetric map of the Main channel and Courtenay Bay. Longitudinal depth profiles along the approximate center of the channel were drawn to show the variation in along channel depths. The Main Channel showed more variation in depth than Courtenay Bay. (See Figure 2.3).

Within Saint John Harbour, the Main harbour Channel and Courtenay Bay are of particular concern for this research because there are two water masses of different physical properties interacting with each other in each channel. This interaction is not limited only by the geometry of the channel, but also influenced by other factors such as currents, tides and differences in density of the water masses, all of which play key roles in understanding the circulation patterns.

In Saint John Harbour, there is variable input of freshwater (salinity, 0‰ to 10‰ in the summer) from the Saint John River that flows through the Reversing Falls before entering the Main Harbour channel under the harbour bridge. As the surface freshwater flows into Harbour, it comes in contact with the incoming salt water (32‰) at rising tide from the Bay of Fundy. For the Courtenay Bay channel there is no significant input of freshwater at the head of this channel therefore, Courtenay Bay channel circulation is attributed mainly to the incoming sources of water from the channel's mouth bounded by the triangle separating it from the Main harbour and the breakwater structure to the eastern side.

The main characteristics of Saint John Harbour that affects the salinity and hence density distributions are the climate, the tides, the river discharge and the bathymetry of the area. Understanding the influences that these physical factors have on estuarine circulation of the Saint John Harbour will provide a better understanding of oceanographic processes which can be integrated with other studies to help solve sedimentation issues in the harbour.

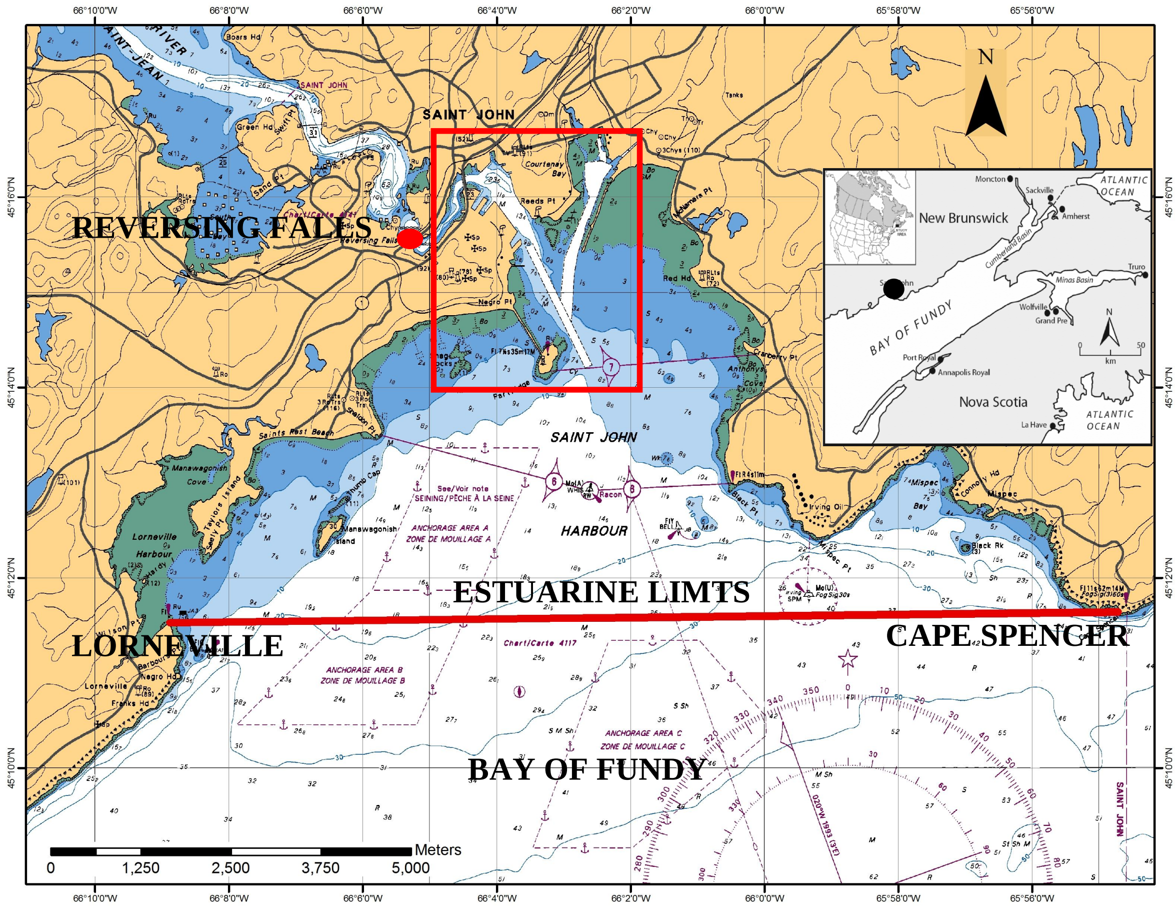


Figure 2.1: Showing the Location of the Saint John Harbour outer estuarine limits between Lornevile and Cape Spencer [Neu, 1960].

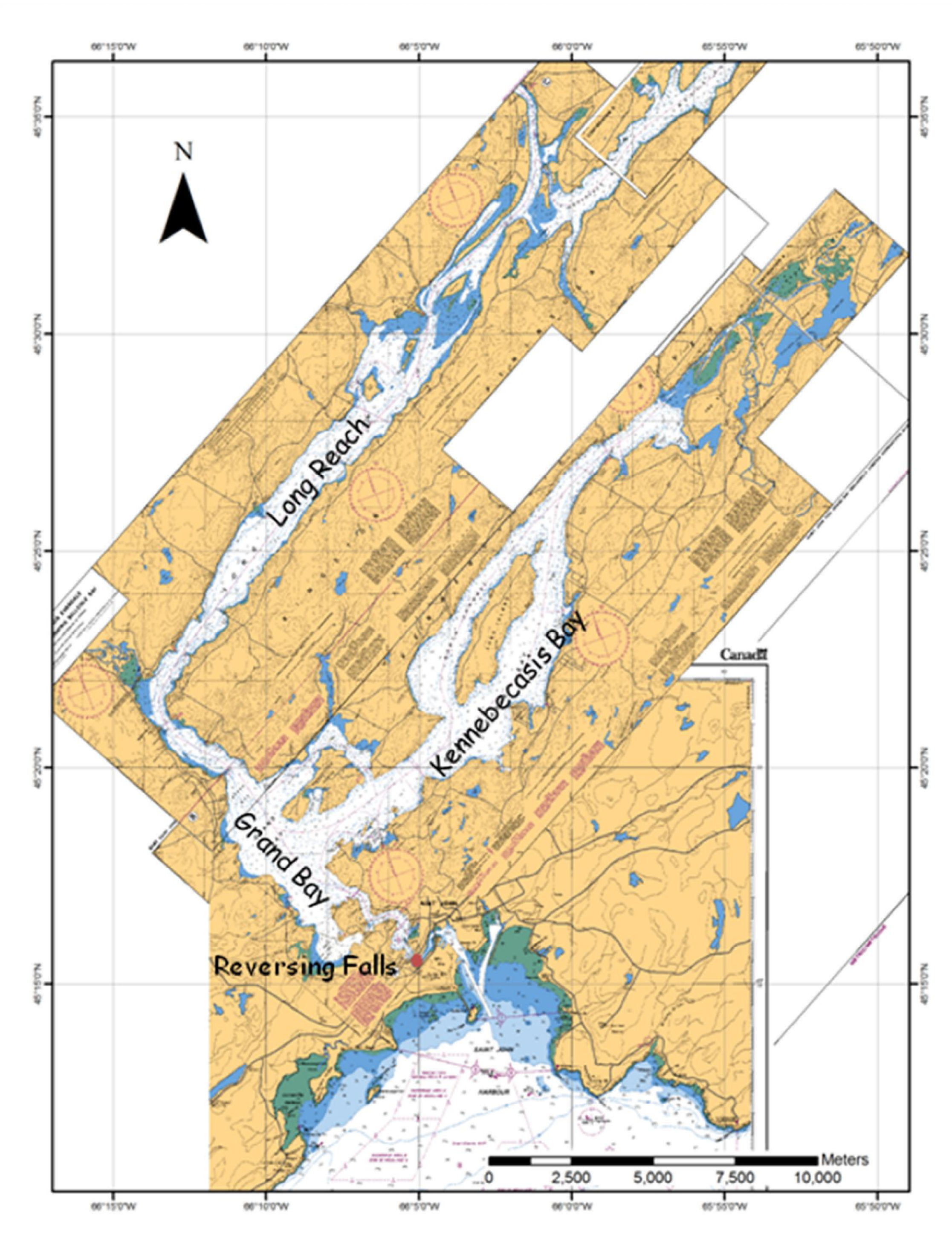


Figure 2.2: Image of the study area Location of the Port of Saint John with respect to the Bay of Fundy. [Canadian Hydrographic Service chart numbers: Saint John #4117 and Kennebecasis Bay and Long Reach #4141].

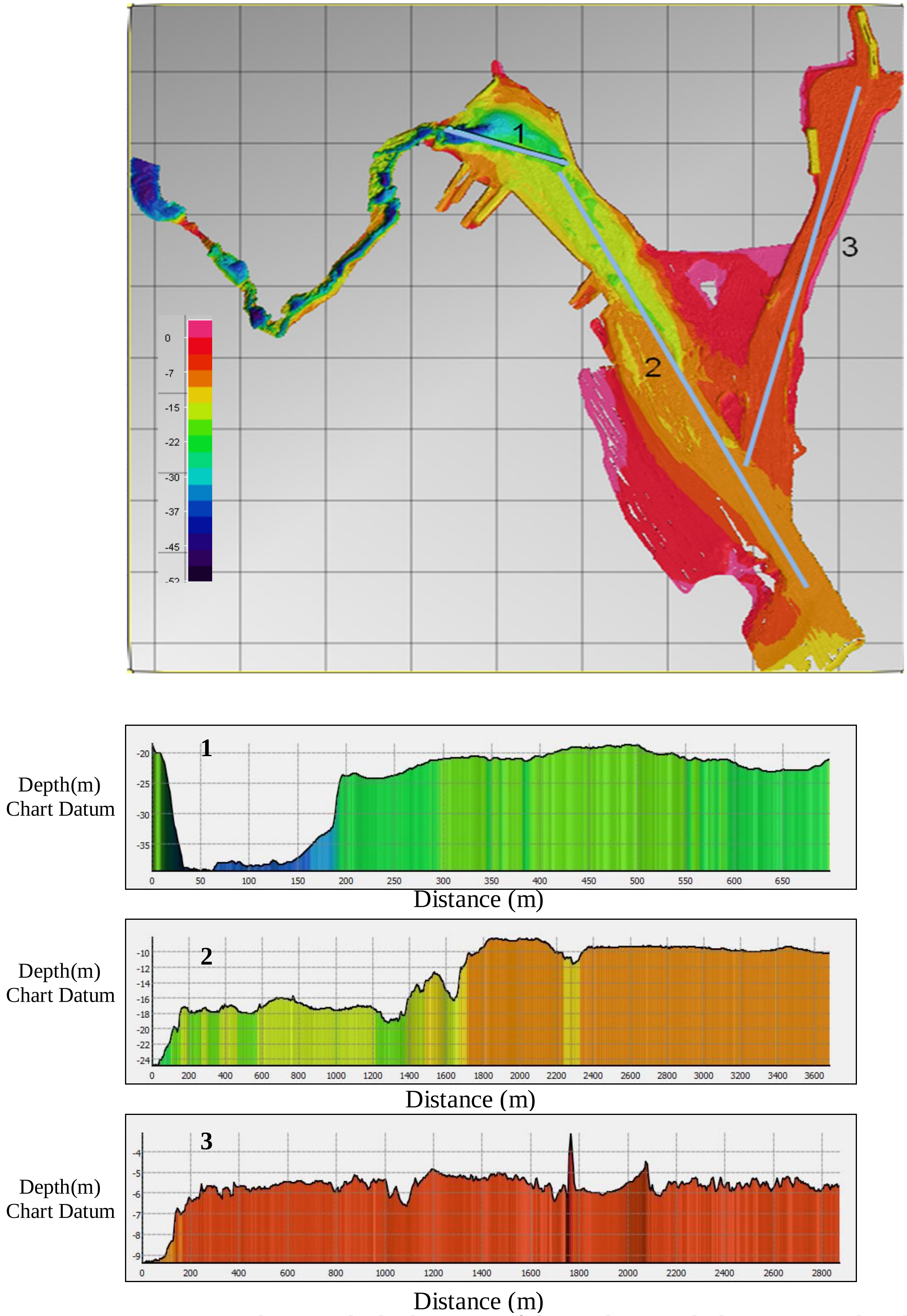


Figure 2.1: Showing the bathymetry of the Harbour with the corresponding longitudinal depth profiles 1, 2 and 3 of the Main Harbour Channel and Courtenay Bay.

2.2 Offshore Wave and Climate Study

To demonstrate the variations in local climate and its effects on the Saint John Harbour, data for mean temperature, total rainfall and snowfall were closely examined for the area with special focus on the times that the survey were conducted. The duration of the four seasons of the region can basically be defined as Spring (March to June), Summer (June to September), Fall (October to November) and Winter (December to March). Saint John Harbour and the Bay of Fundy remains ice free year round making the Port active for shipping traffic throughout the year. The Bay of Fundy has an average summer surface water temperature of between 8-12°C and winter temperatures of 0-4°C. This results in cooler summer temperatures and warmer winter temperatures than inland. [Environment Canada, 2009].

From the historical statistics provided by Environment Canada (2009) (see Figure 2.4), the average air temperature in January is between -7°C and -12°C while the average July temperature is in the range of 15°C and 19°C. July and August historically prove to contain the highest temperatures and January the lowest.

For the rainfall patterns, this fluctuates throughout the year, however historically there seems to be more rainfall during the Spring, from March to June and then again in the Fall during the months of October and November. Comparing the seasons in 2008 and 2009, there was a significant amount of rainfall in July and October 2009, almost twice the amount which occurred in the same months in 2008. However, still there was much more annual rainfall in 2008 (1352mm) and 2009 (1308mm) compared to the historical mean statistics (886mm) (See Figure 2.5). Winter months normally stretch from December to March with the highest amount of snowfall in January. The total annual snowfall in 2009 was approximately (264 cm) which exceeded that of 2008 by approximately 5cm (See Figure 2.6).

An understanding of the variations in annual precipitation and general climatology of the Saint John area is important when commencing the evaluation of estuarine circulation and flow in exchanges between tidal and non-tidal influences in estuaries. For the Saint John area, the inter-annual variability of spring temperatures and precipitation is directly linked to freeze-thaw processes of the ice in the river. All these processes can contribute to earlier thaws, several flooding events and even rainstorm events which would lead to higher freshwater flows reigning from the Saint John River through the harbour region during freshet periods. [Hare et al. 1997].

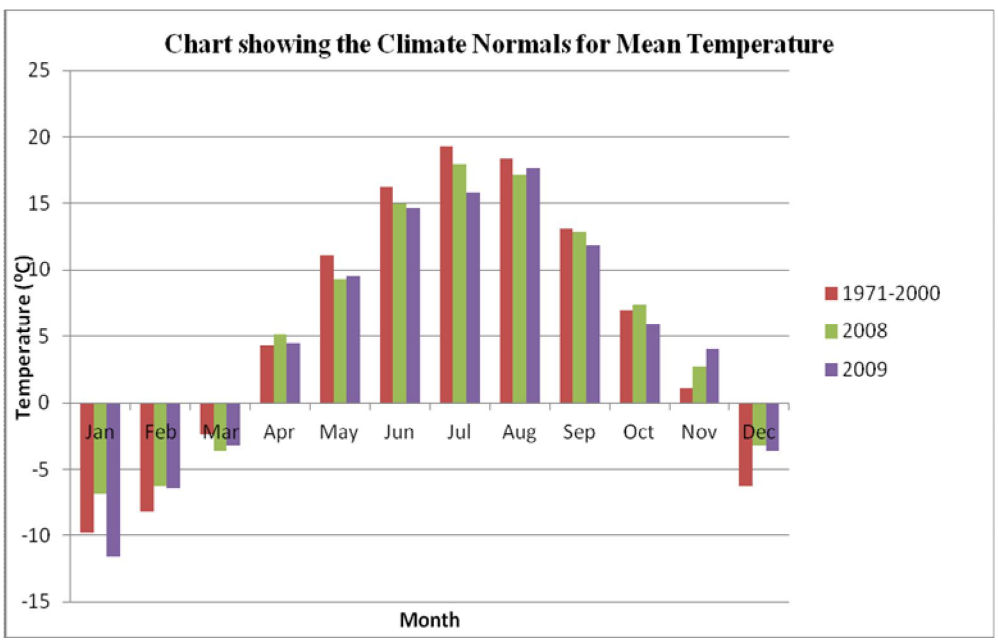


Figure2.4: Showing the Mean Monthly Temperature (2008/2009 versus 1972-2000) for the Saint John region [Environment Canada, 2009].

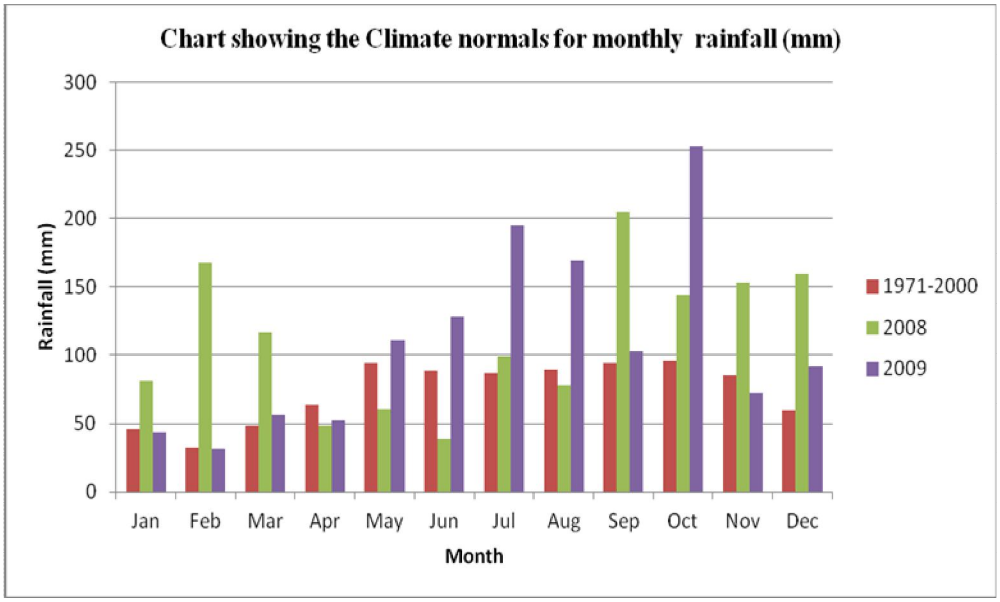


Figure 2.5: Showing the Total Monthly Rainfall (2008/2009 versus 1972-2000) for Saint John region. [Environment Canada, 2009].

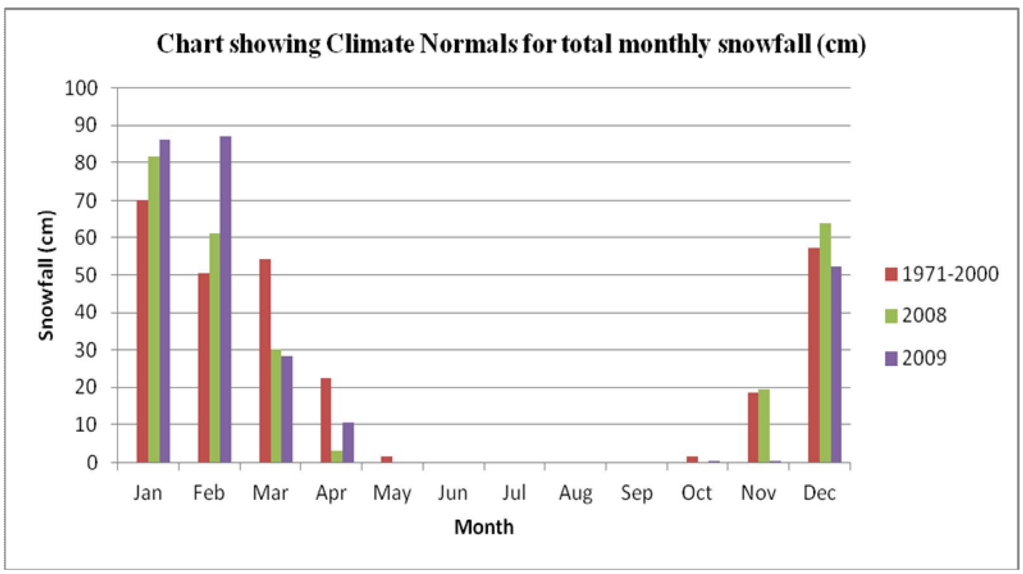


Figure 2.6: Showing the Total Monthly Snowfall (2008/2009 versus 1972-2000) for Saint John region [Environment Canada, 2009].

2.3 Water Levels, Tides and River Discharge

2.3.1 Tidal Influence in the Saint John Harbour study area

The Bay of Fundy has the highest record of tides in the World's Oceans. The reason for these high ranges is due to the fact that the natural period of the Gulf of Maine, Bay of Fundy system is close to, but slightly above, the M2 period of 12.42 hours oscillation [Greenberg, 1979]. The Bay of Fundy configuration resembles a V-shaped channel from Yarmouth located near the southern end of Nova Scotia to Diligent at the northern end of the Bay of Fundy. This "narrowing" passage of approximately 200 miles long slopes upwards from the mouth to the head which forces the incoming water to rise as a result of the combination of the shallowing seabed and the narrowing width towards the head of the Bay of Fundy. The range of the tides from the southern end of Nova Scotia is 6m and as it increases to 16m as it makes its way up into the Minas Basin (see Figure 2.7).

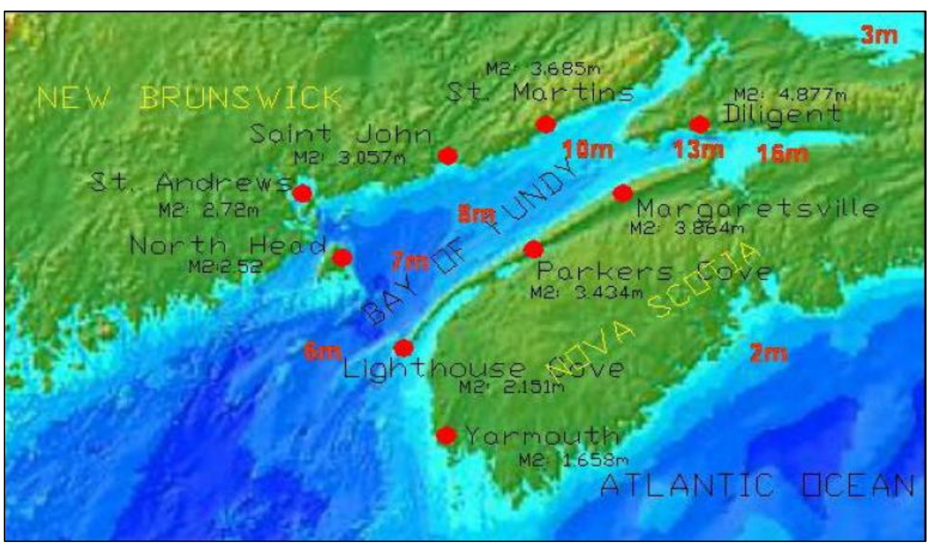


Figure 2.7:Showing the tidal ranges at various locations in the Bay of Fundy and Nova Scotia. The M2 tidal amplitude is 3.057m in Saint John. [from Delpeche, 2006, pg 13].

2.3.2 River Discharge

The Saint John River, which flows through the Provinces of New Brunswick and Quebec and also the State of Maine, has a total drainage area of approximately 59,570 km^2 [Neu, 1960]. There is monthly freshwater discharge variability and an even more dramatic change in volume inter-annually depending on changes in climatology parameters. The freshwater discharge from the Saint John River itself is estimated to range from about $500m^3s^{-1}$ in the summer (June – August) and peaking at $3400m^3s^{-1}$ in the spring freshet(April – May) (see Figure 2.9). The highest or dominant flows in the Saint John River system result from the spring snowmelt in the upper and lower portions of river and the lowest occur during very cold winter weather during the freezing season with the next lowest period being mid-summer with minimum precipitation. Additionally, there is a secondary peak freshet or moderate discharge period in the Fall before the freeze-up from August to November, until mid or late December. Here the mean annual flow in April and May is about six times greater than the Winter and Summer flows (see Figures 2.8 and 2.9). Figures 2.8 and 2.9 are statistical averages from the river gauge located at Pokiok, which is the closest to the Port of Saint John

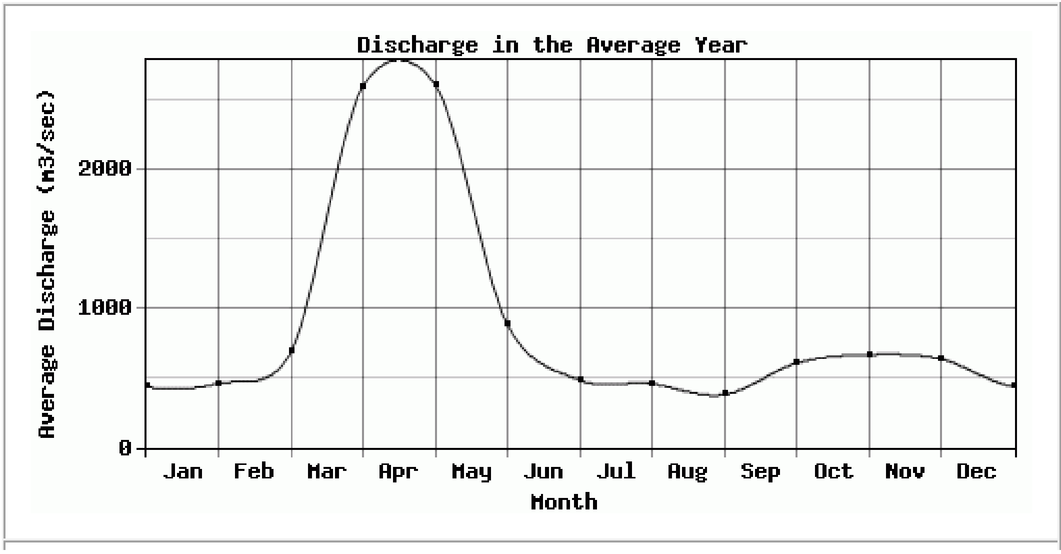


Figure 2.8: Monthly averaged river discharge composed from a database from 1973 - 1984 (HYDAT-Environment Canada) for the station Pokiok. [Water Survey of Canada, 2009]

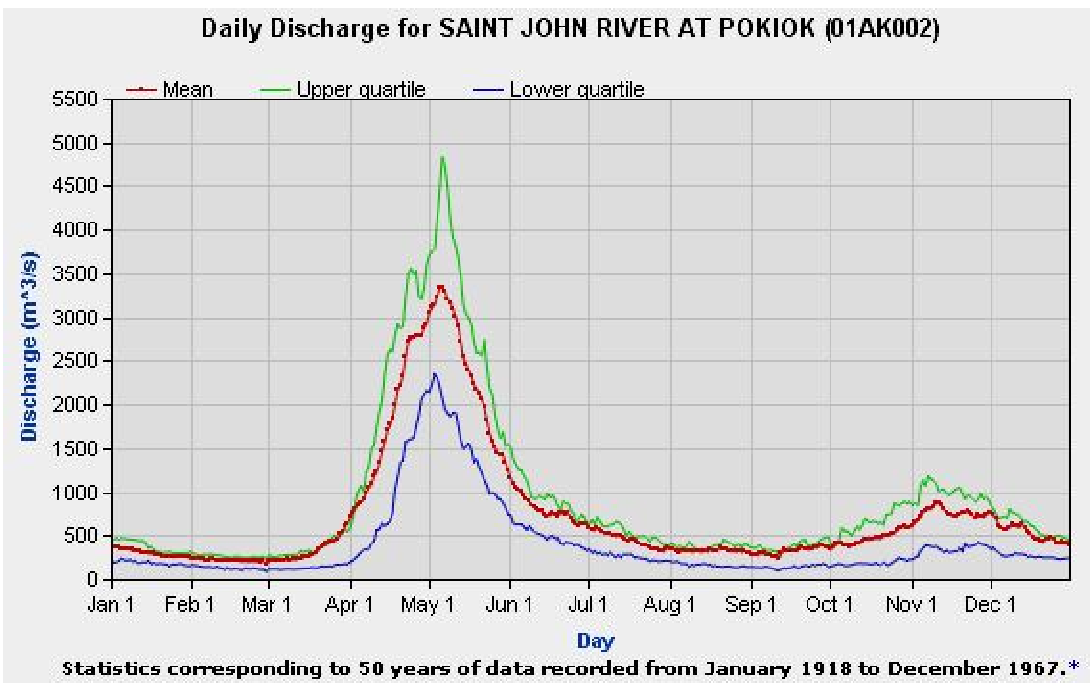


Figure 2.9: Showing the Discharge Flow at the Pokiok Station from 50 years of acquired data. [HYDAT-Environment Canada, 2009].

2.3.3 River Water levels for the Oceanographic Surveys of the Saint John Harbour

During different times of the year, there are seasonal changes in the river water levels and river discharge rates. From Figures 2.10 and 2.11, there is a clear indication from the historical (40 years of data) water levels and the observed water levels in 2008 and 2009 at the time of the oceanographic surveys, that the peak river flows, occur in Spring and in late Fall. However there are yearly variations in the magnitude, timing and extent of these freshets. [Metcalfe et al, 1976].

In the Saint John Harbour the large tides are opposed by the strong river outflow into the harbour during the river peak outflows at different times of the year. Therefore, in order to understand the influences of the non-tidal water level variations caused by the seasonal changes in the river discharge levels, observed water levels at the Indiantown tide gauge were examined for the tidal cycles deliberately conducted at these four river level stages. As seen in Figures 2.11, the maximum spring freshet occurs in late April or beginning of May and is always greater than that of the Fall freshet in November.

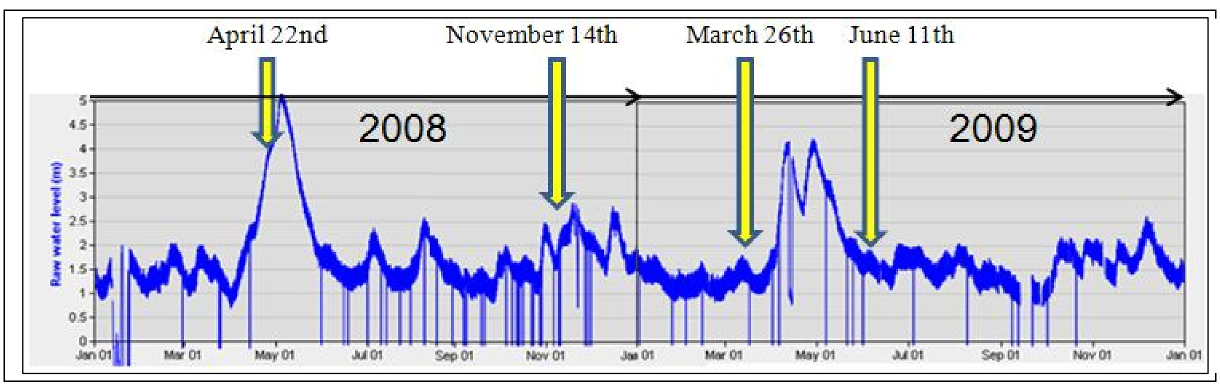


Figure 2.10: Comparison of Annual water level curves at Indiantown tide gauge (April 22nd, November 14th, March 26th and June 11th) during different seasons which reflect varying fresh water discharge rates upstream of the Reversing Falls. [Environment Canada, 2009, Hughes Clarke 2009].

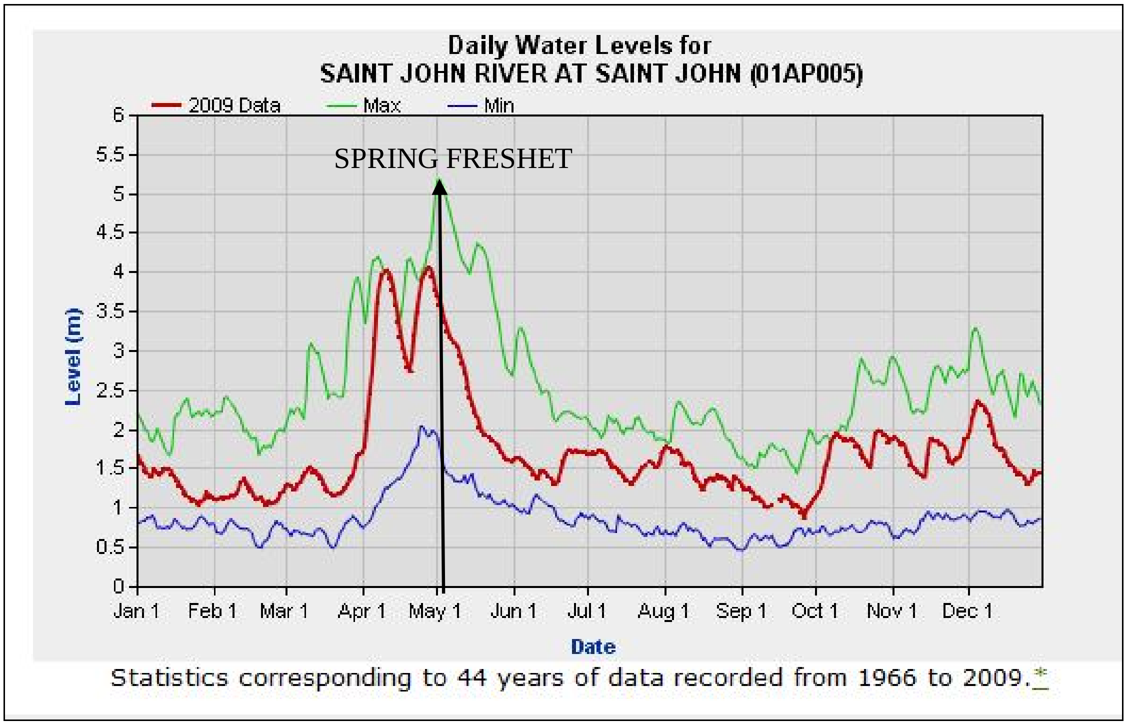


Figure 2.11: Historical statistics of Daily mean river levels from 1966 to 2009. [Environment Canada].

Historical water levels and flood events are very fundamental in understanding its effects during the spring freshets when the ice is melting and the rainfall precipitation is significantly high because this brings about high river discharge rates. Environment Canada always keeps a close watch at the gauge station in Fredericton lest the water levels near Fredericton reach a flood level stage of 6.5m where at this time flood alerts are publicised. There have been serious damages due to flooding in the past such as in the year 1973 where the water levels reached a high of 8.61m. Also, recently in 2008, (the year of the April and November freshet observation for this thesis), the water levels rose to a height of 8.36m, 0.25m less that the 1973 flood event. The peak water level at Saint John is typically ~3m less that Fredericton which is still enough to prevent the Falls from reversing.

Table 0.1: Showing the Saint John River Flood Levels. (Environment Canada, *Water Survey of Canada*)

HISTORIC WATER LEVELS (m)

Years		1962	1970	1973	1976	1979	1981	1983	1986	1987	1993	1994	2003	2005	2008
LOCATIONS	Flood Level (meter)														
Clair / Fort Kent	156.2	----	----	156.84	----	157.31	----	----	----	----	----	----	----	156.27	158.18
Edmundston	139.0	----	----	-----	----	141.41	----	----	----	----	----	----	----	140.10	143.10
Perth Andover	77.2	-----	-----	-----	78.20	-----	-----	-----	-----	79.30	78.70	77.25	-----	-----	78.29
Simonds	48.5	-----	-----	-----	-----	-----	-----	-----	51.16	49.26	47.86	48.95	-----	50.12	49.64
Hartland	45.7	-----	-----	-----	47.68	-----	-----	-----	48.01	47.72	45.82	-----	-----	46.97	47.91
Woodstock	41.4	-----	-----	-----	43.08	-----	-----	-----	40.62	44.02	43.14	42.44	-----	-----	41.83
Nashwaak (Durham Bridge)	21.0	-----	21.61	22.25	-----	20.98	-----	21.31	-----	-----	-----	21.26	-----	-----	
Kennebecasis (Apohaqui)	13.0	13.435	-----	-----	-----	-----	13.67	-----	-----	-----	-----	-----	13.451	-----	
Fredericton	6.5	-----	-----	8.61	-----	8.06	-----	-----	-----	-----	6.60	7.87	-----	7.83	8.36
Maugerville	6.0	-----	-----	7.11	-----	6.47	-----	-----	-----	-----	5.58	6.43	-----	6.49	6.92
Jemseg	4.3	-----	-----	6.36	-----	5.50	-----	-----	-----	-----	4.52	5.17	-----	5.69	6.11
Grand Lake	5.0	-----	-----	6.45	-----	5.68	-----	-----	-----	-----	4.51	5.19	-----	5.83	6.24
Sheffield-Lakeville Corner	5.1	-----	-----	-----	-----	-----	-----	-----	-----	-----	4.53	5.25	-----	5.94	6.45
Oak Point	4.7	-----	-----	5.74	-----	4.74	-----	-----	-----	-----	3.89	4.45	-----	4.98	5.36
Quispamsis-Saint John	4.2	-----	-----	5.31	-----	4.54	-----	-----	-----	-----	3.75	4.27	-----	4.83	5.20

The quantity of freshwater flow delivered through the Saint John River system can have a significant effect on the upper and lower parts of the Saint John River estuary where there is also a tidal influence from the Bay of Fundy. The discharge can affect the freshwater/saltwater balance of the estuary which is directly linked to changes in vertical salinity distribution and the shoaling patterns [USACE, 1991]. During the Spring freshets the constant discharge of freshwater flowing out through the Reversing Falls gives rise to enhanced density driven flows in the Saint John Harbour section of the estuary where the freshwater discharge competes with the tidal flow which enters and exits the Main Harbour channel and Courtenay Bay twice every day.

As part of the investigation into the oceanography of the harbour, four series of tidal cycle experiments were designed to capture the seasonal variation of the flows in the Main Channel harbour and Courtenay Bay. Two tidal cycle surveys were conducted in April and November of 2008 during the freshet conditions and the remaining two in March and June of 2009, during the minimum discharge conditions (see Figure 2.10). Figure 2.12 shows the graphs of the four tidal cycles which also coincides with the four river level stages (winter minimum, spring freshet, summer minimum and fall freshet). The November tidal cycle survey was conducted during a spring tide unlike the other tidal cycles. The observed tidal data from the tide gauge located at the mouth of the harbour were not available for all four datasets. Therefore for consistency in the reporting, the tidal data used for representation and analysis were the predicted tides (see Figure 2.13) obtained from Canadian Hydrographic Service [2009].

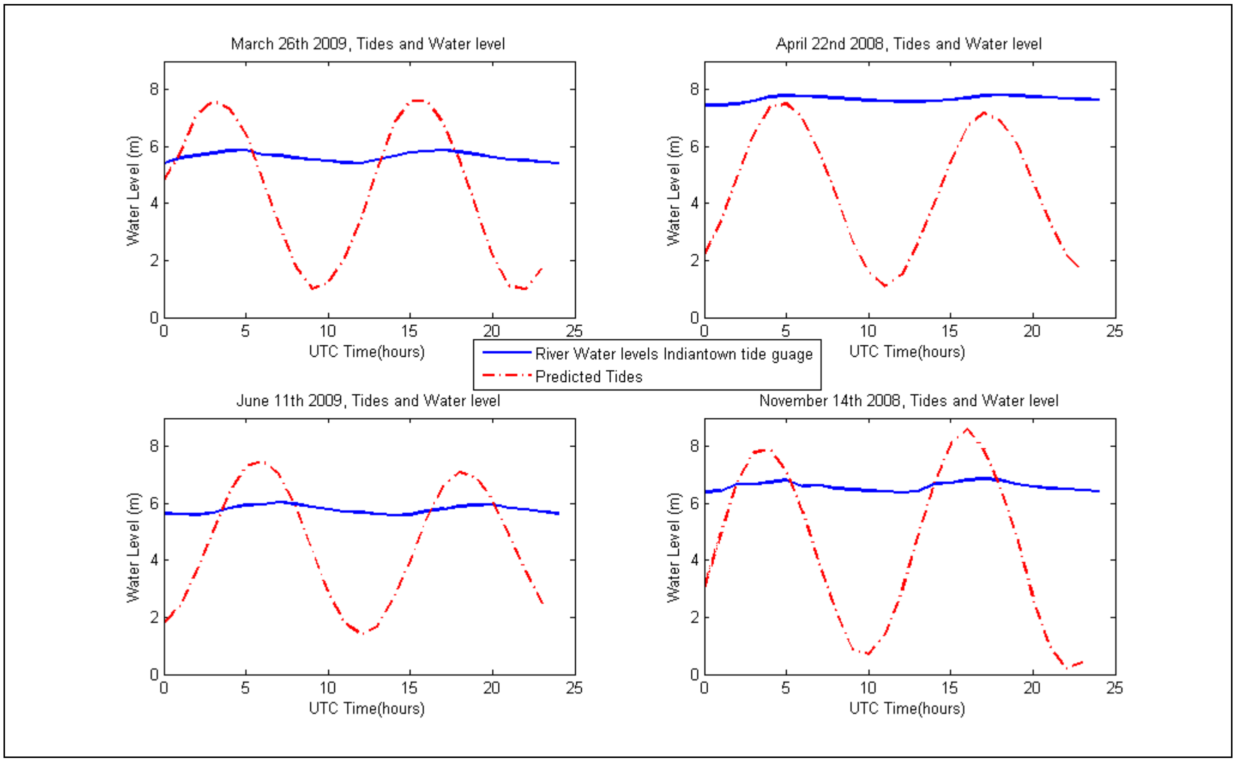


Figure 2.12: Relationship between the Tidal elevations at the mouth of the Saint John Harbour (Pugsley Terminal) and the water levels at Indiantown tide gauge (relative to chart datum) above the Reversing Falls for all surveys conducted for this project.

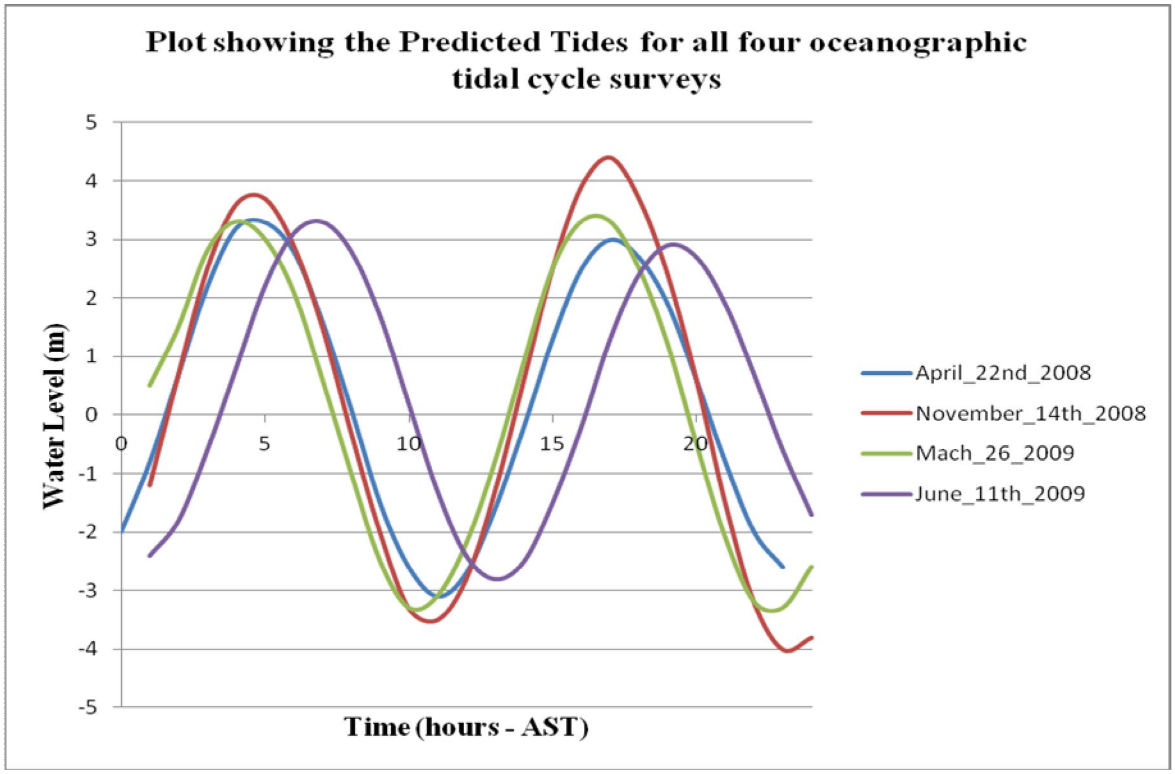


Figure 2.13: Plot showing the Predicted Tides during all four survey operations (March 26th 2009, April 22nd 2008, June 11th 2009 and November 14th 2008).

2.3.4 Wind and Wave Activities affecting the Saint John Harbour

Another factor to consider that might interfere with the interaction between the river outflow and the spring – neap tidal variations is the wind forcing and the direction of the winds in the Main Channel and Courtenay Bay. Winds are strongest and highly variable in the colder months from October to March and blow most frequently from the west or northwest as the cold arctic air moves in. In the summer, winds from the southeast or south predominate. Figure 2.14 and 2.15 show the hourly wind speeds and directions for the dates that the surveys were conducted in the harbour.

The maximum wind speeds are observed during the months of March 26th 2009 and November 14th 2008 with wind speeds exceeding 22km/h. For March 26th 2009, the directions the winds were predominantly from the North. On April 22nd 2008 the winds dominated from the south and for June and November surveys the wind directions prevailed from the south-easterly direction.

Thus, for the case of the four tidal cycle surveys, the wind speeds were unremarkable and given the protected nature of the harbour it did not have a significant impact on the harbour circulation. In the case of a major storm event however, this might affect the inner harbour areas.

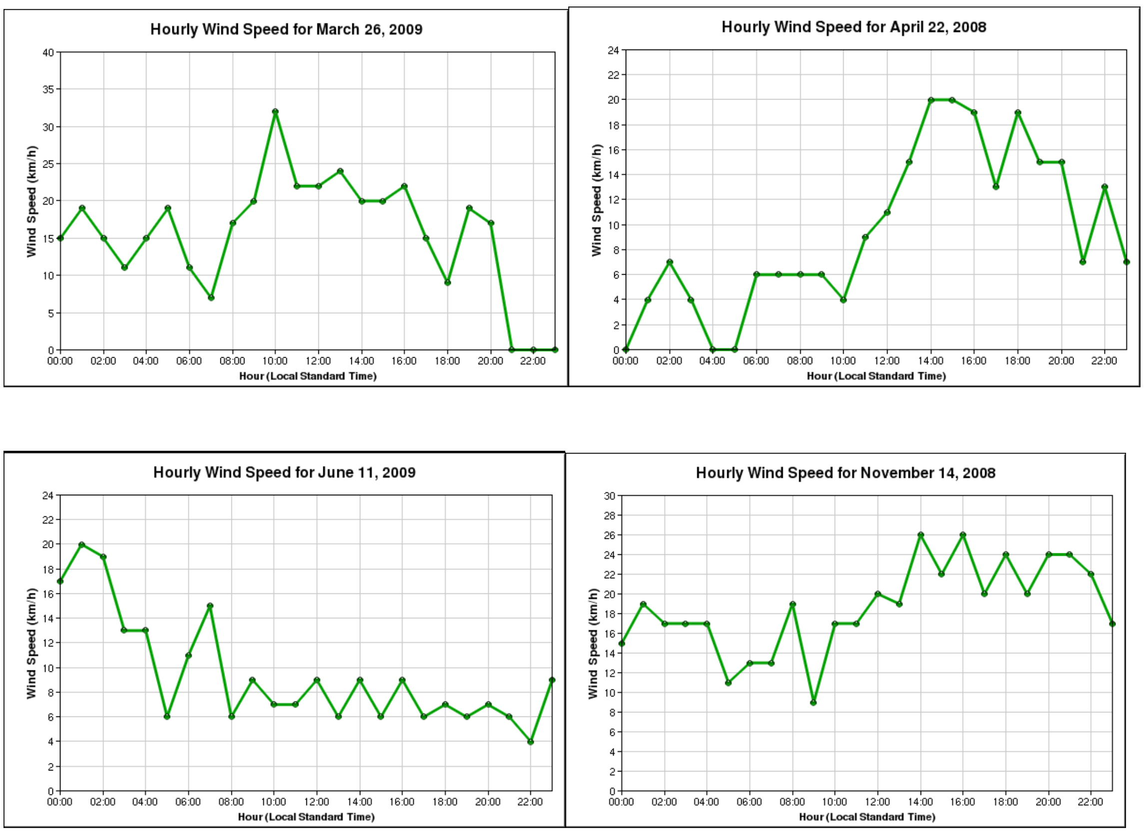


Figure 2.14: Graphs showing the hourly wind speed for the surveys conducted in March April, June and November respectively [Environment Canada, 2009].

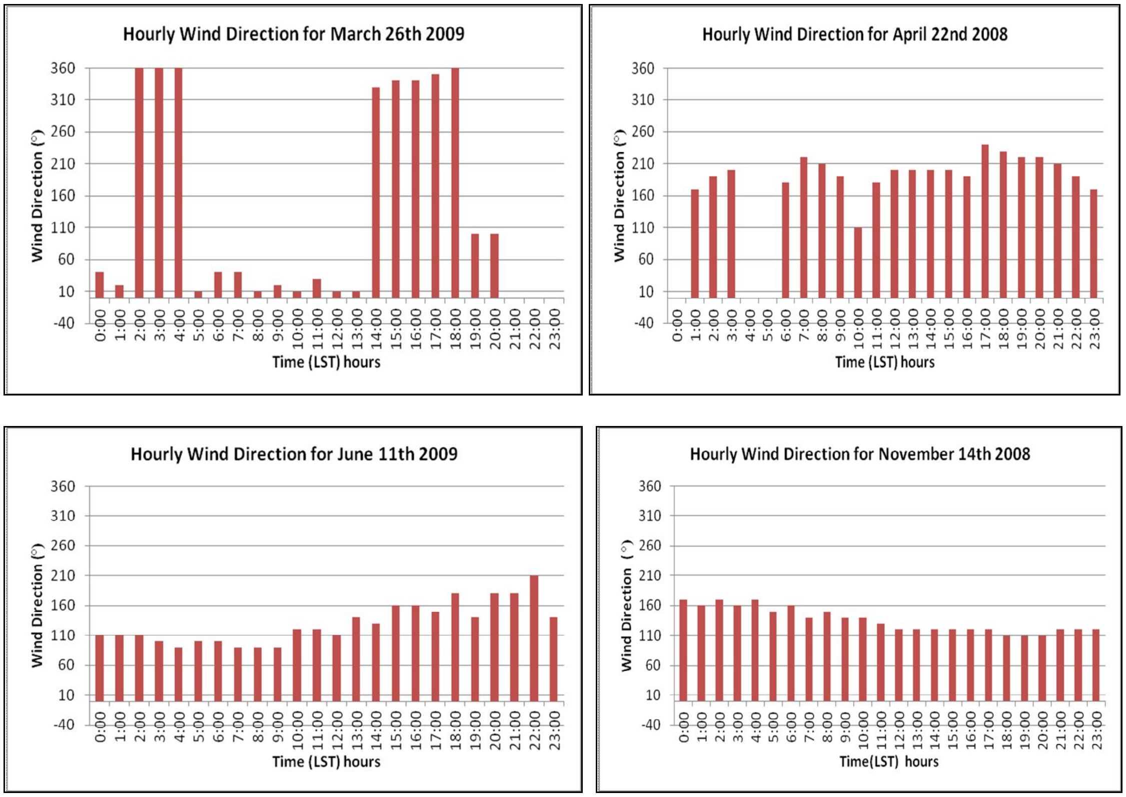


Figure 2.15:Graphs showing the corresponding wind direction for the surveys conducted on March, April, June and November respectively [Environment Canada, 2009].

2.4 Siltation processes in the harbour

The mechanism behind the siltation in Saint John Harbour is of major importance to the Port of Saint John because it is a busy shipping channel which needs to be operational at all times. The Port conducts annual maintenance dredging in the harbour, Main Channel, Courtenay Bay and the berthing areas for the ships, for which most of the dredging and high costs are incurred in the berthing areas and Courtney Bay. It is relevant to note that the main local sources of sediments are from the River, the Bay of Fundy and the eroding coastlines [Leys, 2007].

In order to begin understanding the siltation process or the transportation processes of sediments in any harbour, one has to first understand the circulation of the waters in which the sediments are being transported and also the availability of the sediments. The estuarine sedimentation processes in the harbour are highly correlated with the current velocities and salinity differences of the waters in which the two main sources of sediments can be found. Field studies conducted here have shown that the transportation of the sediments are directly linked to either the river derived sediments which appear in the upper fresh water layer carried downstream from the river discharge or resuspended sediments from offshore carried upstream in the lower salt water. Note that these offshore resuspended sediments were perhaps predominantly originally derived from the river flow. Hence understanding the oceanographic influences can improve the estimations of seabed erosion and accretion patterns over seasonal and tidal changes.

The distribution of the sediments is affected by two physical phenomena present in the Saint John Harbour estuary; the bed shear stresses of the currents during the high and low tide which control the ability to erode or deposit sediments and longitudinal salinity distribution over a tidal cycle which control flocculation of sediments. Assessing the salinity distribution along both channels in the harbour can help determine the sediment concentrations (obtained from the optical backscatter) in both the freshwater layer and the salt water layer. The salinity measurements are important also because it primarily determines the nature of the estuarine flow in the harbour. The salinity affects the settling velocity of the suspended clay-sized sediments by either aiding or hindering the flocculation process. The flow of the water can transport the material contributing to siltation in basically two ways:

1. As a suspended load which is held in suspension by the upward components of turbulence. In the parts of the harbour where there is little or no current activity, for instance in the berthing areas and along the Courtenay Bay channel, the sediments transported in the water settle more in these areas.
2. As a bed load that consists of particles that are pushed or rolled along the bottom of the seabed.

What controls the rate of sedimentation or transportation of materials is the local current field of the estuary system because this affects whether the sediments being transported will either be trapped and begin to settle out or move along the length of the estuary. The effects of the tidal currents, the river outflow and hence the circulation pattern is therefore responsible for the dispersal of the sediments in the study area. According to Figure 2.16 (Leys, 2007), in the Main Channel are mostly made up of sand and silt, with a negligible amount being that of clay. Courtenay Bay channel however consists of approximately 70% of silt, with approximately 25% of it being fine sand, most probably found in the outer parts of Courtenay Bay. Also it is clearly indicated by the chart that the predominant sediment type found in the SW and NE Marine Wharf areas is sand with the presence of gravel material as well. This would mean that in these areas there is greater energy in the flow present because of the bigger grain size distribution of particles found in this area which is not of dredging concern to the Port. In contrast, in the areas being dredged, smaller fine grained particles are found on the seabed.

Matheron [2010] collected field samples from July 2009 to June 2010 and showed that almost all dredged material from the harbour was organic silt. Matheron also noted that *"the suspended sediment composition is the same regardless of the water layer the* *particles are in; they are mainly composed of organic silica, quartz, muscovite and biotite"*. For a more in depth look at the grain size distribution of in-situ measurements taken along The Main Channel, Courtenay Bay, the mouth of these channels and on the eastern side of the breakwater structure, the experimental data presented by Matheron [2010] can be referred to.

As part of this extensive collaborative project to determine the hydrodynamic and sedimentation in the harbour, Commandeur [Unpublished] is has investigated the seabed change in the harbour. The research uses the acoustic backscatter images provided by the EM3002 echo sounder. The backscatter images can help us determine seabed sediment characterization by providing a stable map of significant contrast in seabed backscatter strength [Commandeur, Unpublished]. From Figure 2.17 there is a noticeable difference between the bottom sediment types distributed along the channels and the outer harbour area. The high backscatter strengths (bright areas) are representative of the coarser material such as gravel and sand. The lower backscatter strengths (dark areas) are representative of the fine sediments such as fine sands and clay. A bathymetric difference map of the hydrographic surveys conducted in April 2008 and May of 2009 are presented in Figure 2.17 showing significant accretion patterns in Courtenay Bay channel. In the Main Channel most of the accretion patterns are shown in the berthing areas of the harbour.

It is imperative to support the field experiments conducted by Matheron [2010] with oceanography data in order to understand the circulation, current regime, tides and salinity distribution that are factors with affect the distribution of the sediments in the Main Channel and Courtenay Bay. This thesis gives a qualitative description and quantitative analysis of the oceanographic data collected which aids in describing the oceanographic circulation of the harbour.

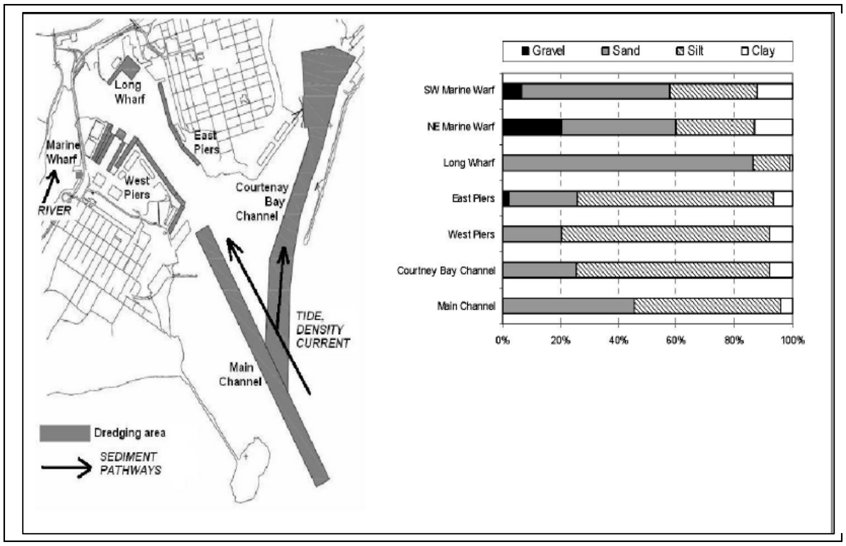


Figure 2.16: Showing the Saint John Harbour target areas for dredging and grain size distribution. (from Leys [2007, p.5]).

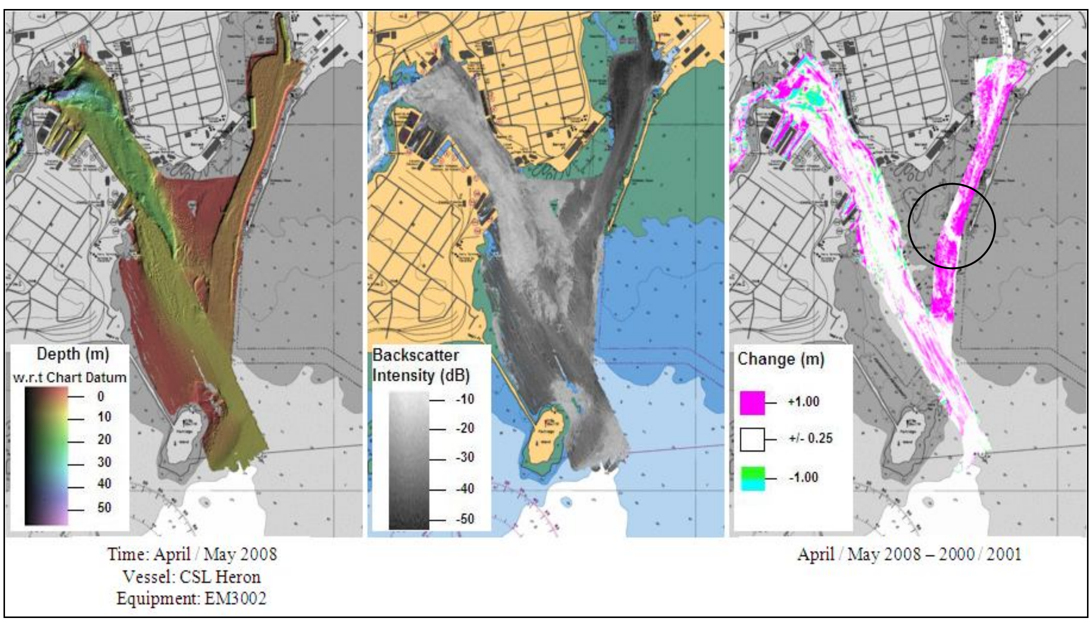


Figure 2.17:Maps from survey April/May 2008. (Left) Map with the bathymetry depths in color and relief sun-illumination at 315° azimuth, and 45° elevation. (Middle) Map with the seabed backscatter strength high absorption are dark and high reflection are light. (Right) Illustrating the depth change calculated by differencing 2009-2000. [Commandeur, Unpublished].

Chapter 3: ESTUARINE CIRCULATION AND SEDIMENTATION CONTROL

3.1 Review of the characteristics of the Saint John Estuarine System

Estuarine classification can be based on several factors due to their wide range of forms. These different forms are developed based on the basic principle of the interaction between the river and marine processes. Therefore there are several important characteristics used to classify estuaries, some of which are as follows:

a) The mode of formation of the estuary or basin which is related to the topography and geomorphologic features.

b) The dominant driving forces such as wind, tides and fresh water influences

c) The characteristics of the circulation pattern and therefore the salinity structure of the estuary.

The hydrodynamics of the section of the Saint John Harbour, which is the seamost part of the Saint John estuary system is subject to a combination of multiple processes including the topography of the Reversing Falls and the harbour, the tidal processes (large tides in the area) and the seasonally variable freshwater discharge from the Saint John River which drains through the Reversing Falls into the Main channel of the harbour. These important parameters give rise to the salinity structure which varies seasonally with the fresh water discharge from the Saint John River which flows into the harbour. The density stratification and the mixing processes within the harbour section of the estuary are classified based on their salinity and velocity flow characteristics. (Dyer, 1997).

Pritchard [1955] and Cameron and Pritchard [1963] classified estuaries into the following four main types based on the salinity structure of an estuary, which are:

1. Highly stratified or salt wedge
2. Partially mixed
3. Well mixed
4. Fjord type

Pritchard [1955] defined an estuary "as a semi-enclosed coastal body of water which has a free connection to the open sea, extending into the river as far as the limit of tidal influence, and within which seawater is measurably diluted with freshwater derived from land drainage".

The entire lower Saint John River Estuary can be broken up into sections that are classified quite differently. For this project the estuary section inland limit will be defined by the Reversing Falls and the outward limit as the boundary between Lorneville and Cape Spencer out in the Bay of Fundy (see Figure 2.2). The Saint John Harbour cannot be defined as just one of the above four classifications and therefore in later sections it will be seen that the harbour exhibits characteristics of a stratified and partially stratified type estuary. This again is due to the large seasonal variation of freshwater discharge through the Reversing Falls and the tidal fluctuations experienced in the harbour.

The most significant feature which affects the flow and the characteristics of the Saint John Harbour and the upper estuary system is the Reversing Falls [Metcalfe et al. 1976]. The upper sections of the estuary, such as Long Reach and Kennebacasis show salt wedge fjord type characteristics respectively. As for well mixed estuary features, the Bay of Fundy shows close relation to this type. In the Bay, the influence of the high tidal range and the wave activity from offshore produces enough turbulence and velocity shear to mix the water column.

3.1.1 The Reversing Falls

Upstream of the Saint John Harbour there is a unique point of interest known as the Reversing Falls. The river discharges into the harbour across a 200m wide ridge then through a shallow and narrow rock ridge which is 5m in depth. Knowing the dynamics of the Reversing Falls is very important when trying to understand the circulation in the Port of Saint John because it acts as a hydraulic control point for the Reversing Falls flow system [Leys 2007]. The configuration of the sill along with the rise and fall of the tide cause variation in water levels on either side of the sill. At high tide and normal river levels, the water level on the seaward side of the Reversing Falls is higher than the river level, causing the inflow from the Bay of Fundy to rise over the Reversing Falls sill. Therefore there is a net flow of seawater flowing upstream. At falling tide, the flow reverses (see Figure 3.1). During the high river discharge Spring freshet, the water level on the landward side of the sill is always higher at all phases of the tidal inflow of the Bay of Fundy (see Figure 2.13). The net flow is thus always seaward at this point and the Falls do not reverse.

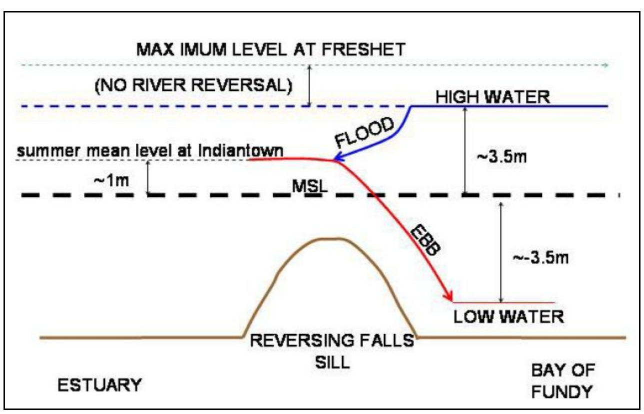


Figure 3.1: Showing the flow over the Reversing Falls at high tide, low tide and high river discharge (from Delpeche [2006, p.33]).

3.1.2 Kennebacasis Bay

The study done by Trites [1959] indicates that the Kennebacasis Bay is an example of a fjord-like estuary above the Reversing Falls with maximum and average depth of 60m and 35m respectively. At the entrance of the Kennebacasis Bay, there is a sill of 11m in depth which restricts the flow between the estuary waters and the Kennebcasis Bay waters making the temperature and salinity distribution seasonally variable from the surface to the bottom. The Bay is a distinct two layer system with a permanent pycnocline present. The surface layer of 5-10m is brackish with salinity varying from 1-10‰ and a deep layer of 21-23‰ which remains relatively constant. The surface temperatures are influenced by surface heating and vary from 0-20°C while the bottom temperatures remain at about 4.9°C. Trites [1959] concluded that the mixture of the Bay of Fundy water and fresh water from the river at high tide, would flow over the sill at the head of the Kennebacasis Bay and inward towards the bottom of the Bay. However, in contrast, research done by Hughes Clarke and Haigh [2005] suggests that the water which flows over the sill does not sink to the bottom, but instead "triggers an internal wave" along the density interface of the two layered system. This implies that the mixture of water flowing over the sill into the Kennebacasis Bay would have similar density structure to that at the density interface. [Haigh and Hughes Clarke, 2005].

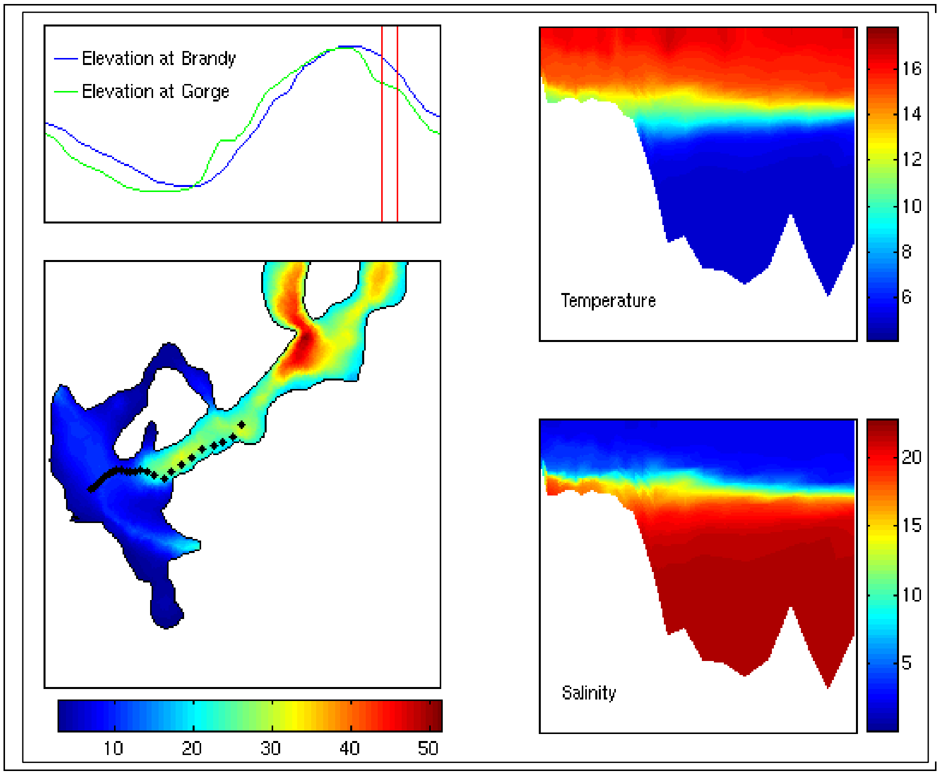


Figure 3.2: Observations made from Saint John River into Kennebecasis Bay. [Haigh, and Hughes Clarke, 2005].

3.1.3 Estuarine characteristics of the Saint John Harbour

There are a few historically significant studies conducted on the hydrographic features and the oceanography of the Saint John Harbour. These include Hachey [1939], Trites [1959] and Neu [1960]. Hachey's [1939] study focused on an investigation of the salinity distribution between the Reversing Falls and in the vicinity of the Sugar Refinery located on the eastern side of the Main Harbour channel. The goal of the study was to determine the relationship between the freshwater discharge through the Reversing Falls and the harbour salinities. Neu [1960] however, was the most detailed hydrographic study done which included the Main Harbour Channel and Courtenay Bay.

The two major influences on the estuarine characteristics of Saint John Harbour are:

1. Freshwater flow from the Saint John River and

2. The salt water inflow from the Bay of Fundy

When these two flows meet, they form density currents due to the differences in the density of the fresh and salt water. These two flows can be looked at as a two layer flow represented by the distinction of the freshwater flow from the Saint John River having a density of approximately $1000 kgm^{-3}$ and the tidally driven seawater from the Bay of Fundy having a density usually greater than approximately $1024\ kgm^{-3}$. Therefore the Saint John Harbour estuarine circulation can be characterised by the mean surface outflow from the Saint John River and the bottom inflow from the Bay of Fundy. Volume flux calculations presented later in this thesis will examine the relative magnitude of these two flows.

Neu [1960] conducted extensive hydrographic surveys during the summer of 1958 and during the spring of 1959. Neu designed the surveys for the Saint John Harbour and Courtenay Bay to include 70 stations along the Saint John estuary and the harbour.

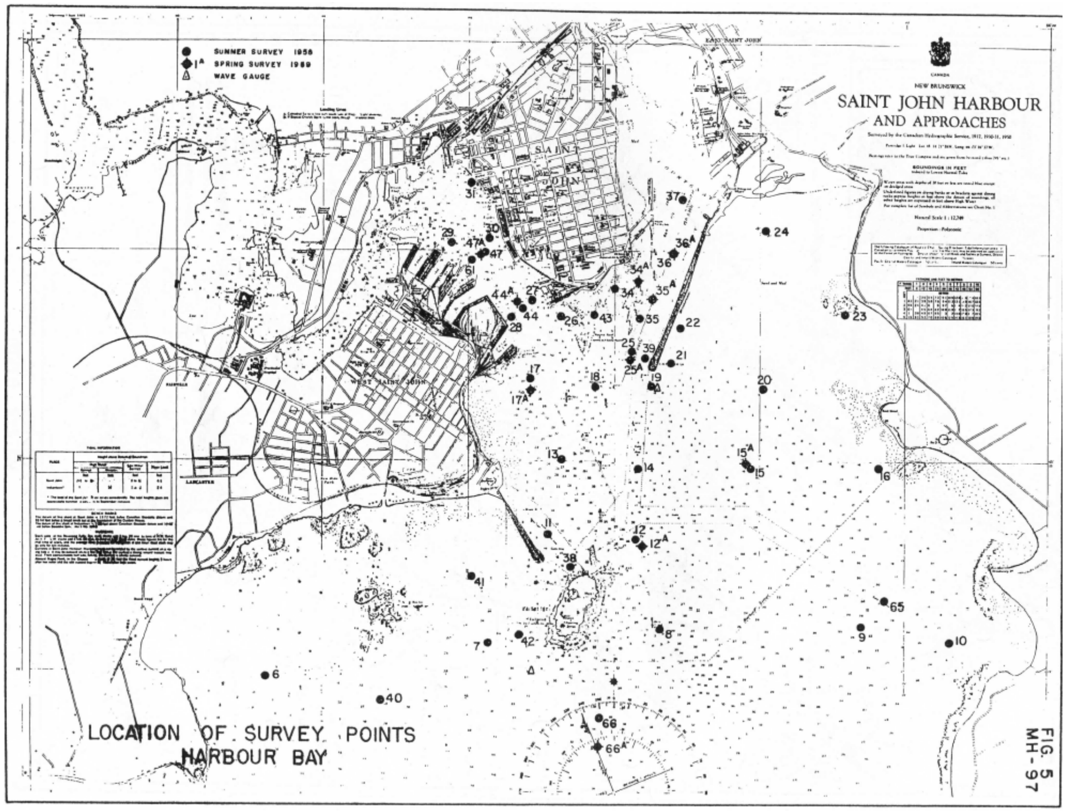


Figure 3.3: Map showing the survey locations in the Main Channel, Courtenay Bay and the outer parts of the harbour where Neu [1960] undertook his surveys. (from Neu [1960, p.31]).

At each station, the boats were anchored for an entire tidal cycle during which current data (magnitude and direction), temperature, density and silt content of the waters were measured and collected. Neu's study concluded with graphical content displaying all the relevant results showing the surface and bed velocities, areas of equal velocities in the harbour and also the grain size distributions of the bottom sediments at each of the 70 stations. [Baird & Associates, 1987].

Neu's observations show that the current measurements for the Main Harbour support the conclusion that the harbour circulation is characterised by the density currents formed in the channel. According to Neu [1960], at low water there is an outward movement in the first ¾ of depth in the harbour, while the seawater from the

Bay moves inwards. However the density gradient is greatly reduced at this stage of the tide to almost zero. During the rising tide the density gradient increases to a maximum at mean high slack water. At this stage of the tide, however, the net movement of water is zero, because the induced density currents the outward flow at the surface is equal to the inward flow at the bottom. At high water, Neu [1960] observed that the density gradient was significantly reduced. This is followed by the next slack water period after which, the inward flow of the salt water wedge begins again.

For Courtenay Bay observations, Neu [1960] concluded that the densities at the bed and the surface are roughly constant during a tidal period. This observation in Courtenay Bay therefore suggested that the density gradients were also constant. The currents velocities are stronger for the upper half of the depth in Courtenay Bay, with a negligible reversing current in the bottom layer which occurs for a short period before low water [Neu, 1960].

From the current measurements Neu also identified some important circulation patterns in the harbour which suggested “channel infilling”. Firstly, Neu made some observations over the mud flats and the reef triangle between the Main Channel and Courtenay Bay. The current observations show that over a tidal period, the resultant surface velocities in this area are in the order of $0.24ms^{-1}$. Secondly it was inferred that these velocity vectors are the result of the freshwater flow from the Saint John River flowing through the harbour, out over the mud flats and the reef between the channel which are then redirected into Courtenay Bay by the incoming tide from the Bay of Fundy. The remainder of the flow also spreads out at the mouth of the Main Channel in the easterly direction and at the mouth of Courtenay Bay.

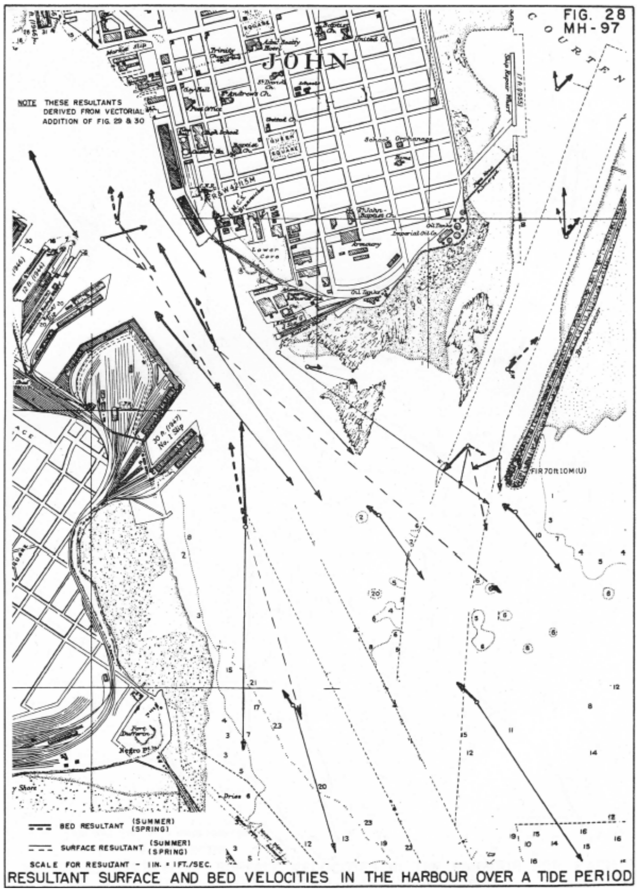


Figure 3.4: Showing the resultant surface and bed velocities in the Harbour over a tide period (from Neu [1960, p.52]).

In addition to the density and water velocity observations Neu [1960] performed a sedimentation analysis which suggested that the freshwater outflow from the Saint John River can transport sediments into the Main Channel and over the Mud flats into the Courtenay Bay Channel. Neu [1960] clearly implied that the source of sedimentation and hence “channel infilling” in Courtenay Bay can be from the Saint John River outflow.

The design of the oceanographic sampling operation, used in this thesis, was developed to improve the spatial density of the sampling undertaken by Neu and to further investigate the phenomena that was identified during his sampling campaign.

Figure 3.5 shows an illustration of the Saint John River estuary in relation to the Saint John Harbour as the main focus of the study.

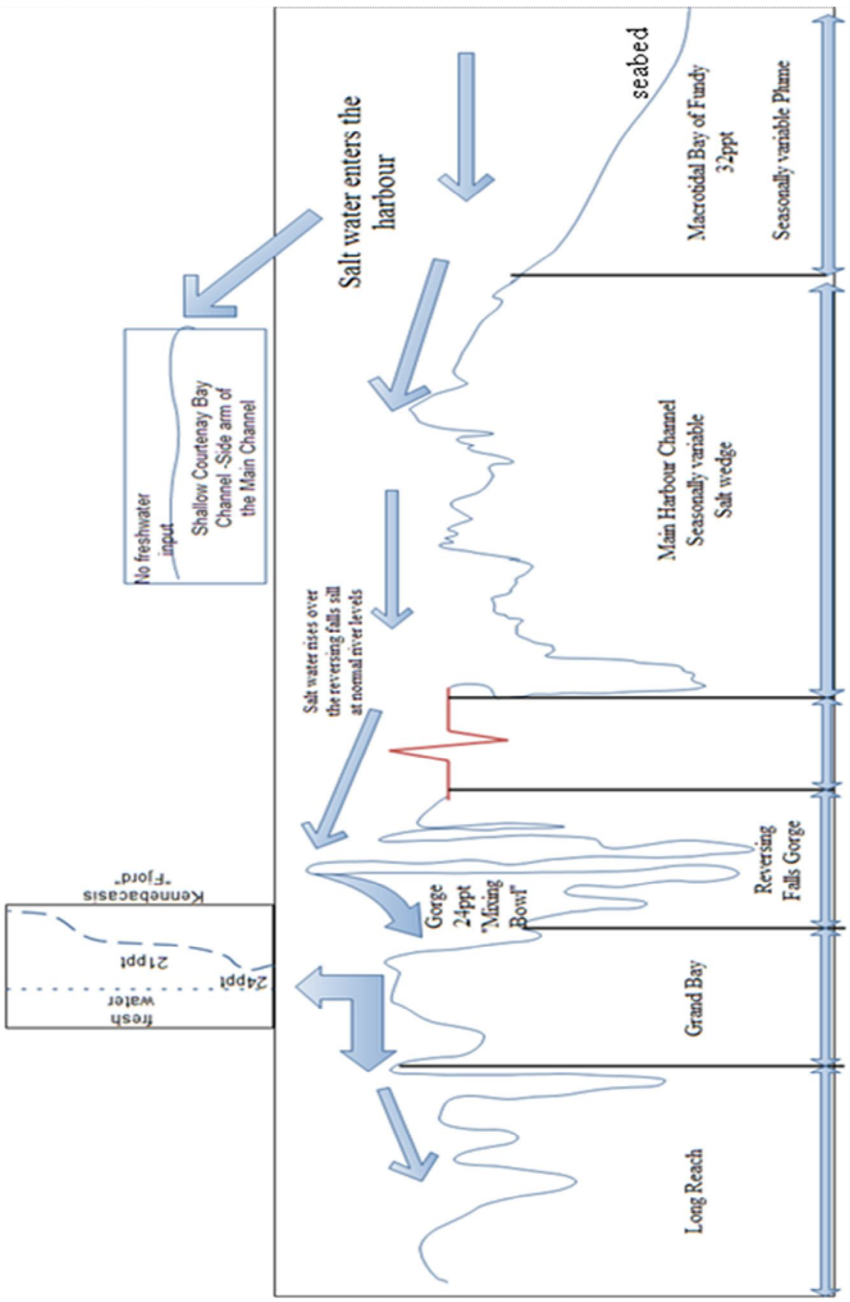


Figure 3.5: Showing the different “Sections of the Saint John River Estuary”. Particular attention should be made to the Saint John Harbour in relation to the other “sections” of the estuary.

3.2 Measurements of Turbulent Mixing in Estuaries

3.2.1 Richardson number (Ri)

To examine and determine the mixing occurring at the density interface in the harbour, this number can be used in stratified environments. The gradient Richardson number (Ri) as “The comparison of the stabilizing forces of the density stratification to the destabilizing influences of the velocity shear” Dyer [1997] and is defined by equation (1). The significance of calculating this value is crucial for comparison of the different interfacial mixing characteristics observed over seasonal and tidal periods in the harbour.

$$Ri = -\frac{\frac{g}{\rho}\frac{\partial \rho}{\partial z}}{(\partial u/\partial z)^2} \qquad (1)$$

Where g = gravitational acceleration (9.81 m/s); ρ = average density; u = velocity.

- Ri>0.25 indicates a subcritical flow - that the stratification is stable and hence turbulence is suppressed. This inhibits the formation of Kelvin Helmholtz instabilities.

- Ri<0.25 indicates the flow is supercritical, where turbulence is enhanced which mixes the water and would prevent further increases in shear. This promotes the formation of the Kelvin Helmholtz instabilities.

- Ri = 0 indicates the flow is neutral whereby no stratification exists.

For water masses that are unstratified, dρ/dz = 0 and therefore Ri is zero. Therefore no analysis for mixing was required for water masses of equal density. The focus in this thesis is on identifying regions of significant changes in the vertical structure of the flow (defined by dρ/dz or the halocline) and seeing whether that interface is stable or rather unstable at a different times in a tidal cycle.

In the observations as part of this thesis, ADCP sections (e.g Figure 3.6) provide du/dz and the CTD (current, temperature and density observations from the MVP provide dρ/dz. Thus we may examine the stability of the pycnocline both spatially along the channels and temporarily during the tidal cycle.

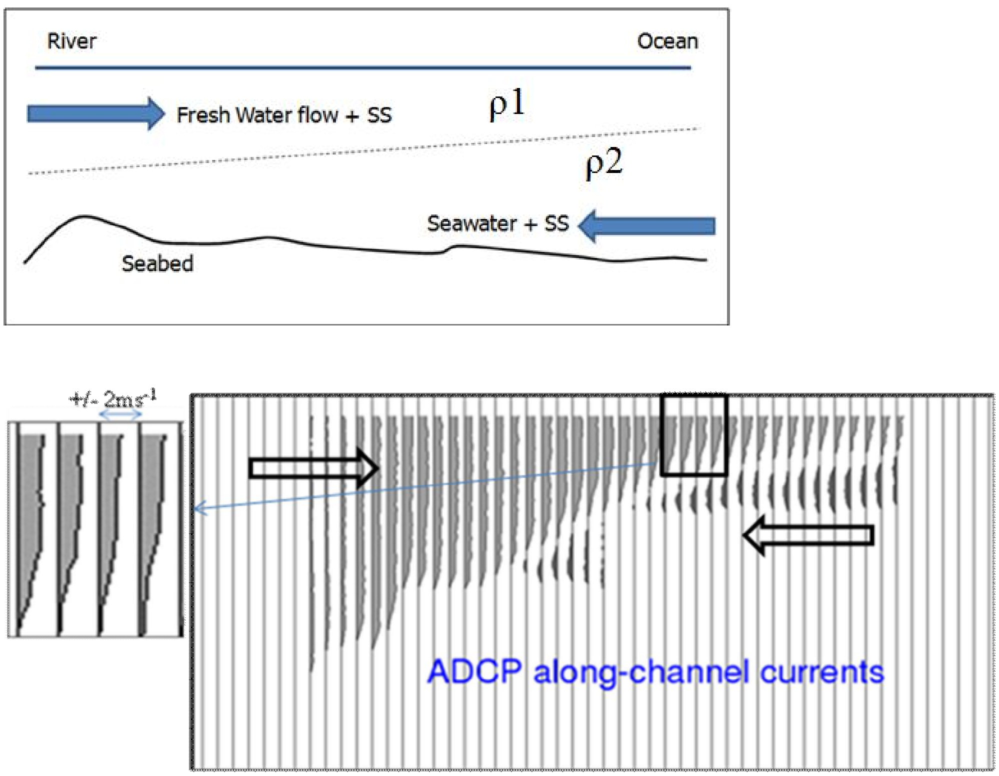


Figure 3.6: Showing the variables used to estimate the mixing. The zoom example shows the velocity scaling used in all subsequent plots of the along-channel currents used in this thesis. SS defines suspended sediments.

3.3 Controls on suspension and deposition of cohesive sediments.

The velocity and turbulent properties of the circulation can affect the extent to which the fresh and salt water remain mixed or unmixed. This has a profound effect on the rates of sedimentation in any harbour. Because of the varying sizes of the sediments, such as gravel, sand, silt and clay from the two different sources in the Harbour, the composition of the seabed in the area is different because the settling velocities of the sediments are different. Larger grain sizes have a greater settling velocity compared to smaller sediments types. This indicates that, as the velocity of the currents become smaller as they progress though the harbour, originating either from the Bay of Fundy or from the river, the heavier, coarser sediments will tend to settle out faster. The currents differ in magnitude in the Main Channel and Courtenay Bay. An example given in Figures 3.7 and 3.8, quantify a maximum magnitude of 1.82ms^{-1} in the Main Channel in contrast to the negligible currents of 0.18ms^{-1} in Courtenay Bay where most of the dredging occurs.

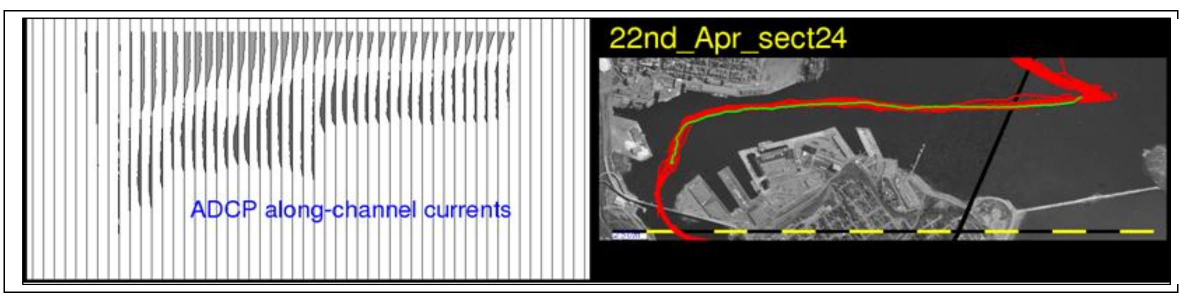


Figure 3.7: Showing the strength of the currents along the main axis of the Main Channel.

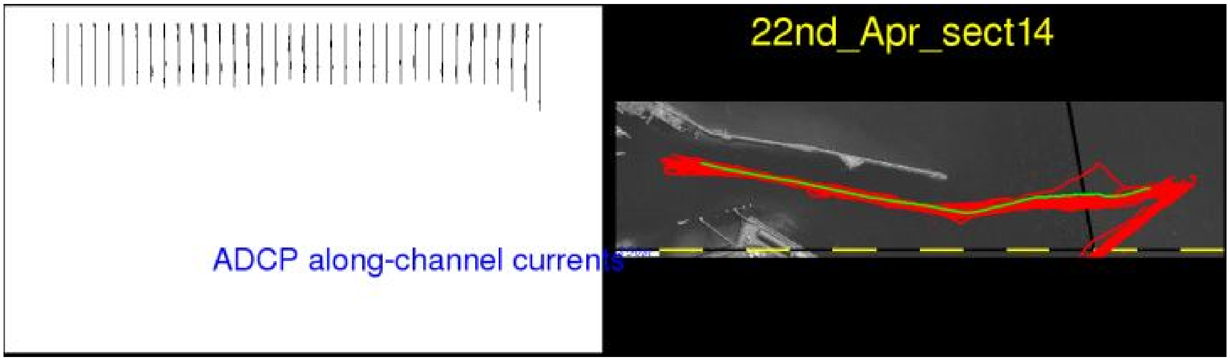


Figure 3.8 : Showing the strength of the currents along the main axis of the Courtenay Bay.

The study done by Neu [1960] on the silt particles found in Courtenay Bay suggests that the particles tend to flocculate strongly when in contact with salt water in this area because of the material makeup classified as organic silt. In theory these organic silts carry a negative charge and when they come in contact with the positively charged ions of the salt water from the Bay of Fundy, they interact “electrically” to give the effect where the particles will attract each other [Einstein and Krone, 1961] Therefore the higher the salt concentration during this interaction, the flocculation of the particles increases and hence the flocculated sediments can then be deposited out of suspension at the bottom of the channel. The settling velocity of a particle is strongly correlated by its surface area to volume ratio. By dumping together individual clay and silt sized particles, the ratio becomes smaller and the particles settle faster.

3.4 Characteristics of the plume of the Saint John River

The map represents 13 major river basins in the province of New Brunswick (see Figure 3.9). The length of the Saint John River is approximately 675km draining a huge area of 54,000km^2. The Saint John River receives approximately 51% of the drainage from the Province of New Brunswick [Department of Fisheries and Oceans Canada, 2002]. This huge volume of water then drains through the Main Harbour channel, into the Bay of Fundy.

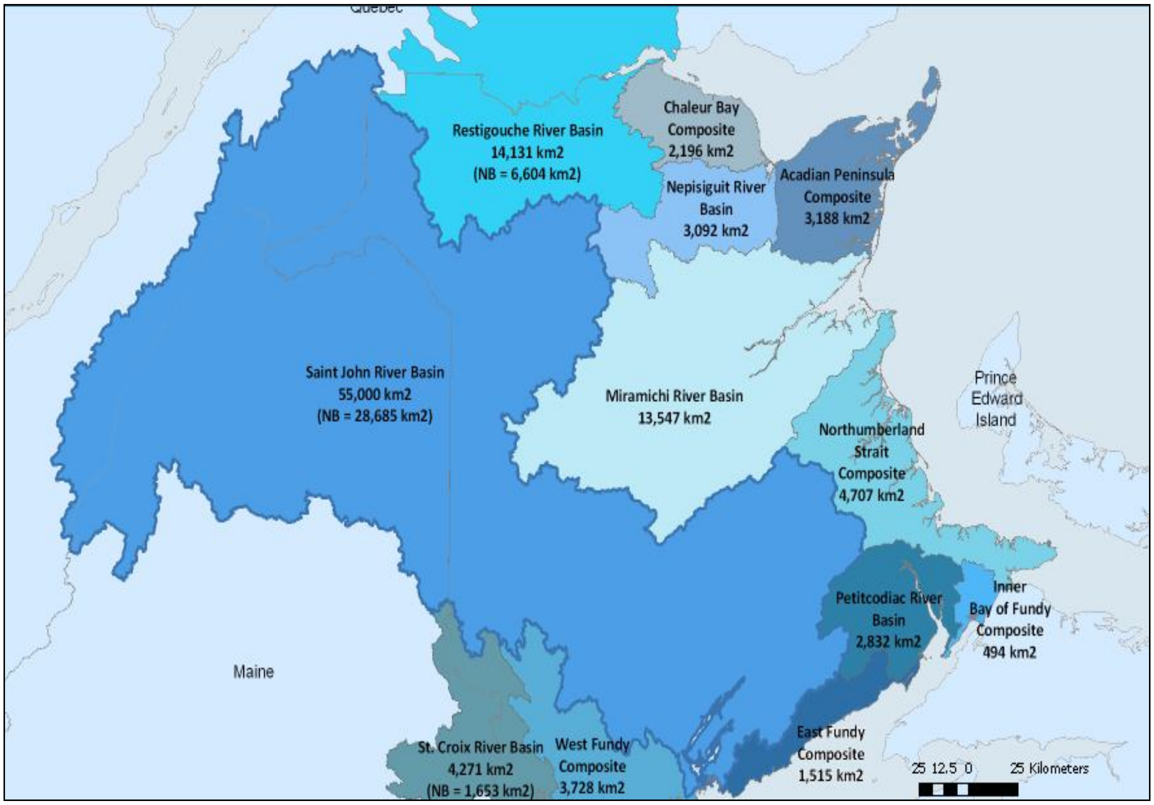


Figure 3.9 : Showing the major river basins in the Province of New Brunswick. [Online: http://cri.nbwaters.unb.ca/sjratlas/site/index.castle].

The buoyant discharge that can be seen radiating from the mouth of the Saint John Harbour into the Bay of Fundy is referred to as a plume. The discharge from the river and estuaries normally carries sediments, nutrients and organic material from the freshwater source towards the ocean. The seasonally variable freshwater discharge from the Saint John River affects the characteristics of the plume discharge. The Saint John River plume is of interest to this study because the freshwater discharges through the Main Channel in the harbour into the Bay of Fundy bringing with it much of the river borne sediments in the upper layer which constitutes the plume. Much of that sediment load bypasses the harbour and is deposited offshore [Parrot et al, 2002]. Those deposited sediments are then potentially the source of reinjected sediments that make their way back into the harbour in the lower salt layer through estuarine circulation. The physical characteristics of the river plume however vary depending on several factors:

- the discharge of the river (which varies seasonally in the watershed)
- temperature of the river discharge
- bathymetry and geometry of the channel mouth, tidal mixing and pulsing of the plume (spring-neap tide variation)
- wave mixing (coastline orientation affected by winds)
- longshore currents (advection of waves due to Coriolis effect)
- Amount of sediments in suspension

Neu [1960] showed this phenomenon of the river plume through aerial photographs from the survey he conducted in the spring of 1959 (see Figure 3.10). There is generally a distinct difference in colour of the river water and the adjacent seawater in the Bay of Fundy. The river plume is normally browner in colour compared to the Bay of Fundy waters. This is a result of the river carrying more suspended particles such as clay and slit. The aerial photograph shows distinct tidal front boundaries south of Patridge Island. This is because of the density and salinity differences between the two water masses shown in this image.

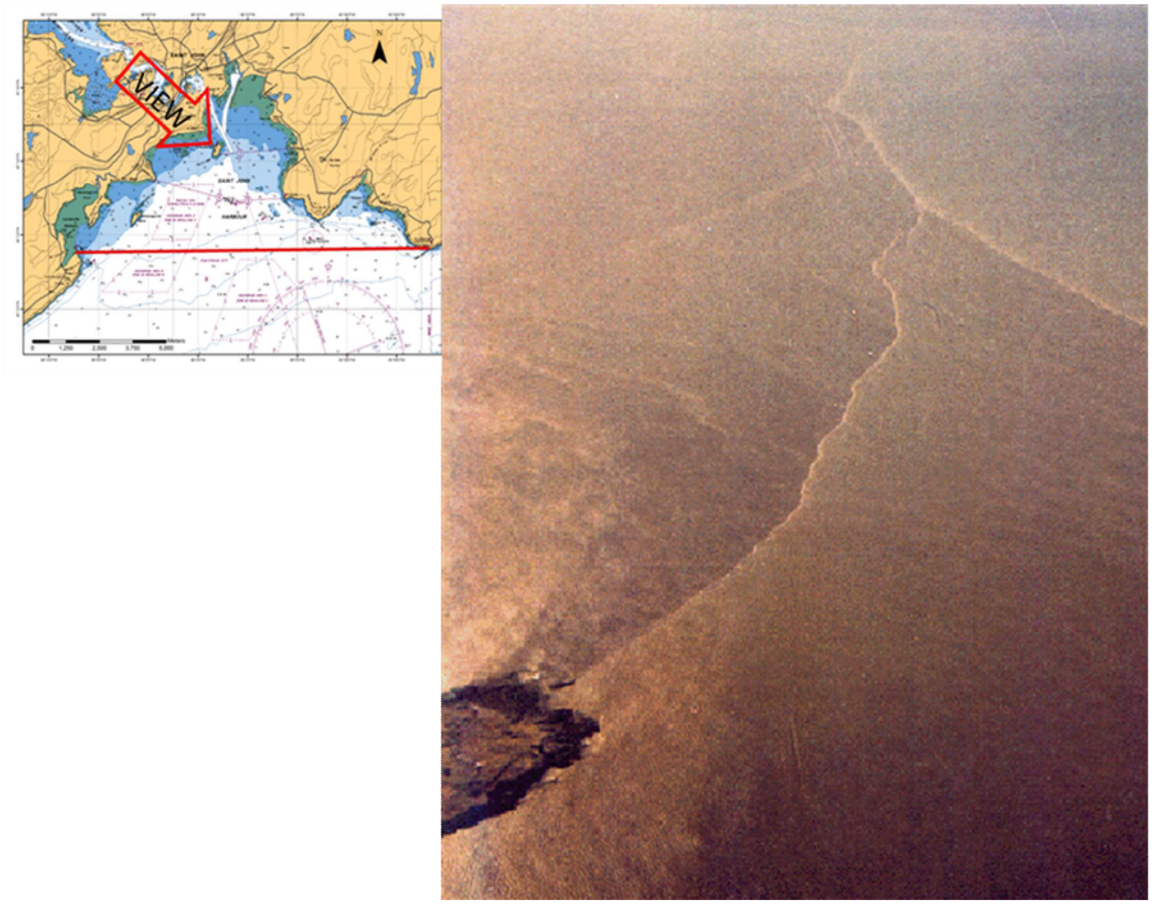


Figure 3.10: Adopted from Neu [1960] showing the distinct tidal boundaries of the Saint John River plume looking south of Patridge Island.

With the help of satellite imagery, the extent of the river plume can now be examined at different phases of the tide. Figure 3.11 shows an example of the location and the extent of the Saint John River plume generated by Hughes Clarke (UNB). Figure 3.11 shows the satellite image of the river plume during the flood phase of the tide on the 21st of October 1990 as the plume retreats back into the Saint John Harbour. Figure 3.12 shows a satellite image of the Saint John River plume during the ebb phase of the tide on June 18th 1991 where the plume extends a greater distance offshore along the western coast with clear evidence of sediment re-suspension to the east and western ends of the plume along the coastline.

The extent of the river plume in an important factor, especially during the ebb tide because this would indicate the seaward most extent of the upper freshwater layer which contains suspended sediments. By examining the salinity, density, velocity and optical backscatter values one can determine the thickness of the river plume and the sediment concentration of river sediments present in the upper layer. This can then be used to determine whether the river borne sediments are depositing at the furthest extent of the plume.

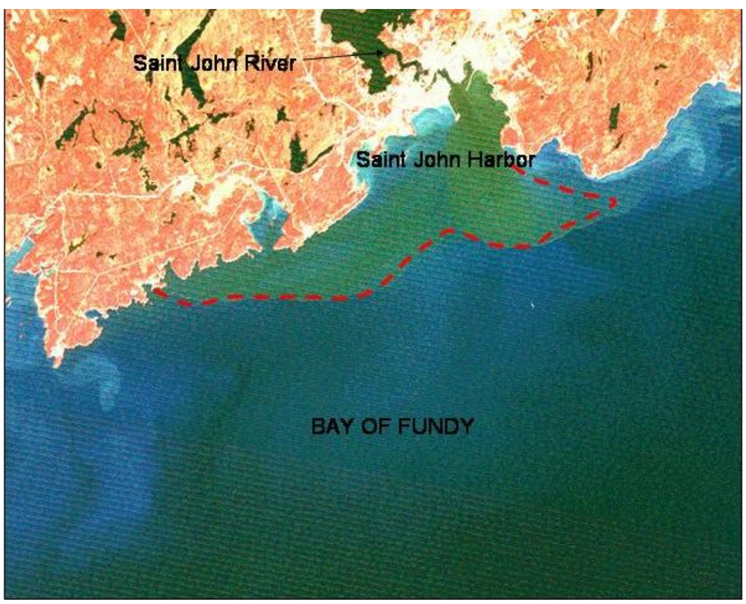


Figure 3.11: Landsat 5 MSS imagery of the Saint John River plume at the the Bay of Fundy on the flood phase of the tide on 21st October 1990 at time 14:27:19 [Image taken from lectures; Hughes Clarke, 2008]

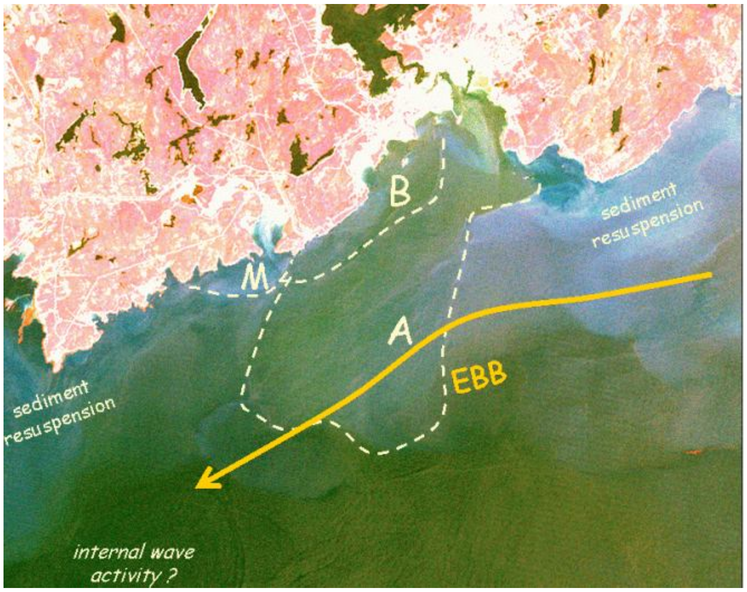


Figure 3.12: Landsat 5 MSS imagery of the Saint John River plume at the Bay of Fundy on the ebb phase of the tide on June 18th 1991 at time 14:30:40. A and B shows the river plume from the Saint John estuary and M is the river plume from the Musquash estuary. [Image taken from lectures; Hughes Clarke, 2008].

Chapter 4: Survey Instrumentation and Methodology

The research vessel used to conduct the oceanographic surveys was the CSL Heron. It is approximately 10m in length and 2.5 m in width (see Figure 4.1). The Heron has a draft of 1.15m and is capable of operating at 6m/s at 2100rpm and 4m/s at 1800rpm. For this research the vessel speed used was approximately 4ms^{-1}. The main instrumentation used to collect the oceanographic data is shown in Figure 4.1.

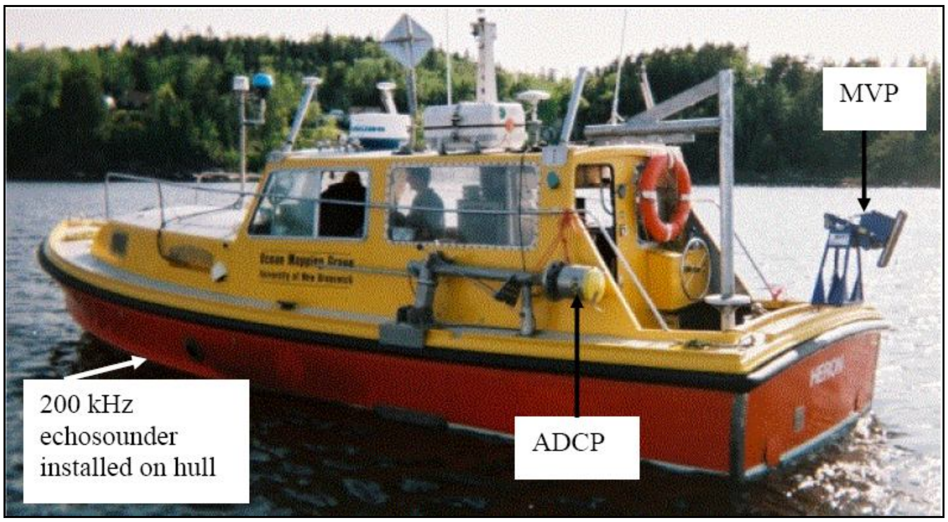


Figure 4.1: Ocean Mapping Group Survey Vessel showing the sensors used in data collection.

4.1 Principles of the Acoustic Doppler Current Profiler (RDI Workhorse Monitor 600kHz)

For this research project, the RDI 600 kHz ADCP was used to measure the magnitude and direction of the currents in the channels. The ADCP allows us to track the current velocities (volume fluxes) above and below the halocline. The ADCP also provides a 600 kHz backscatter image which was of less direct use (too low resolution) for this project [Hughes Clarke, 2000].

Previously, point located current meters were used to collect current measurements (as with Neu, [1960]) with the disadvantages of obtaining smaller data sets where observations were limited to the location of the instrument which were generally either at the surface, mid-depth or near the bottom. With the improved ADCP technology, this instrument measures a vertical profile in three directions, x, y and z, and was ideal for the collection of water current velocities and magnitude over the 12.42hr tidal cycles because of its flexibility to be mounted onto the moving vessel while collecting the data continuously without stopping the vessel.

The ADCP current measurements are based on the principle of the Doppler effect, where acoustic waves are emitted at a fixed frequency throughout the water column and the backscattered signal from the scatterers (such as zooplankton, sediments and density interfaces in the water column) reflect the sound back to the ADCP. It is an important assumption that these scatterers move at the same velocity as the water (RD Instruments, 1996). When the sound waves are reflected back, they return with a different frequency to the ADCP. The scatterers which have reflected the sound waves while moving away from the ADCP, send back a return signal of a lower frequency. Scatterers moving toward the instrument send back higher frequency waves.

The difference in frequency between the waves that the profiler sends out and the waves it receives is called the Doppler shift. By measuring the time it takes for the waves to bounce back and the Doppler shift and vessel speed, the profiler can measure current speed at many different depths with each series of pings.

For this project, the ADCP is mounted on a pole located on the port side of the vessel, with a draft of approximately 1.2m. This model ADCP consists of four beams, each of width 20°. As the vessel moves, the ADCP emits pulses of sound which are reflected by scatterers in the channel moving relative to the ADCP. While the vessel was operating at speed of 4m/s, the ping rate of the ADCP was approximately 1Hz. The frequency of the pings controls the horizontal spatial resolution of the data obtained, which in this case would be 4m.

4.1.1 Depth Cell (Bin Size) and Range Gate

The ADCP measures the water column by dividing it into equal depth intervals called depth cells or bins and in this case the size was set to 0.5m. Each depth cell can be looked at as one current meter. However the ADCP averages the velocity measurements over the depth range of the depth cell (or bins). "*Smoothing the observed velocity over the range of the depth cell rejects velocities with vertical variations smaller than a depth cell, and thus reduces measurement uncertainty*" [RD Instruments, 1996].

The size of the depth cell (or bin) is related to the range gate (see Figure 4.2). The echoes that are sent back to the ADCP are range gated according to the size of the depth cell. Range gating is a process whereby the received signal is divided into successive time segments for independent processing. Therefore, the range gates indicate the times at which the segmented echoes will be recorded. Echoes far from the ADCP take a longer time to return to the ADCP than echoes at a closer range. Therefore, as the distance of the depth cell increases away from the ADCP, the corresponding echo determines the successive range gates. The center of each range gate has the most velocity data, compared to the top and bottom of each range gate. The velocity data is averaged within each range gate to arrive at one velocity value allocated at the center of each depth cell.

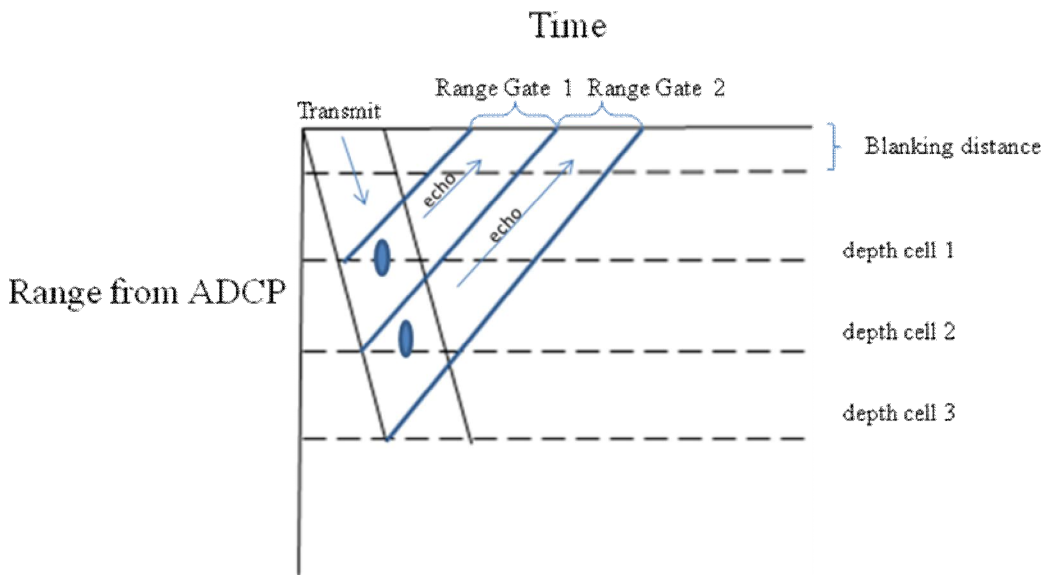


Figure 4.2: Showing the relationship between the depth cell size and the range gate using for ADCP velocity measurement. [Modified from the RD Instruments Manual, 1996].

4.1.2 Bottom Tracking of the ADCP

The Doppler shift effect observed is relative to the motion of the vessel on which the instrument is installed. The bottom tracking capability of the ADCP allows for absolute current measurements. Separate pings can be transmitted from the ADCP to measure the Doppler shift of that return signal from the channel bottom. The measurement can be used to correct the water velocity measurements relative to the boat speed. When bottom-tracking is unavailable, navigation can be used to estimate ship velocity. [RD Instruments, 2006].

4.1.3 Limitations of using the ADCP for current measurements

Although there are many advantages associated with the use of ADCP for current measurements in estuaries and harbour cross sections, there are a few limitations associated with ADCP's which are deployed from the vessel. Some of these may include:

- It is not possible for the ADCP to measure all the way to the surface due to the blanking distance and the draft of the transducer. Therefore for a complete velocity profile there must be a method chosen by the user to extend or extrapolate the velocities from the first good measurement to the surface. (see Figure 4.3 and 4.4).

- It is also not possible for the ADCP to accurately measure all the way to the bottom of the channel. Velocity measurements near the channel bottom are affected by side lobe interference which affect the reflections of the scatterers in the water. The measurements are also affected by the acoustic reflection being too close to the seabed. The size of the 'contaminated velocity' region near the bed depends on beam geometry and bin size. (Muste, 2004). Thus for the flux measurements, the deepest valid velocity is linearly interpolated to zero at the bottom depth. (see Figure 4.3 and 4.4).

- When the boat speed increases to more than 4ms-1 the velocity data gets miscalculated because of the bubbles created along the face of the transducer. This same principle applies when the vessel makes a turn or there is backwash from other vessels passing nearby.

- Compass errors. The compass of the ADCP is likely to have errors associated with it due to its position on the ship and due to tilting errors. To compensate for these errors requires comparing observations made with the compass with that of a sensor which does not use the same compass. This can be performed using DGPS system or a Gyro. (Delpeche, 2006).
- Ensemble averaging is necessary for the single ping observations because they are too noisy or contain too many random errors. Therefore for greater accuracy of the velocity measurements along the profile, ensemble averages are performed to the individual velocity measurements to arrive at a more precise solution. Thus while there are observations every 4m in the along track, they are too noisy to usefully resolve changes in current speed over those length scales. A 10 ping ensemble, corresponding to 40m along track averaging was found to be necessary to get usable low noise current speed estimates.

Due to the draft of the transducer (1.2m) and the blanking size of 0.5m, measurement of the velocities close to the sea surface is impractical; therefore the first "good" velocity measurement would be approximately 1.7m below the water level surface. An ADCP with a 20^{o} beam angle has the potential for sidelobe contamination at (distance to the boundary)*cos(20^{o}), or equivalently, the last 6% of the profile. Refer to Table 4.1 for a summary of the parameters of the 600kHz ADCP.

[Online : http://www.rdinstruments.com].

Table 4.1: Summary of parameters of the Workhorse 600kHz ADCP used for current measurements in the Main channel and Courtenay Bay.

No. of beams	4
Frequency	600kHz
Beam angle	20°
Bin size	0.5m
Sampling rate	~1Hz
Maximum depth	50m
First good bin	~2m
Last good bin	~6% above the seabed
Horizontal spacing of pings	4m
Horizontal spacing of ensemble	40m

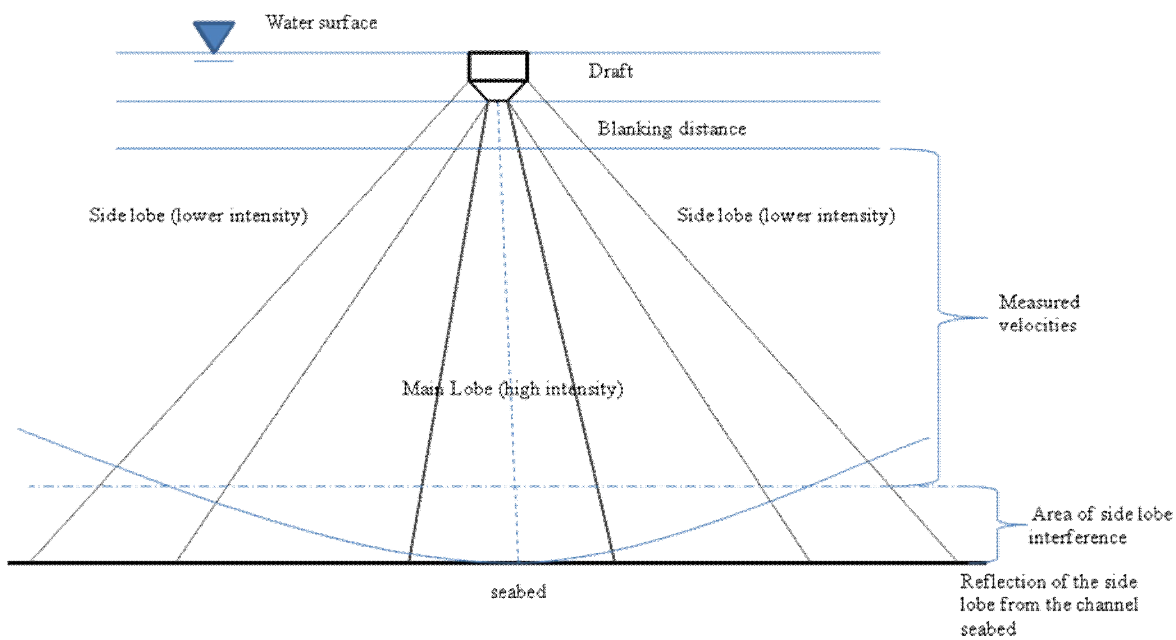


Figure 4.3: Showing the basic ADCP limitations of operation including the draft, blanking distance and side lobe interference.

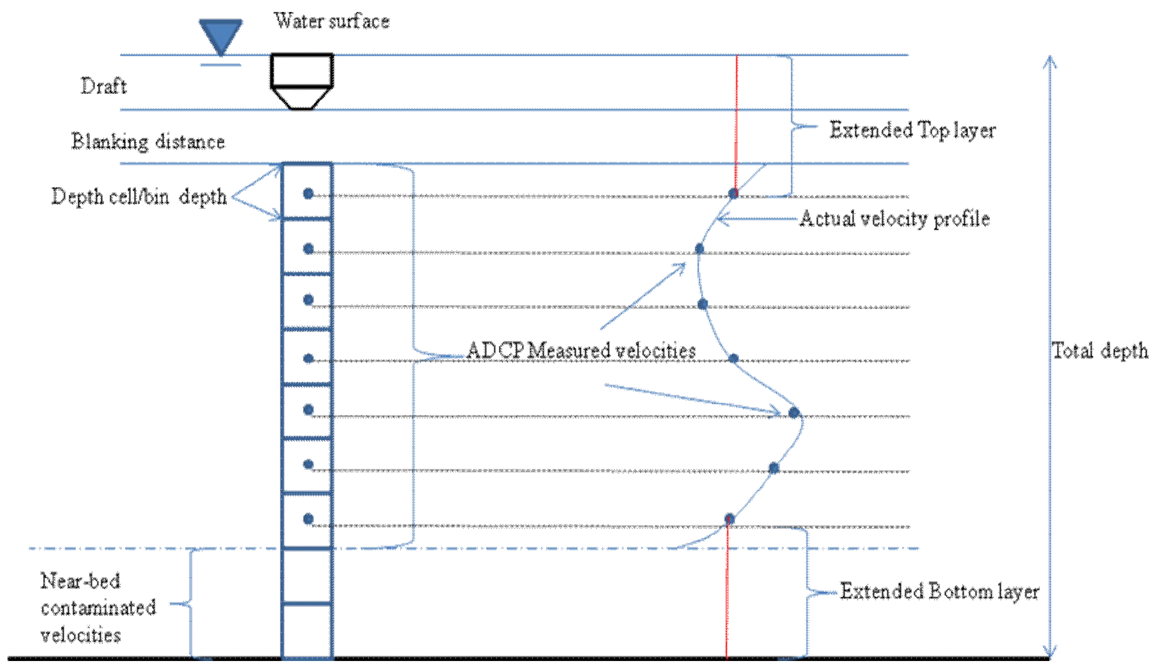


Figure 4.4: Showing the relationship between the allocated velocity measurements that are used to produce the profile and the linear extrapolation to the surface and bottom needed to complete the profile.

4.3 Moving Vessel Profiler with CTD sensors

This Saint John Harbour area of study represents an area of research where the water mass properties are changing rapidly in time and space. The MVP 30 profiler is a an efficient tool which now allows us to capture these changes in a relatively short space of time by collecting a large number of profiles without stopping the vessel, unlike previous methods used to collect CTD data.

The MVP is an autonomous, free fall system that measures vertical profiles of sound velocity and CTD while the vessel is underway. The system consists of a free fall fish (CTD probe including an optical backscatter sensor), a hydraulic winch controlled by the computer and a cable metering and an overboarding system to allow free falling of the fish when deployed. This computer controlled system is programmed by the user to vertically measure the profiles up to 2m and 3m off the seabed bottom in some cases. When surveying in areas of irregular bathymetry the greatest depth reached by the fish ranges from 1m to 3m depending on the irregular bathymetry encountered during the survey (see Figure 4.5).

The horizontal resolution or distance between dips depends on the depth at the time of the dip and the speed of the vessel. From the oceanographic surveys conducted, the time between dips varied along the Main Channel transects and that of Courtenay Bay (see Figure 4.6). The Main Channel bathymetry is more irregular compared to the shallow bathymetry associated with Courtenay Bay. The average distance between dips (at a vessel speed of approximately $4ms^{-1}$) taken at an average depth of 20m in the Main Channel is 443m and approximately 230m at a depth of 8.5m at the mouth of the Main Channel. The average distance between dips taken at an average depth of 5.3m at the mouth of Courtenay Bay channel is approximately 190m and at the head of the channel the distance between the dips is approximately 345m (see Figure 4.6). The vertical resolution of the MVP dips were 0.1m for the length of the profile.

One limitation of the MVP is that, the MVP always had to be programmed at a set depth (standard at about 2m above the seabed) to avoid collision of the fish (CTD probe) with the underlying seabed. The CTD information between the maximum depth that the fish reaches and the seabed is therefore not measured. As with the ADCP velocity profiles, the last measurement from the MVP cast has to be extrapolated down to the seabed to allow for complete profiling of the water column. This extrapolation was important for the volume flux calculation presented later on.

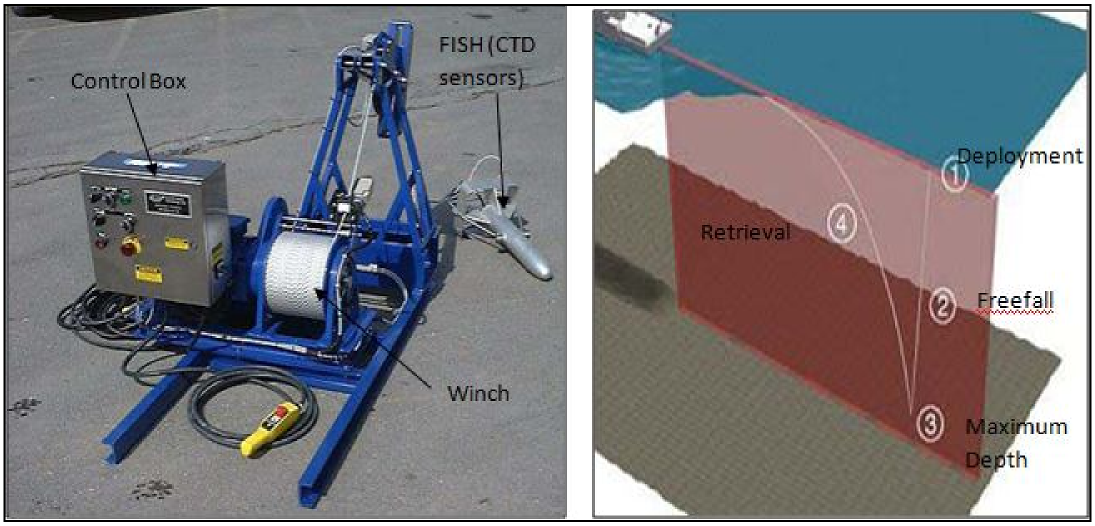


Figure 4.5: Components of MVP and stages of the MVP vertical profiles (source: http://www.brooke-ocean.com/)

Figure 4.6: Showing an example of the distribution of MVP dips along the Main Channel (red dots) and Courtenay Bay (purple dots). The number of dips is related to the vessel speed and the bathymetry in the area.

4.3.1 Optical Backscatter

The optical backscatter results reveal the sediment concentration in the water column of the harbour channels. The optical backscatter (measured in mV), is correlated with the sediment concentration mgl^{-1} using the calibration data (see Table 4.2). The calibration graph below shows the relationship between the OBS output and the sediment concentration in gl^{-1}. The equation for the best fit line from the calibration [NRCan, 2004] graph ($y = mx+c$) is used to determine the sediment concentration; where the x values are the results obtained from each OBS profile, m is the gradient and c is a constant (the y intercept) of the graph (see Figure 4.7).

Table 4.2: Showing the results of the OBS calibration done by NRCan on 02/04/04. These calibration results were used in the instrument used in the 2009/2009 oceanographic surveys.

	***OBS (VDC)* (X)**	***Sed. Conc. (g/l)* (Y)**	***Slope (M)***	***Intercept (b)***	***R Squared***
1	0.303	0.0036	**0.014**	**-0.002**	**0.988**
2	0.472	0.0050			
3	0.784	0.0084			
4	1.091	0.0142			
5	1.541	0.0188			
6	2.004	0.0238			
7	2.452	0.0298			
8	2.849	0.0388			
9	3.268	0.0448			
10	3.683	0.0476			
11	4.080	0.0600			

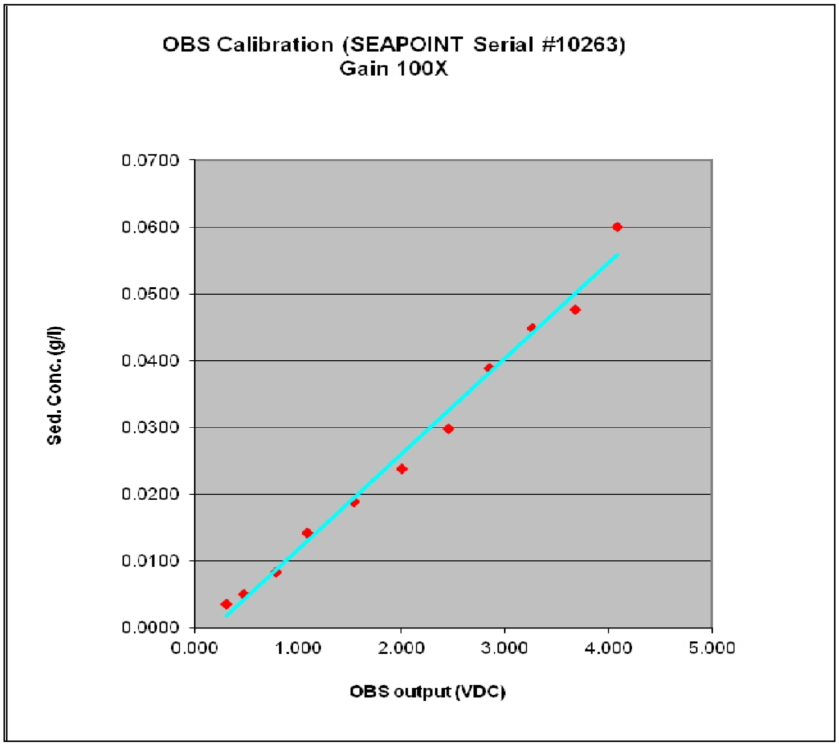


Figure 4.7: Showing the relationship between the OBS output and the corresponding sediment concentration. [NRCan, 2004].

4.4 Knudsen 320 B/P 200 kHz echo sounder

A Knudsen 320 B/P 200 kHz echo sounder with a beam width of 6° and pulse duration of 0.1ms was used. Thus the echosounder had a pulse length of 0.15m and an effective range resolution of 0.075m. For the surveys the gain was set to its highest (100) whilst the power was set to its lowest (1). The system is equipped with an amplifier that increases the intensity of the return echo. Amplification of the signal (increasing the gain) was preferred rather than increasing the power to prevent reverberation from the multiple echoes of the previous ping. The echosounder was also used to detect the short wave length variability in the shape of the halocline. The range of the echosounder was set to measure depth of up to 50m.

4.5 Quantification of Volumetric Fluxes: Freshwater flux, Saltwater flux and Sediment Flux

The principle mechanism driving the circulation in the Port of Saint John is the density currents which are set up by the differences in flow between the freshwater discharge from the Saint John River and the incoming salt water from the Bay of Fundy. The four tidal cycle surveys conducted for this experiment were intentionally designed to capture the variation of the salinity and velocity gradients and hence the density gradients both in time and space within the harbour.

The high resolution velocity and salinity measurements as well as the acoustic imagery give a clear picture of how the flow in the harbour changes over the tidal cycles at different stages of the freshwater discharge from the Saint John River. Exchange and flow between the two layers of water in the harbour is crucial for understanding and conducting future research for sediment transport and deposition in areas of the harbour where there is a growing concern for reducing or even elimination of the costly dredging process.

As mentioned previously in this chapter data were collected from shipboard instrumentation, Acoustic Doppler Current Profilers (ADCP) operating at 600kHz, towed CTD sensors measuring; conductivity, temperature, salinity, density and optical backscatter. The data were collected approximately along the centerline of the Main Channel and Courtenay Bay, starting at the head of the Main Channel, continuing into Courtenay Bay and back again for the duration of each of the 12.42hr tidal cycles.

There are two types of data being represented in this thesis for analysis and comparison of each tidal cycle at different river level stages and seasons. For the Main

Channel and Courtenay Bay's physical oceanography, a qualitative description is given for the data collected. These results show how the salinity, optical backscatter as well as the pycnocline shown from the 200kHz acoustic backscatter vary over the tidal cycle along the longitudinal sections of both channels at different stages of the tide. Aside from the qualitative analysis and demonstration of these results, a further, quantitative analysis of the flow is done for the Main Channel only. A cross section for analysis of the exchange flow was chosen at a location 700m south and seaward of Rodney terminal across the Main Channel (see Figure 4.8). A cross sectional analysis of the data collected in Courtenay Bay was not carried out because of the relatively low (and therefore poorly resolved) currents observed from the ADCP data collected in this channel.

4.5.1 Calculations for Fluxes

The purpose of the investigational method chosen in conjunction with the descriptive discussion of the seasonal and tidal variations of the estuarine circulation is to aid in understanding the possibility of an alternative source of sediment which is derived from offshore resuspension. By measuring and quantifying the estuarine fluxes in the upper, middle and lower layers, a comparison can be made to determine if the fluxes in the lower layer (typically from offshore) are high enough to provide an effect on the sedimentation rates in the harbour.

These fluxes in the harbour are measured and determined by using the velocity, salinity and OBS concentrations at different water depths along the vertical cross section chosen. Several studies such as Kjerfve [2002] and Uncles [1979] have conducted experiments to determine salt fluxes and assess the relative importance of different transport processes in estuaries. Observations of currents and salinity collected at one location along the cross-section of a main channel within an estuarine system can provide a valid experimental approach when assessing the relative importance of different transport processes [Ayub, 2010].

The steps involved in the flux calculation are as follows:

1. The cross section location was carefully chosen at the entrance of the Main Channel in a through flow area where there are supposed to be less eddy currents and the flow is thus associated with less eddies as indicated from vessel-based observations and a numerical model (by Church and Haigh, Unpublished) Courtenay Bay was not selected to do a cross sectional analysis due to the low current activity in the channel.
2. Measure the area, ***A***, of the cross section through which the fluxes are being measured.
    - This was done by first measuring the distance across the channel from a bathymetric map provided by the Ocean mapping group (Figure 4.8). The information extracted from the map was distance from the start (west side of channel) to end (east side of the Main channel). The distance had corresponding depth values. The maximum distance across the channel was 385m with a maximum depth of 17.6m (chart datum) (see Figure 4.9).

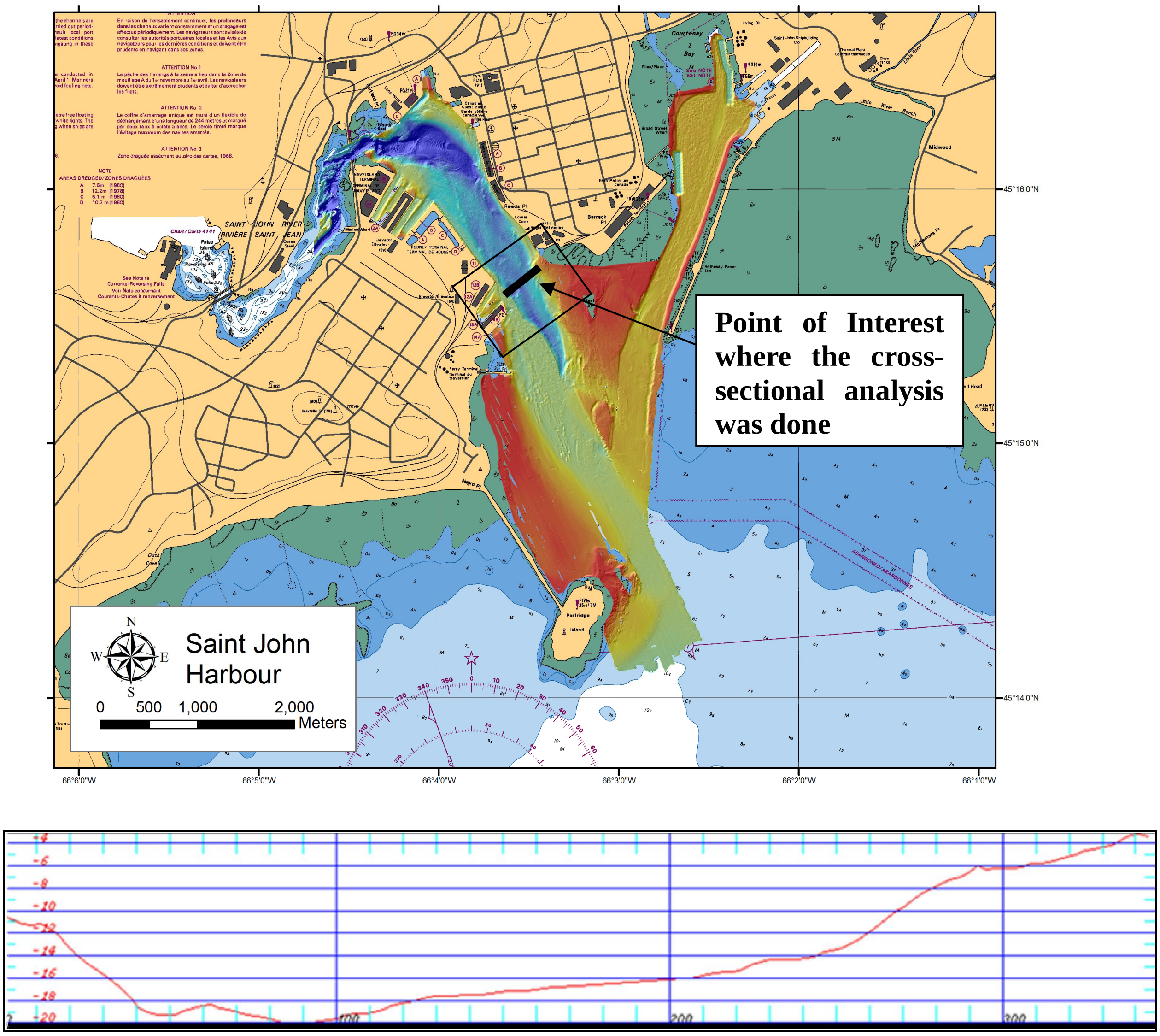


Figure 4.8: Showing the map used for measuring the cross-section and the point of interest in the Main Channel where the gradient Richardson numbers, volumetric flow, volumetric layer flux, and sediment flux calculations were utilized.

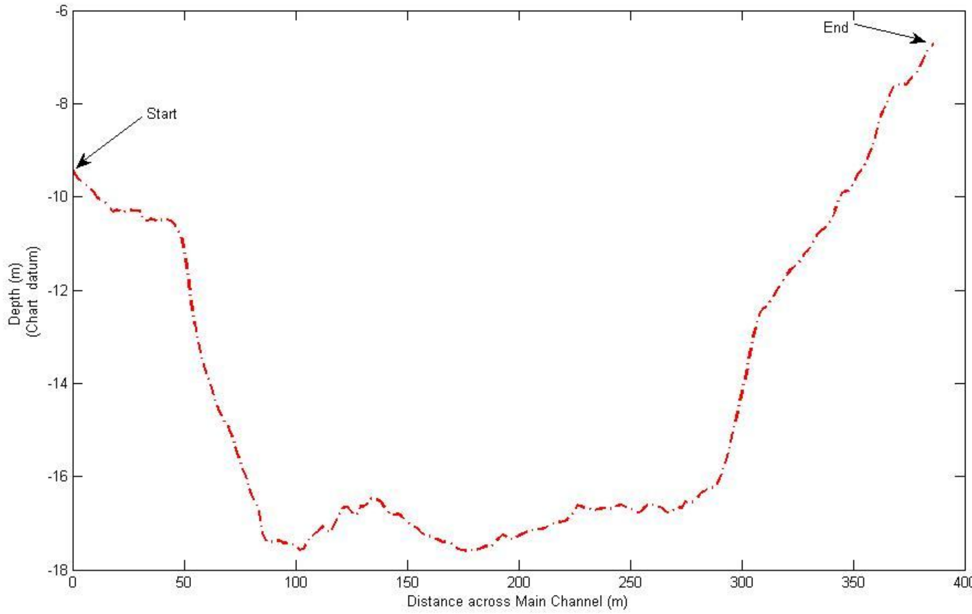


Figure 4.9: Plot showing the cross section of the Main channel. The depths here are reference to chart datum.

- For a smoother cross sectional profile the data were manipulated using Matlab. The total length of the across track distance was divided into separate 50m ranges. For each across track range a polynomial curve fitting function was applied to each range separately to define a combined smooth curve of the seafloor. A new cross section was then plotted, depth referenced to the geoid versus the distance from the start (see Figure 4.10).

- The areas above the curves were then calculated at 1m depth intervals. For ease with calculations any areas shallower than 12m were approximated to be 385m^2 (see Figure 4.10). (This is based on the fact that the two sides are both vertical dock walls). *Quadrature* is a numerical method used to find the area under the graph of a function, i.e to compute the definite integral (Matlab). This function was used to calculate the irregular areas close to the bottom of the channel.

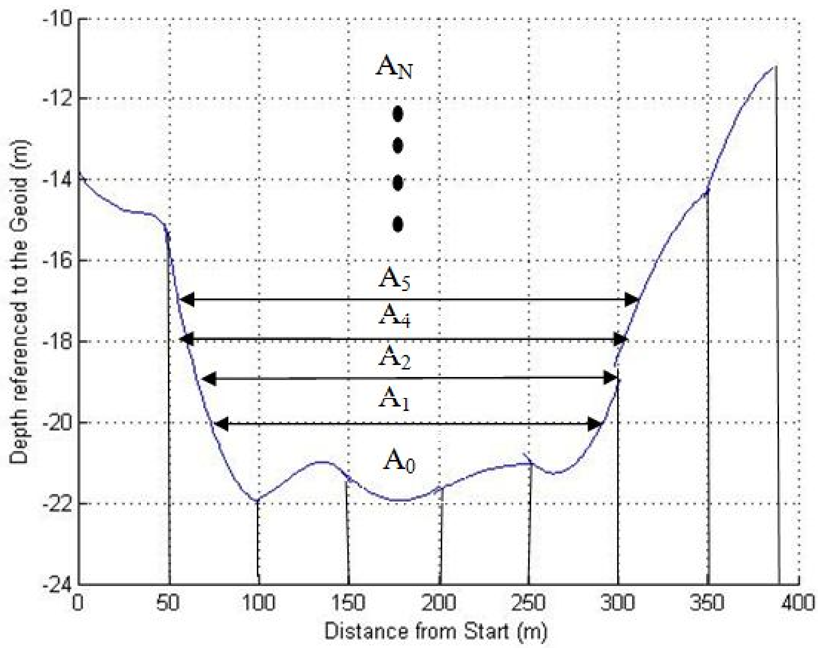


Figure 4.10: Plot showing the concept of how the areas at 1m depth intervals were calculated.

3. The current velocity, normal to the cross sectional area, ***v***, is required for the any flux measurement. At the intersection between the along track ADCP transect and the cross section profile, with the use of OMG software, a (200x200)m region is defined to do a static ensemble average of the ADCP velocities at that location. A single velocity profile results from this application. The velocity used is the section normal component. Therefore any section parallel (referred to as cross-channel flow) is assumed insignificant as just part of local eddies. This profile is adjusted from instantaneous sea-level, referenced to the geoid, using the instantaneous tide water levels.

4. At each 1m depth interval from the channel bottom upwards, static volumetric fluxes can be calculated using:

$$Q = A * v$$

Where Q = Volumetric Flux (m^3s^{-1})

A is the cross sectional area (m^2) and

v (ms^{-1}) is the velocity normal to the cross sectional area which is acquired from the ADCP profile.

- Also the layer flux, defined by the volume of water with a particular salinity per unit width can be calculated using the same formula. The unit to define layer flux is represented as a volume (m^3s^{-1}) which has representative salinity conditions of less than 10‰, between 10‰ and 20‰ and greater than 20‰.

- Mass flux or sediment flux may also be determined by multiplying the volumetric flux by the sediment concentration obtained from the OBS. This gives the total mass of sediments which pass through the cross sectional area, A per unit time.

Sediment Flux ($\boldsymbol{F_{sed}}$) = Volumetric Flux (***Q***) * Sediment Concentration (***SC***)
(kgs^{-1}) (m^3s^{-1}) (kgm^{-3})

4.5.2 Calculation for the Gradient Richardson Number

Section 3.1.1 shows that in order to calculate the gradient Richardson number (Ri), calculations for the following must be made:

1. Density gradient ($d\rho/dz$)

2. Velocity gradient (du/dz)

The velocity data are obtained from the ADCP data which have a vertical resolution of 0.5m and is based on an ensemble average of all pings within 100m (typically 25 pings). The density data are obtained from the CTD profiles which have a vertical resolution of 0.1m. To calculate the gradients, the corresponding velocity and density values would therefore have to be at the same horizontal position for it to be calculated. Since the CTD data are at a greater vertical resolution, for every velocity value at the 0.5m depth an average of the density values that fall within each 0.5m depth range would have to be derived to arrive at a single corresponding density value. (See Figure 4.11).

The ensemble averaging of the pings that produces the velocity profile will reflect in a slight smoothing of the true vertical velocity profile. This smoothing will thus artificially increase the apparent values of the Ri numbers as the velocity gradient will appear lower. At the cross section chosen in the Main Harbour channel, each vertical velocity and salinity profile for each section for the duration of the tidal cycle was used in calculating the Gradient Richardson number for the four surveys. The Gradient Richardson numbers are presented later on to examine whether the pycnocline was stable or not at different phases of the tide for the representative tidal cycle surveys.

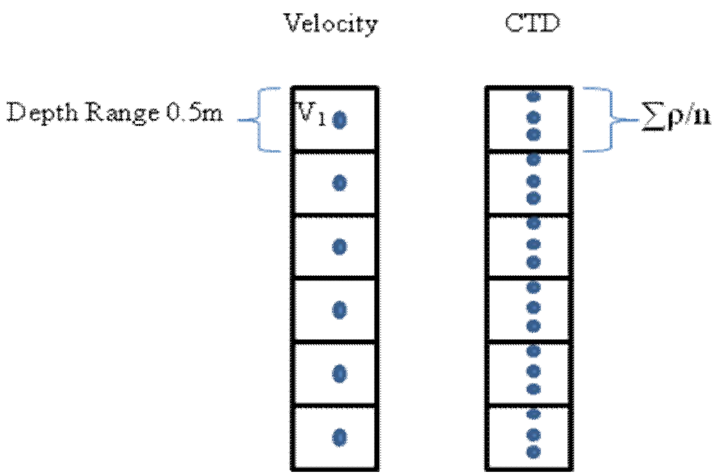


Figure 4.11: Showing an example of how the density values are averaged to match the velocity value of the ADCP at the 0.5m depth range.

Chapter 5: RESULTS AND ANALYSIS

5.1. Main Harbour Channel Oceanographic Results

The Main Channel results include the longitudinal oceanographic profiles taken at approximately 20 minute intervals for April, November, March and June. The flows are dominated by the variation in salinity and hence determined by the balance between the freshwater inflow from the Saint John River and the incoming salt water from the Bay of Fundy. Discussions of the patterns of salinity and velocity variations over the tidal cycles give a qualitative idea of the oceanographic flow and circulation in the estuary. Also the visualization of optical backscatter results gives an indication of the variation in sediment transport along the longitudinal section during a tidal cycle.

The following discussion examines the seasonal variability of the along-channel estuarine circulation over a tidal cycle. While there is seasonal variability, there is a common aspect that is seen in all times of the year for which the oceanographic surveys were undertaken.

At all times of the year, the advance and retreat of the lower salt water intrusion is clearly a major phenomenon present in the Main Channel of the harbour. The lower, high salinity layer can be thought of as a wedge that thins as it advances upstream through the harbour.

At high water, the nose of the salt wedge extends beyond the surveyed area and extends into the gorge and, during the lower discharge periods, actually penetrates over the Reversing Falls sill. At low water, the nose of the salt wedge is forced back downstream, but usually remains just upstream of the step down of the seabed located approximately 2000m downstream from the harbour bridge.

To quantitatively examine the nature of the mixing between the two layers, the central section adjacent to the ferry wharf has been focused on and a zoomed in water column imagery (see Figure 5.1) is provided for this section along with a detailed analysis of the velocity and density structure at that location. At that location, volume flux calculation will be derived in Section 5.8.

The plots presented, contain a combination of four panels for each along channel section representative of low tide, rising tide, high tide and falling tide. The remaining plots for the other times over the 12.42 hr tidal cycle can be acquired online (See APPENDIX I). The panels are the 200kHz backscatter, salinity, ADCP along-channel currents, optical backscatter (suspended sediments). The ADCP along-channel currents are positive downstream (towards the Bay of Fundy) and negative landwards. Figure 5.2 shows the respective scales for the physical quantities measured. Figure 5.3 shows the vessel's transects along which the shipped travelled to collect the data for the Main Harbour Channel and Courtenay Bay.

Figure 5.1: Showing the location focused on for the zoomed in water column imagery (200kHz acoustic imagery of section 500m x 500m).

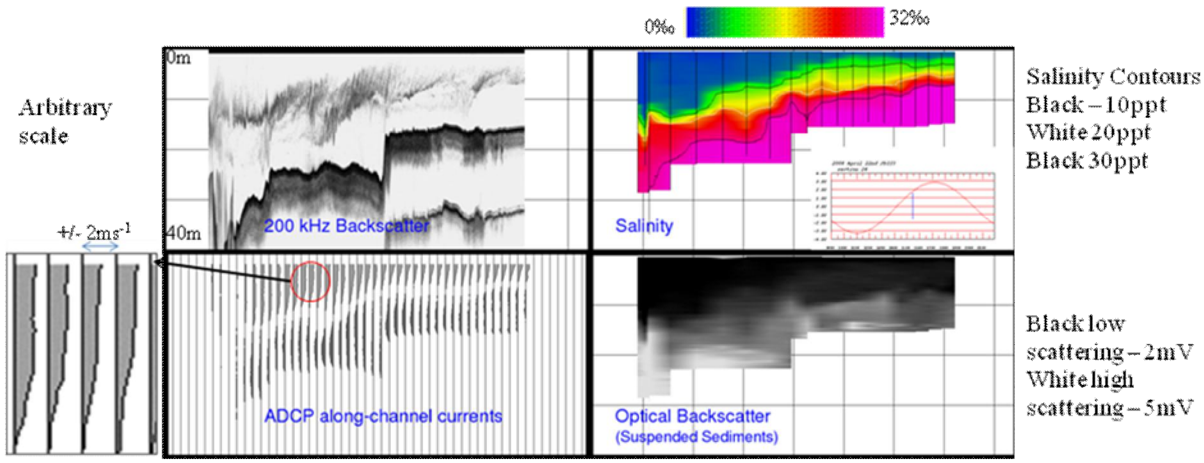


Figure 5.2: Showing an example of the longitudinal section with the respective scales of the measured quantities; 200kHz (arbitrary range of volume scattering to emphasize the mid-water scatters), salinity, along-channel currents, optical backscatter.

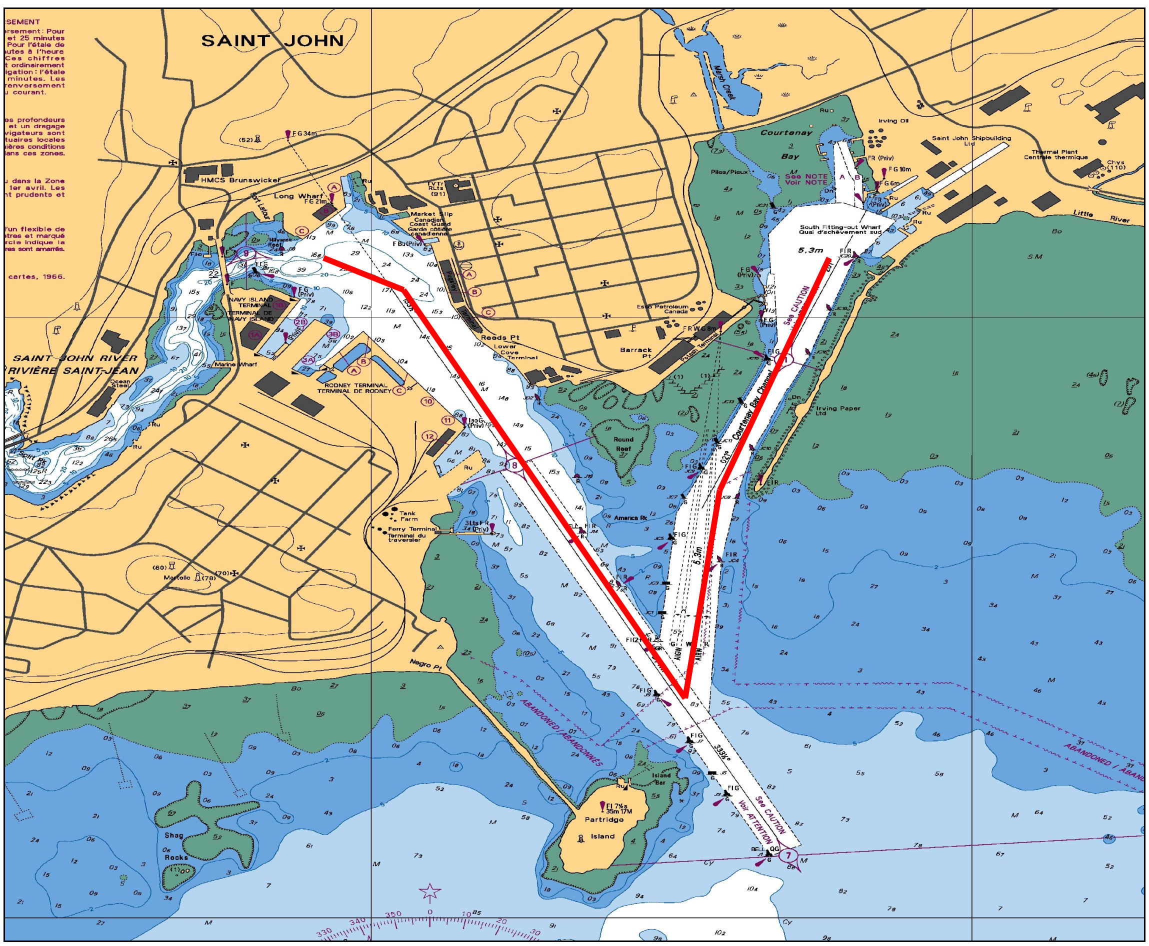


Figure 5.3: Showing the vessel's transects in the Main Harbour Channel and Courtenay Bay. These track lines are repeated over a 12.42hr tidal cycle.

5.2 Tidal Cycle - Winter minimum discharge (March 2009)

The survey conducted on March 26th 2009 started during the flood flow phase of the tide and ended during the low water phase of the tidal cycle.

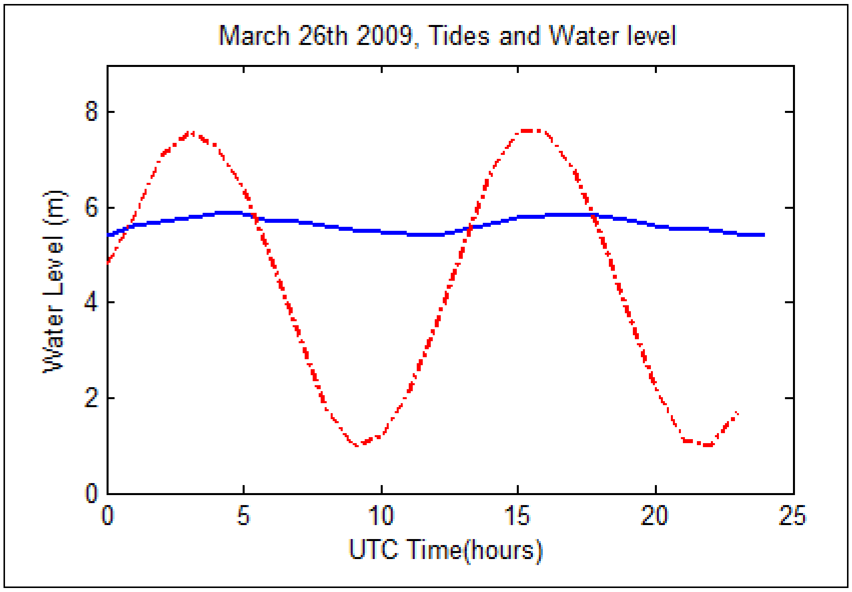


Figure 5.4: Showing the water level at Indiantown tide gauge (blue) w.r.t the tides (red) at the mouth of the Saint John Harbour on March 26th 2009 (relative to chart datum).

The winter minimum Main Harbour circulation is notable for a number of aspects (see Figure 5.5):

- The salinity of the upper layer is greater than 10‰. There is no upper freshwater layer at this time of the year and therefore this is more brackish than any other times of the year examined.
- As soon as the Falls reverse on the rising tide, the halocline goes almost horizontal indicating little horizontal pressure gradient (minimal shear between the two layers). At the same time, the surface brackish layer is as

thin as 2m. This provides a challenge to measure velocities as the ADCP is immersed 1m and only provides the first data value at ~2m. Thus the ADCP derived fluxes of the surface layer may be underestimated.

- The only time any significant suspended sediment concentrations are notable is during the flood tide in the lower salt layer.

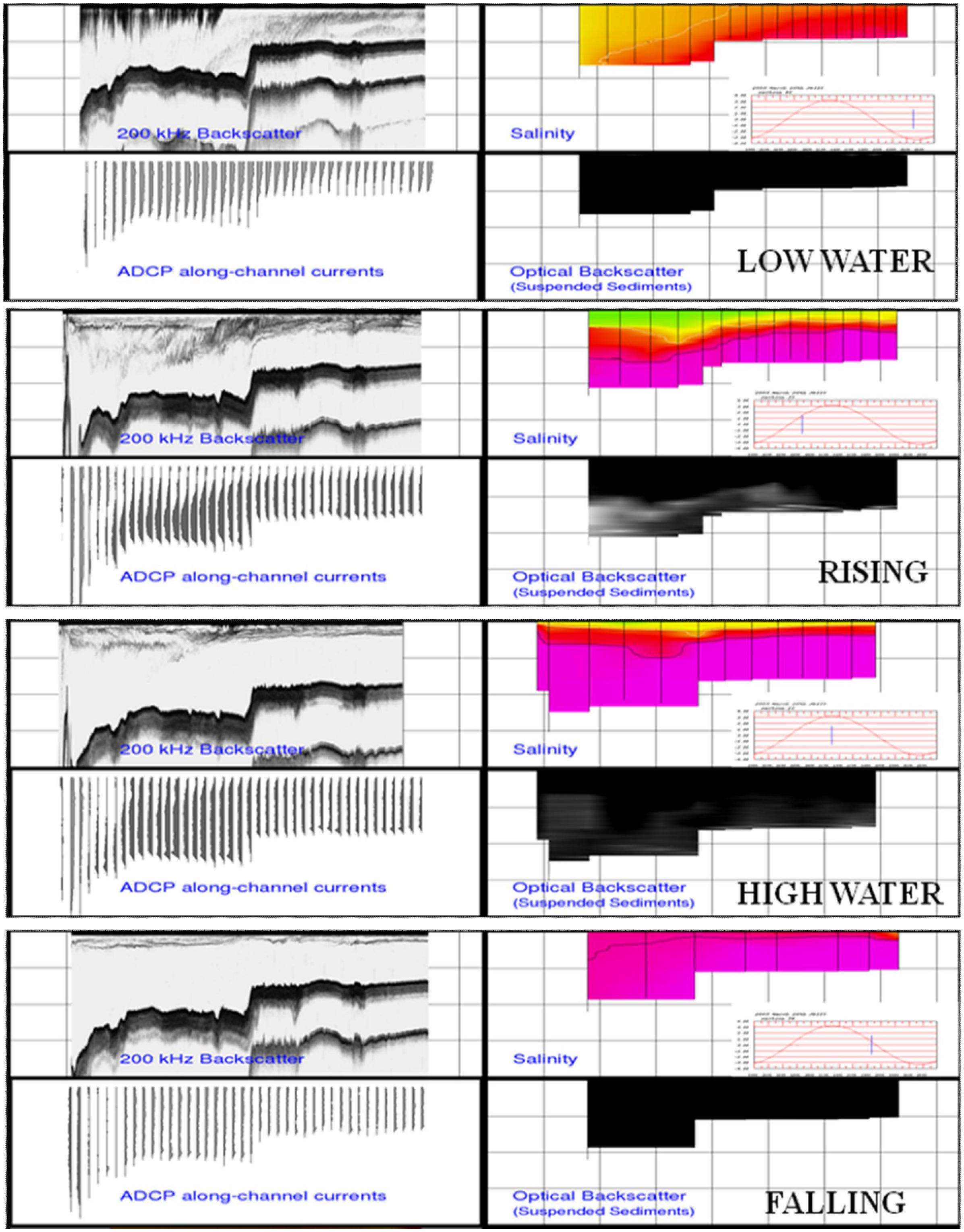


Figure 5.5: Showing the results of the longitudinal sections of the measurements; 200kHz acoustic backscatter, salinity, along-channel currents and optical backscatter for March 26th 2009 survey.

5.2.1 Zoom of the 200kHz acoustic imagery of the halocline during the winter minimum observations.

The four sections of the following figure (see Figure 5.6) illustrates the acoustic volume scattering character of the interface between the fresh and salt layers over the tidal cycle. The zoomed area is a 500m long section just upstream of the step down in the channel depth around the location where the velocity gradient and the density profiles are derived (see Figure 5.1).

At the bottom of the tide, the nose of the salt wedge is visible at this location. Just on the rising tide, very apparent interfacial waves are developed on the halocline. These resemble Kelvin Helmholtz waves as described by Geyer and Farmer (1980) indicating supercritical flow conditions at the interface and thus the potential for entrainment of the salt layer into the overlying brackish layer. At high water and on the falling tide, these interfacial waves disappear and the halocline looks laminar.

This qualitative character of the halocline needs to be interpreted in the light of the density and velocity structure to see whether the presence of the interfacial waves during the rising tides can be associated with the stability of the halocline as defined by the gradient Richardson number.

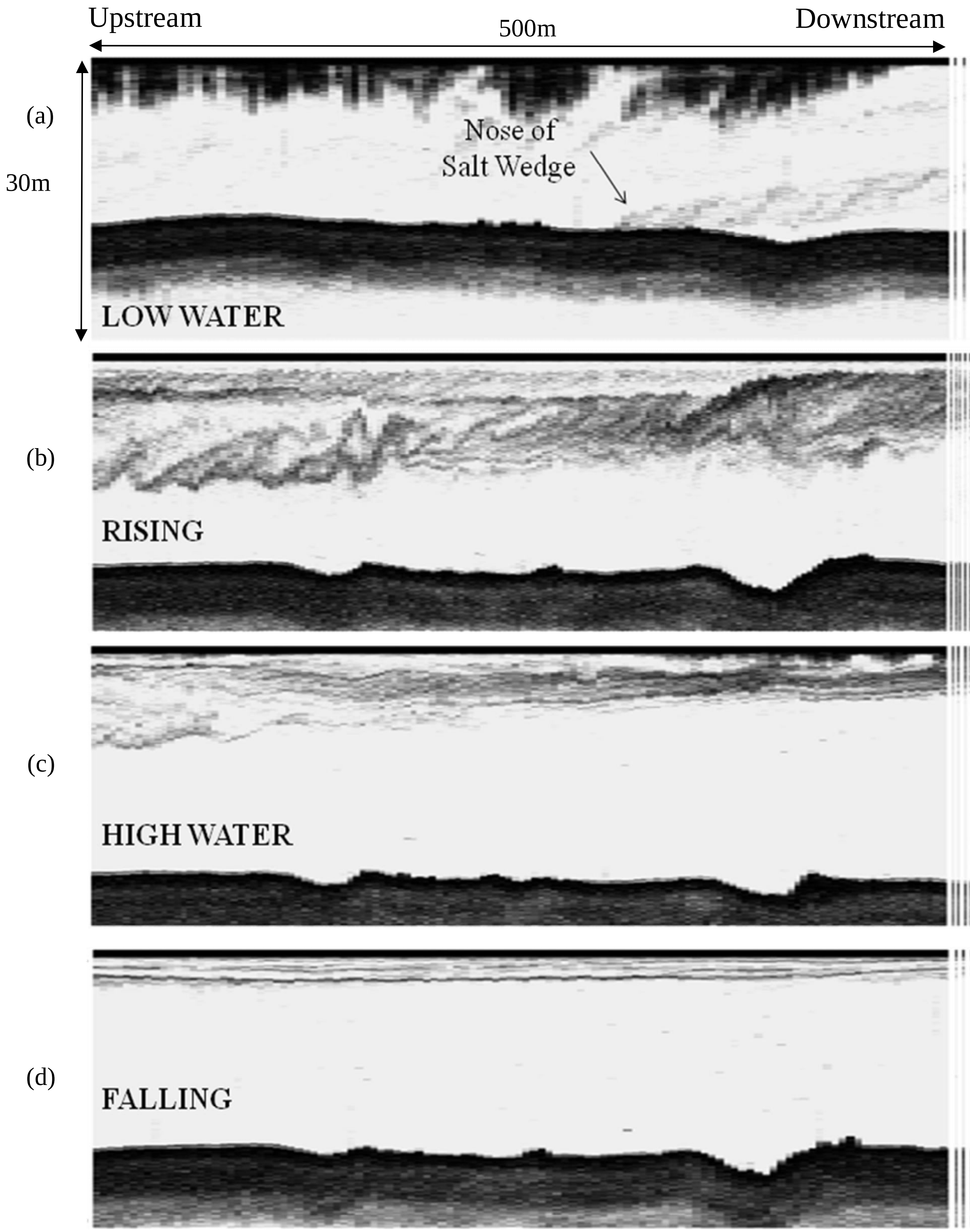


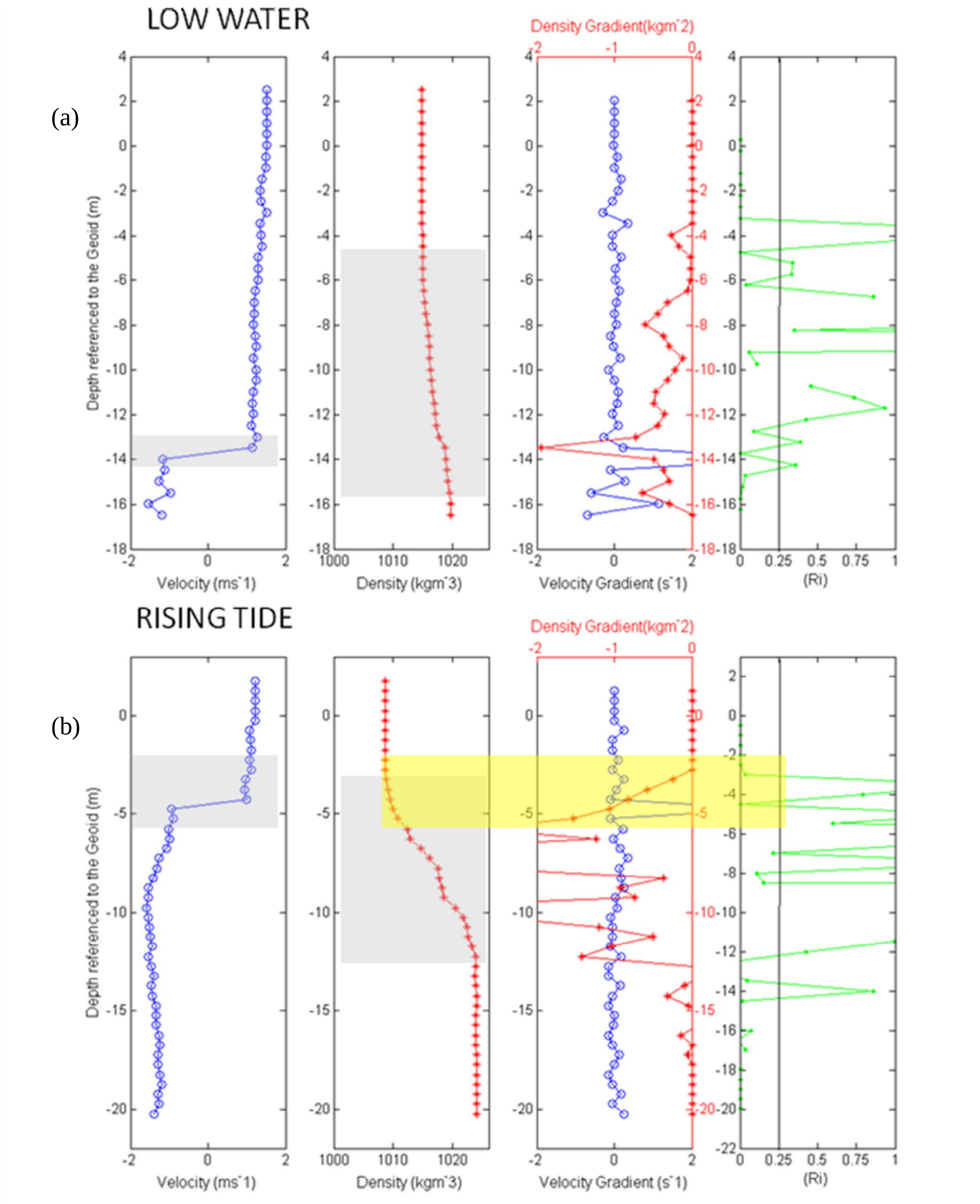
Figure 5.6: Showing the zoomed in images of the halocline for March 26th 2009. (a) Shows the location of the nose of the salt wedge at low tide in the channel and (b) shows that on the rising tide the KH waves are best developed.

5.2.3 Velocity and Density Structure at the cross-section location.

The following four figures (see Figure 5.7) illustrate the depth and magnitude of the principle gradients in along-channel current velocity and density at the four phases of the tide. The aim of these plots is to examine the pycnocline region (identified by the grey shading) and also identify the relative importance of the current shear with respect to the density gradient. The yellow shading indicates the location of the current shear with respect to the pycnocline to identify the region of mixing.

During the winter minimum period, the majority of the current shear is restricted to within a very narrow depth range. At low water, the narrow shear zone occurs at the base of the pycnocline. In contrast in the rising tide, the shear is now focused at the top of the pycnocline. At high water, the shear maximum is now in the middle of the pycnocline.

The gradient Richardson number is calculated for all these sections and notably, wherever the pycnocline is developed, the value is >0.25 suggesting stable flow without significant interfacial mixing. The 200kHz imagery however, suggest KH wave development on the rising tide. Notably this corresponds to the only period when the shear layer extends above the top of the pycnocline allowing the possibility of upward entrainment.


LOW WATER
(a)
Density Gradient(kgm^2)
Depth referenced to the Geoid (m)
Velocity (ms^1)
Density (kgm^3)
Velocity Gradient (s^1)
(Ri)
RISING TIDE
(b)
Density Gradient(kgm^2)
Depth referenced to the Geoid (m)
Velocity (ms^1)
Density (kgm^3)
Velocity Gradient (s^1)
(Ri)

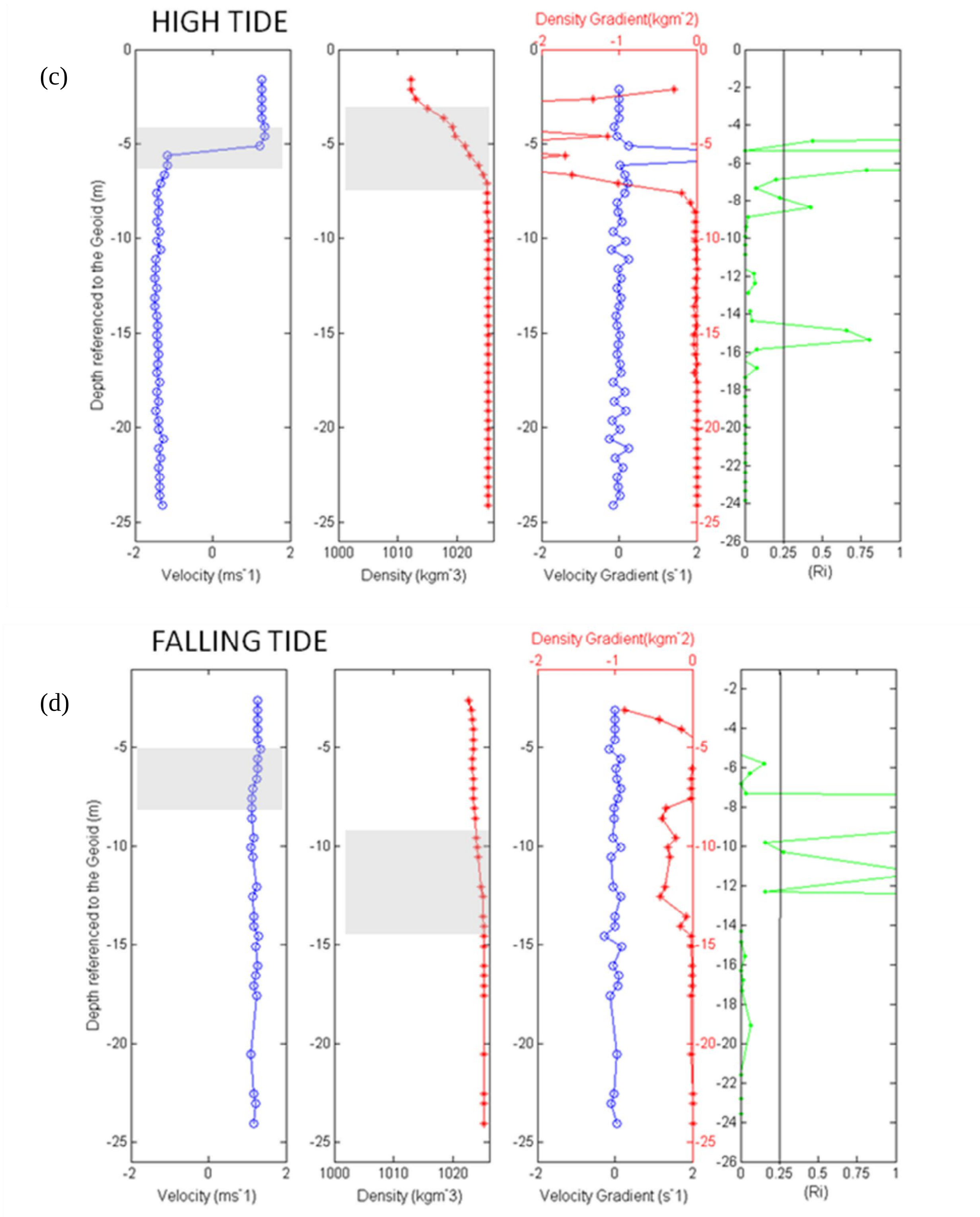


Figure 5.7: Showing the graphical results of the observed velocity and density profiles, density gradients, velocity gradients and the derived Ri numbers for low tide, rising tide, high tide and falling tide in the Main Harbour Channel for the March 26th 2009 survey.

5.3 Tidal Cycle – Spring Freshet Observations (April 2008)

Freshwater discharge rate in the spring freshet is typically $3400 m^3 s^{-1}$ according to the Water Survey of Canada. However in 2008, the river discharge rates exceeded that of the gauge measurement capability according to Environment Canada hydrometric database. It is also important to note that, during the Spring freshet when the river flow is highest and the water level exceeds that of the tidal range, the Reversing Falls never reverse and there is a constant outward flow of freshwater through the gorge into the Main Channel harbour.

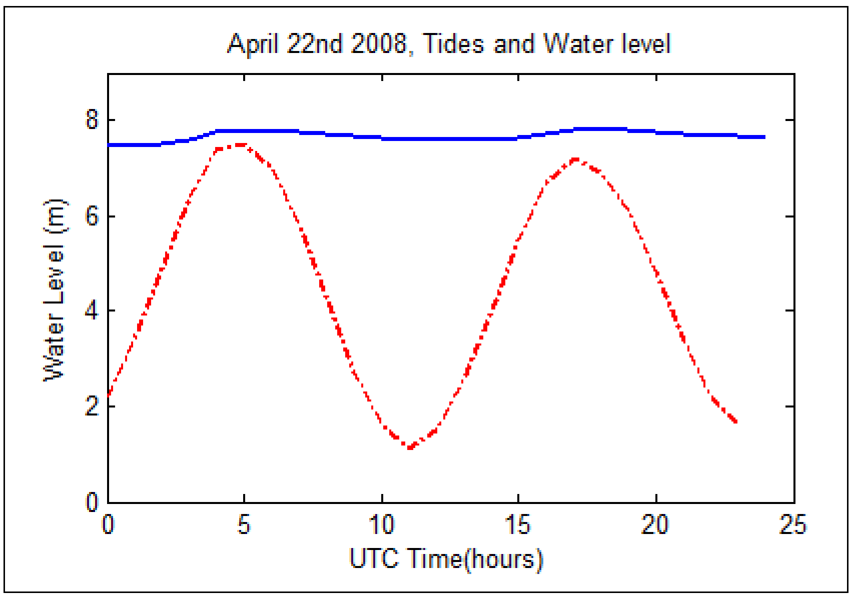


Figure 5.8: Showing the water level at Indiantown tide gauge (blue) (relative to the geoid) with respect to the tides (red) (relative to chart datum) at the mouth of the Saint John Harbour on April 22nd 2008. The water level is always higher than the tidal range during the Spring freshet.

The advance upstream and retreat of the lower salt water intrusion is still present here, but with the increased river discharge, it is now forced further down the harbour by low tide. Therefore the overlying water is now completely fresh.

Unlike during the winter minimum when the halocline became essentially level, once the falls had reversed, at this time of year, as the river level is higher than high water, the falls do not reverse and the freshwater discharge is constant through the Main Channel of the harbour.

The suspended sediment concentrations now show two peak periods and locations:

- Lower Layer on the rising tide and at high water
- Upper layer just at low water.

The lower layer influx of sediment is similar to that seen in the winter, suggesting that the source of sediments are either the influx from outside the harbour or just resuspension of the harbour bottom sediments caused by the incoming lower layer. However, what is new and unique to the spring freshet is the significant suspended sediments load observed in the upper layer (see Figure 5.9).

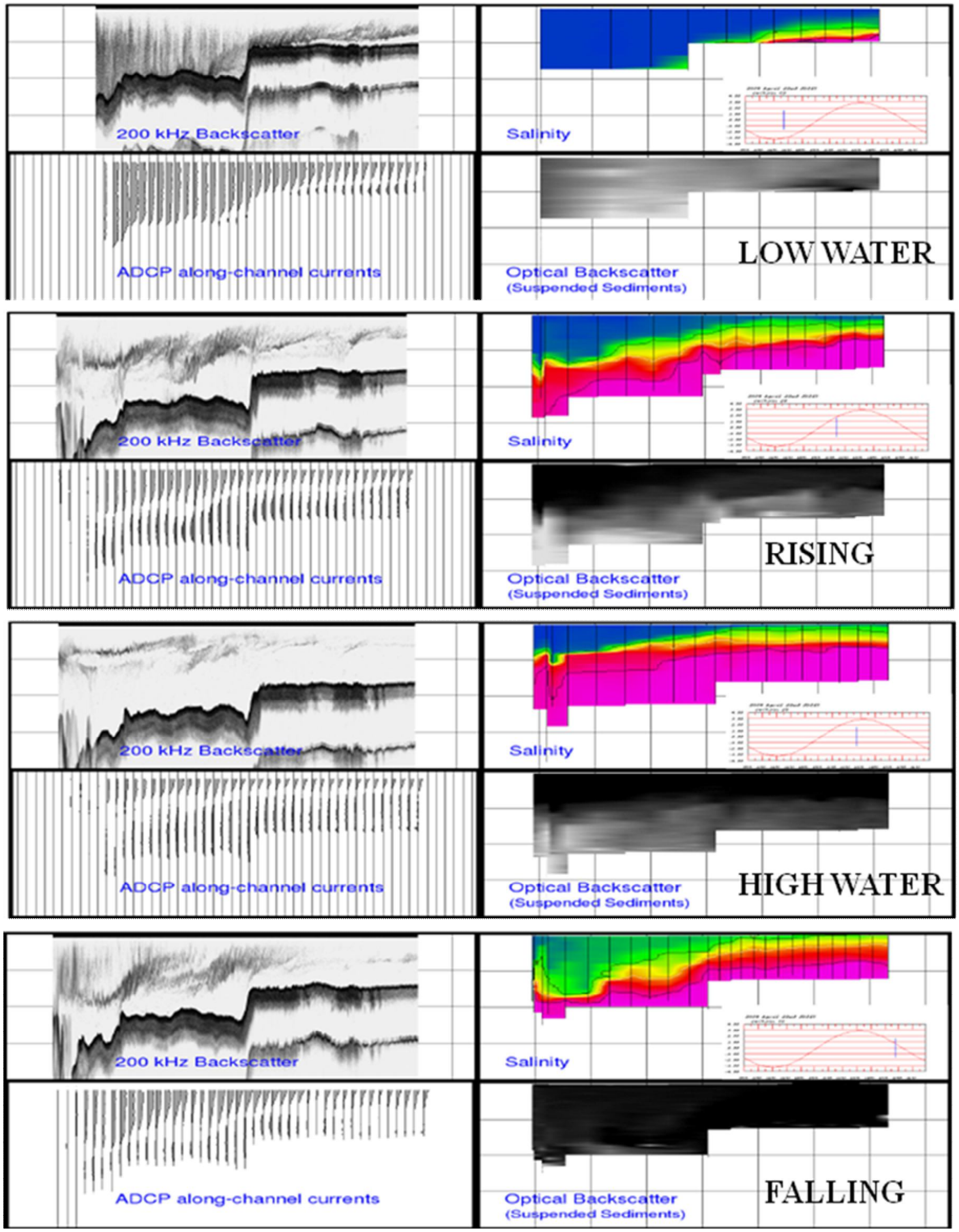


Figure 5.9: Showing the results of the longitudinal sections of the measurements; 200kHz acoustic backscatter, salinity, along-channel currents and optical backscatter at low tide, rising tide, high tide and falling tide for the April 22nd 2008 survey.

5.3.1 Zoom of the 200kHz acoustic imagery of the halocline of the spring freshet observations.

The same 500m section is presented here of the acoustic scattering at 200kHz. Unlike the winter minimum when the interfacial waves were only seen on the rising tide, in this case they are present at all phases of the tide.

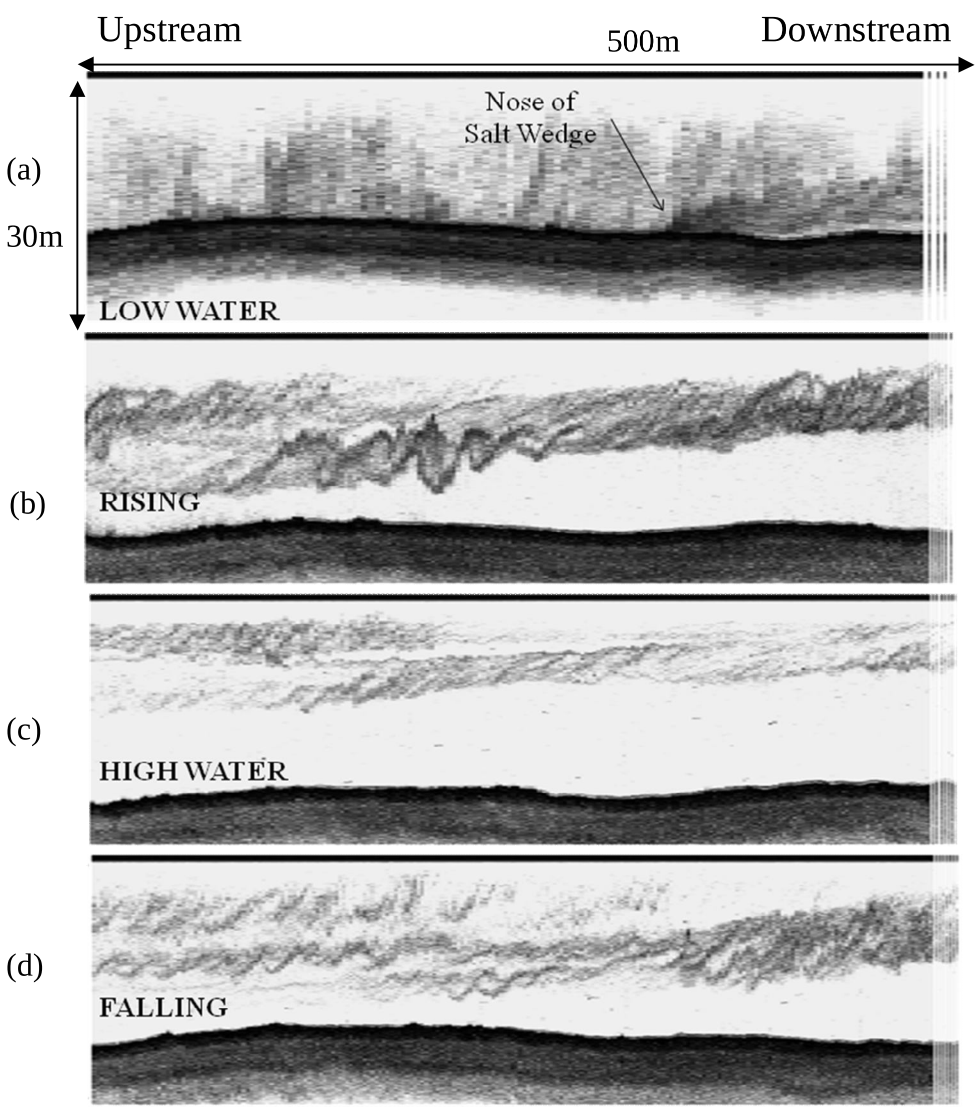


Figure 5.10: Showing the zoomed in images of the halocline for April 22nd 2008. (a) Shows the location of the nose of the salt wedge at low tide in the channel and (b), (c) and (d) shows the interfacial waves.

5.3.2 Velocity and density structure at the cross section location.

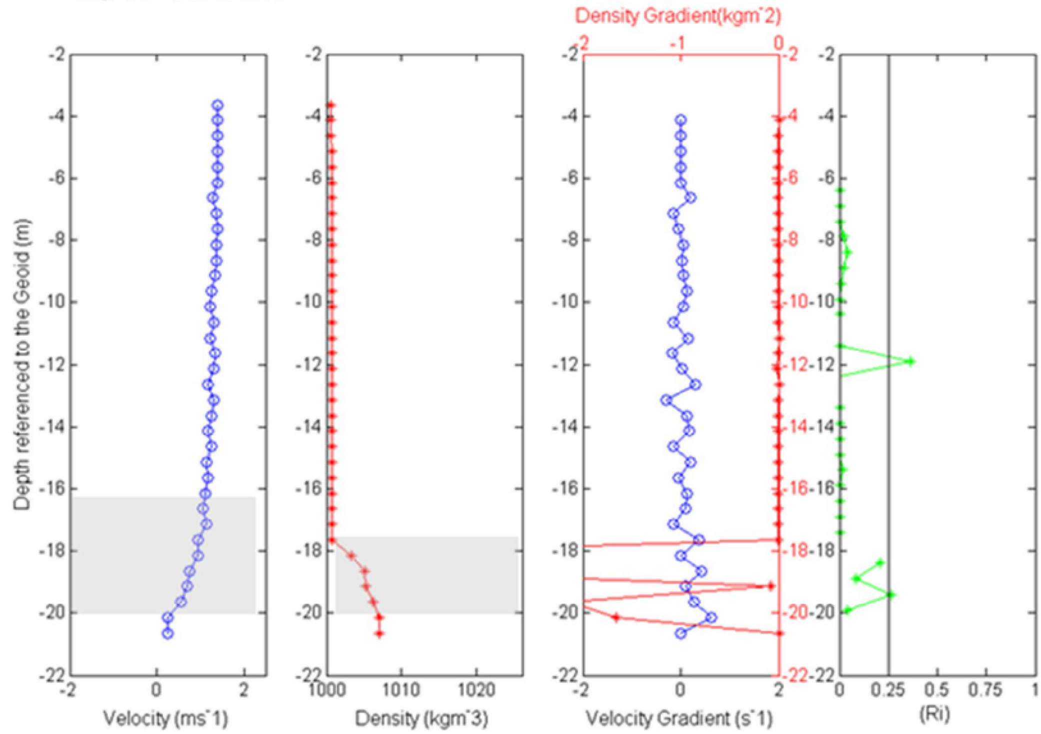
Figures illustrating the depth and magnitude of the principle gradients in the along channel current velocity and density at four phases of the tide are presented for April 22nd 2008 at low tide, rising tide, high tide and falling tide. The grey shading indicates the thickness of the current shear and the pycnocline region. The yellow shading indicates the location of the current shear with respect to the pycnocline to identify the region of mixing (see Figure 5.11).

In contrast to the winter minimum when the current shear zone was very narrow (<5m), in this case the shear zone is now much thicker. It is thinnest at low tide, in part because we are only viewing the nose of the salt wedge.

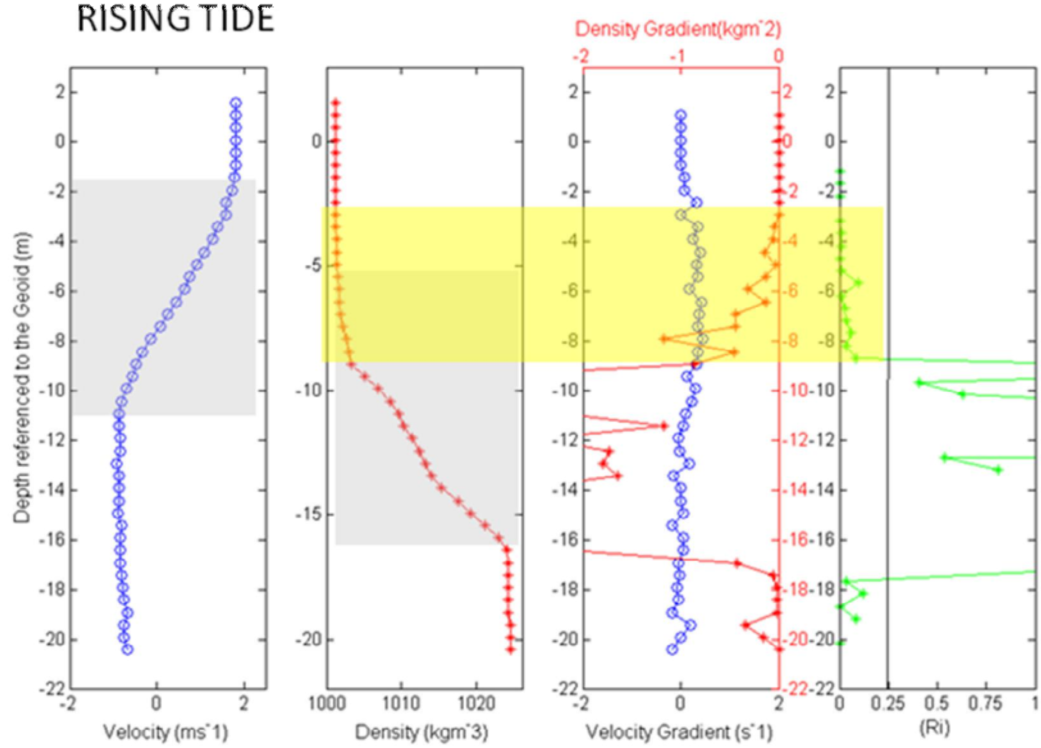
On the rising tide and high tide, the current shear zone is mainly above the pycnocline. This was the same condition during the winter minimum observations in March when the KH waves were developed.

The gradient Richardson numbers indicate subcritical conditions throughout the main pycnocline, only becoming supercritical (Ri<0.25) towards the top of the pycnocline as the density gradient become less. It is inferred that the interfacial waves reflect the mixing of just the top of the pycnocline as the salt water is entrained into the upper layer.

LOW WATER



RISING TIDE



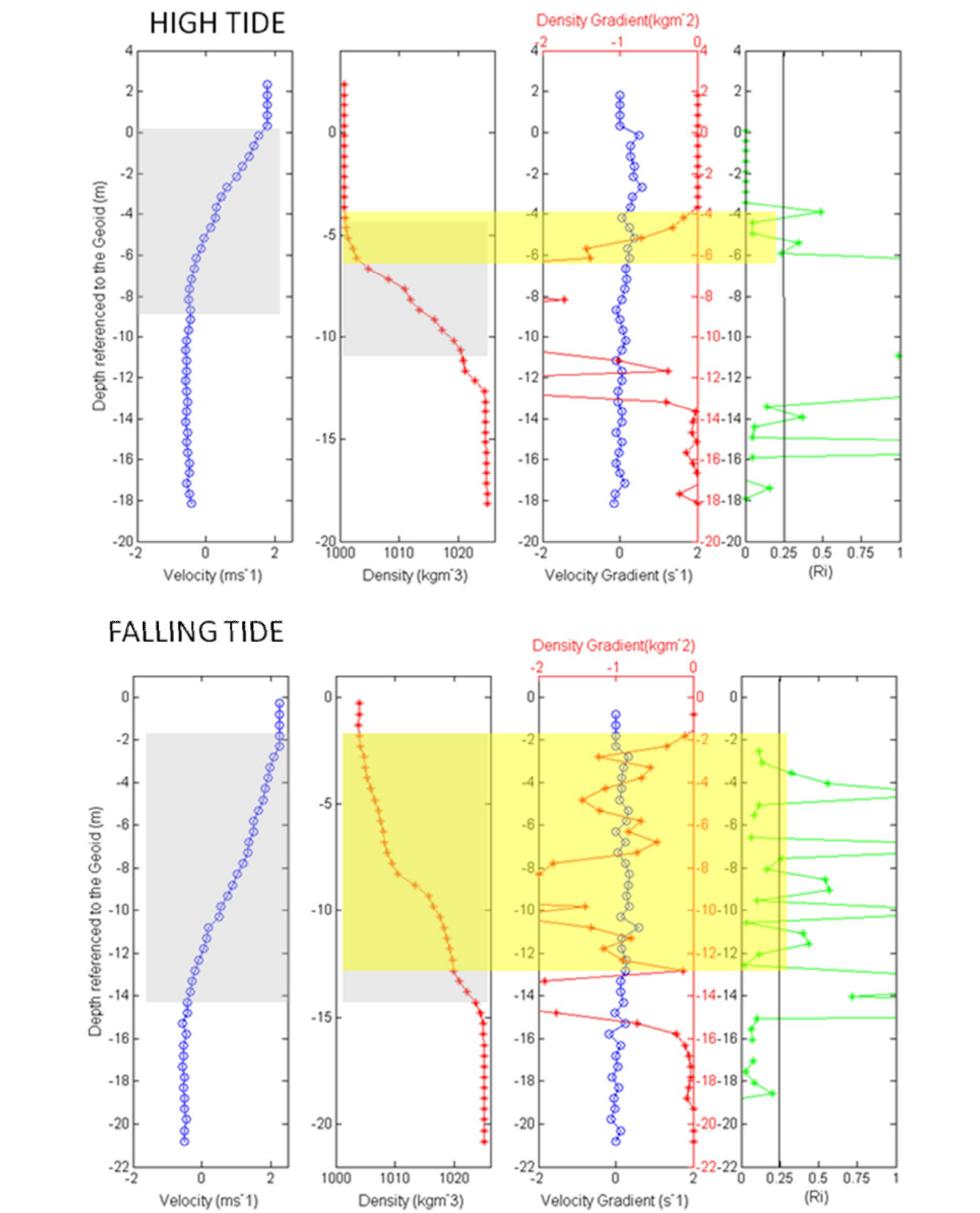


Figure 5.11: Showing the graphical results of the observed velocity and density profiles, density gradients, velocity gradients and the derived Ri numbers at low tide, rising tide, high tide and falling tide for April 22nd 2008 survey.

5.4 Tidal Cycle – Summer Minimum Discharge (June 2009)

The survey conducted on June 11th 2009 reflects very close to the summer minimum discharge. Hachey [1939] observed that during certain phases of the tide when the river levels are low, the salinity of the harbour waters can exceed 29 ‰ throughout the entire water column. It is important to note here that the river water levels are below the high tide range when this survey was conducted This indicates that the summer minimum discharge flow through the Reversing Falls is confronted by the high tide inflow from the Bay of Fundy and hence the Falls reverse during this tidal cycle. Figure 5.12 shows the relationship between the river water levels at Indiantown tide gauge and the tides of the Bay of Fundy during the June 11th survey. This survey started during the flood tide for this cycle.

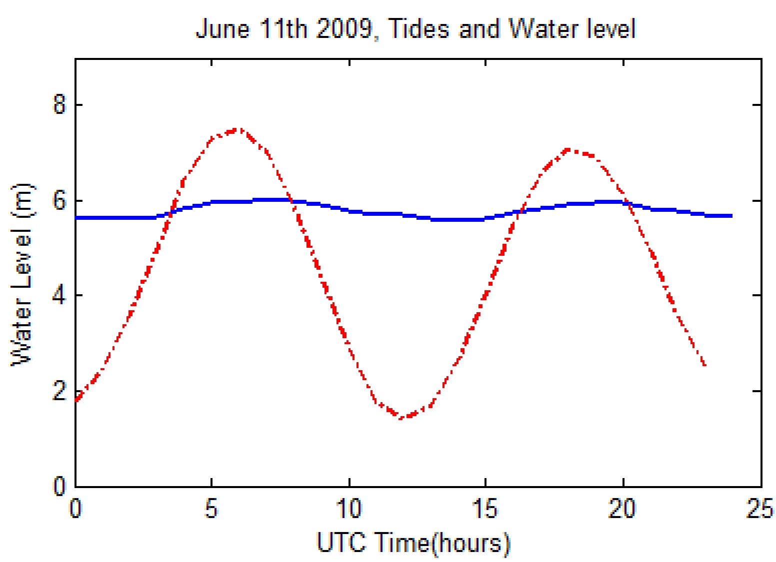


Figure 5.12: Showing the relationship between the water level heights (blue) and the Tidal heights (red) during the June tidal cycle survey (relative to chart datum).

As with the previous two times of the year, the salt wedge advances up the channel on the flood tide. As with the winter minimum conditions though, the surface waters are brackish (7‰ - 20‰) rather than fresh. Again, similar to the winter minimum observations, once the Falls have reversed, the halocline becomes mainly level.

The optical backscatter probe from the towed sensor was broken for this tidal cycle; therefore no data were collected to observe the distribution of sediments throughout the water column. (see Figure 5.13).

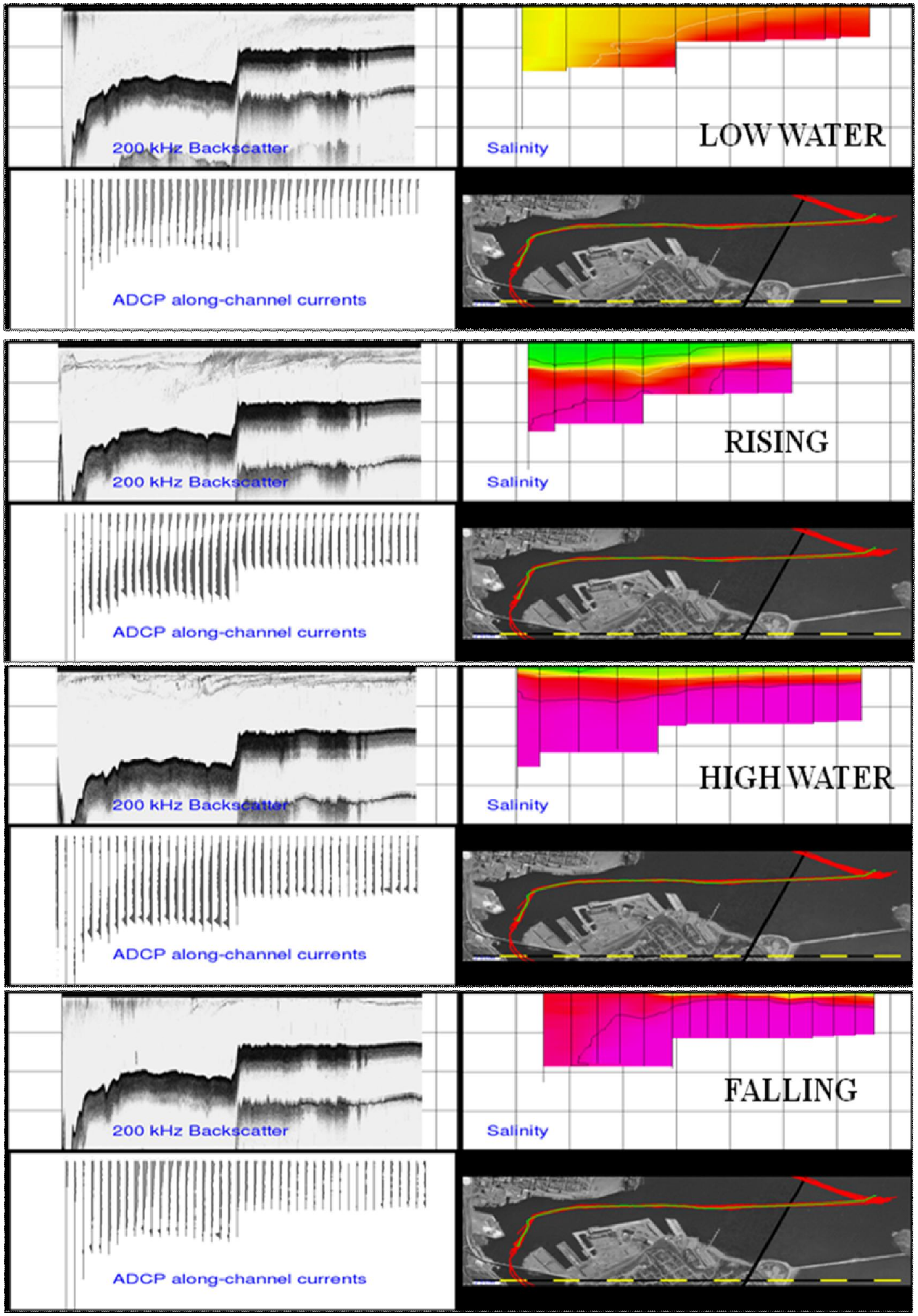


Figure 5.13: Showing the results of the longitudinal sections of the measurements; 200kHz acoustic backscatter, salinity, along-channel currents and optical backscatter for low tide, rising tide, high tide and falling tide for June 11th 2009 survey.

5.4.1 Zoom of the 200kHz acoustic imagery of the halocline during the summer minimum observations.

Presented here is the 500m section of the acoustic scattering at 200kHz. In this case the only time that significant interfacial waves are clearly developed is on the rising tide.

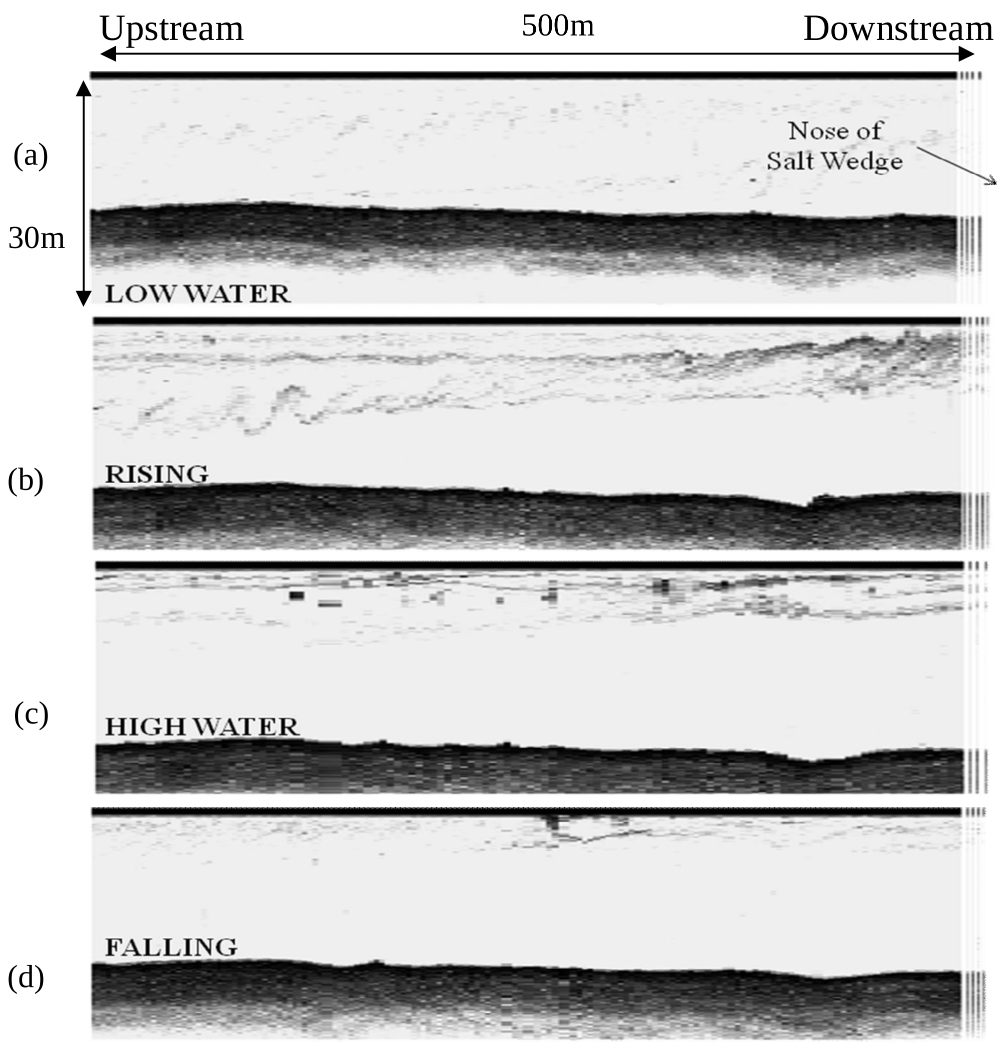


Figure 5.14: Showing the zoomed in images of the halocline for June 11th 2009. (a) Shows the location of the nose of the salt wedge at low tide in the channel and (b) on the rising tide interfacial waves are seen.

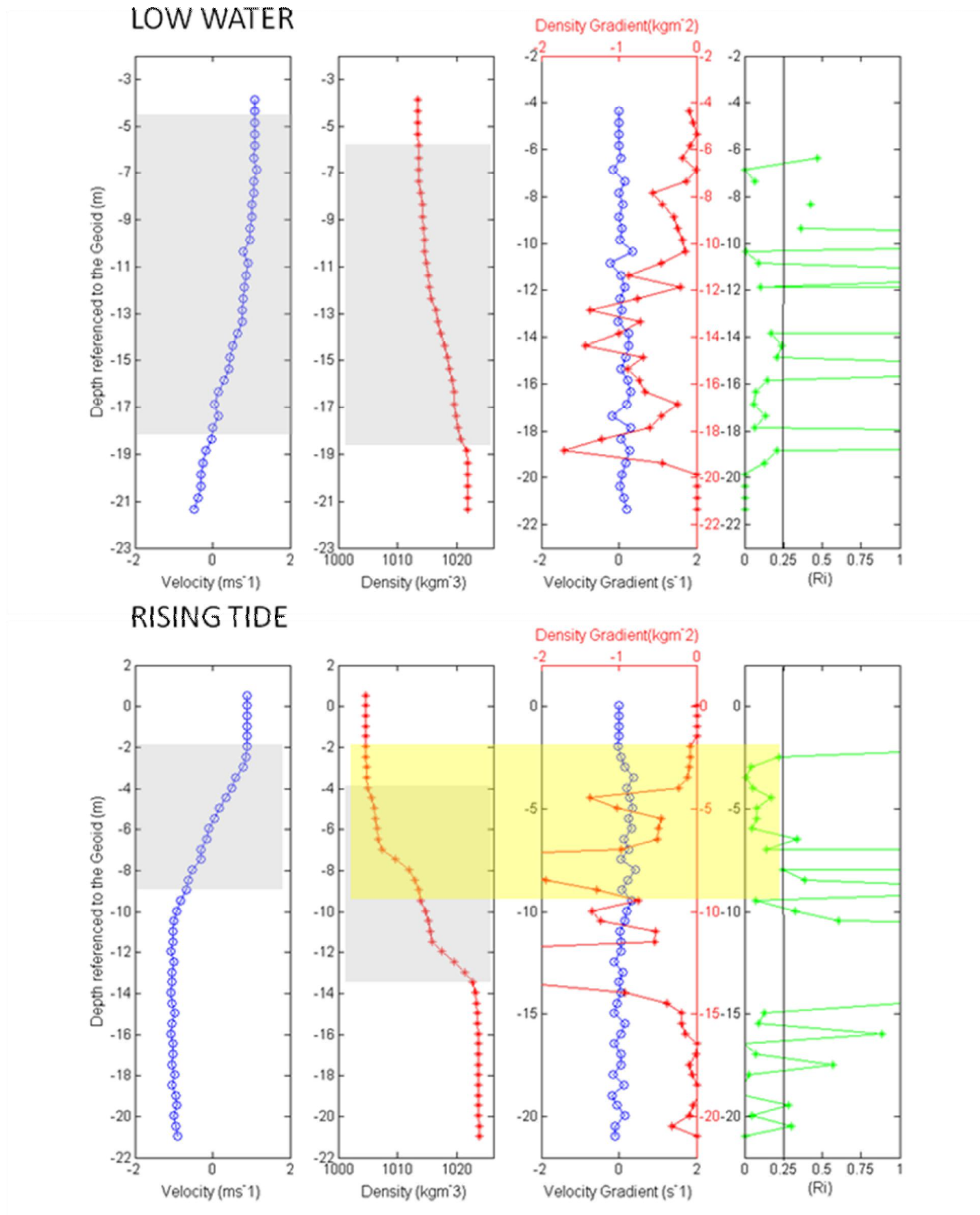
5.4.2 Velocity and density structure of the cross-section location.

Unlike the winter minimum, at low tide, the current shear zone is very thick and extends right across the equally thick pycnocline (see Figure 5.15). The Richardson numbers throughout the pycnocline are highly variable, perhaps suggesting some mixing at this point.

Notably the nose of the salt wedge has retreated downstream of the observation point, so the profile we are looking at in entirely in the brackish layer.

On the rising tide as well as at high water, the shear zone moves up, partly above the pycnocline. The interfacial waves appear to be developed on the top of the pycnocline again implying entrainment of the salt water into the upper layer. The gradient Richardson numbers are subcritical in the main pycnocline but do go supercritical at the top of the layer where the shear zone extends up into the brackish layer with reduced density gradients.

For high water and falling tide, the thickness of the shear zone and the pycnocline are notably reduced (although still thicker than those seen in the winter minimum observations). This confirms that the river discharge in June is higher than in March. Another proxy is that the tidally averaged river level at Indiantown is higher for June than March (see Figure 2.16).


LOW WATER
Density Gradient(kgm^-2)
Depth referenced to the Geoid (m)
Velocity (ms^-1)
Density (kgm^-3)
Velocity Gradient (s^-1)
(Ri)
RISING TIDE
Density Gradient(kgm^-2)
Depth referenced to the Geoid (m)
Velocity (ms^-1)
Density (kgm^-3)
Velocity Gradient (s^-1)
(Ri)

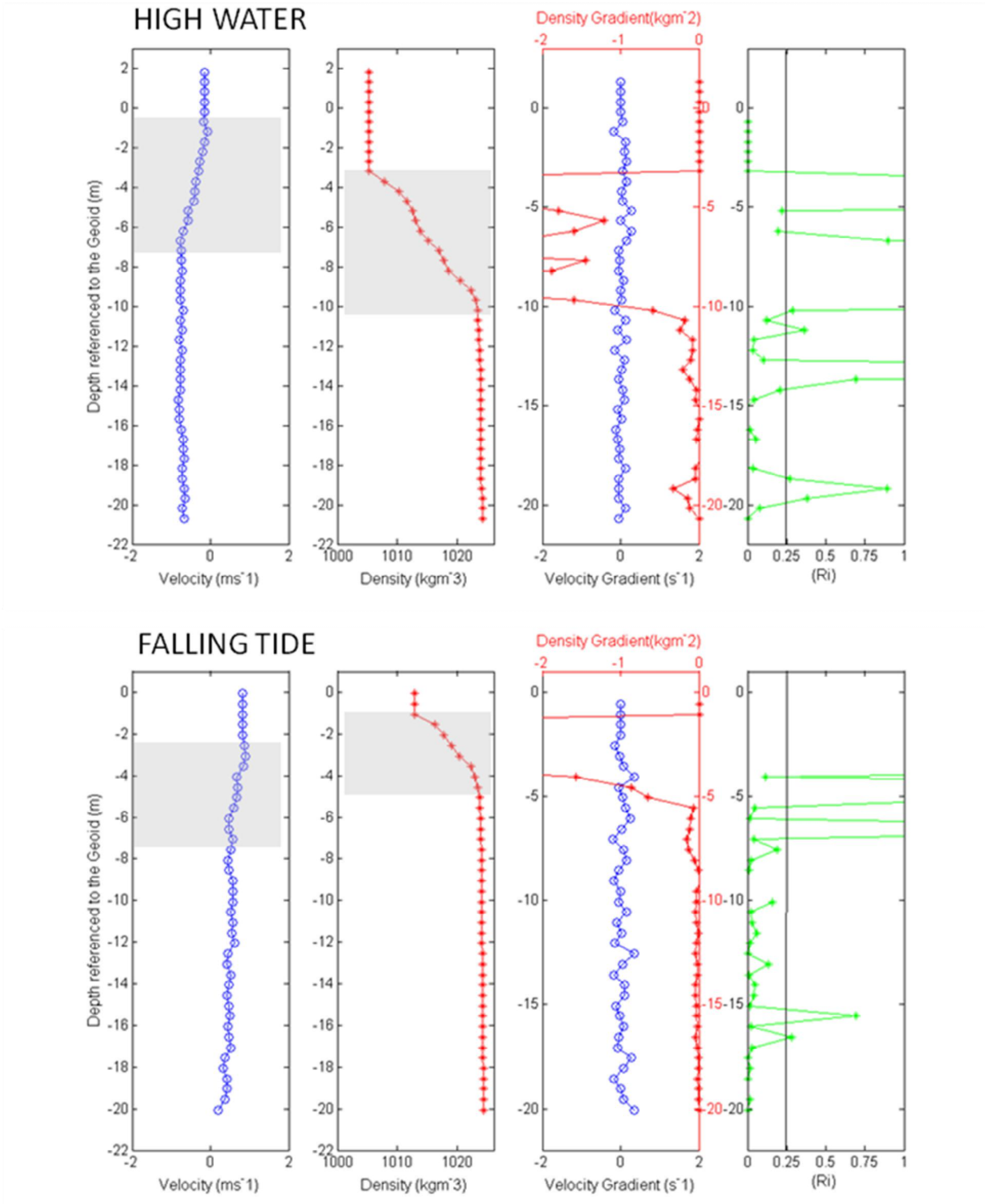


Figure 5.15: Showing the graphical results of the observed velocity and density profiles, density gradients, velocity gradients and the derived Ri numbers at low tide, rising tide, high tide and falling tide for June 11th 2009 survey.

5.5 Tidal Cycle – Fall Secondary Freshet (November 2008)

The survey conducted on November 14th 2008 reflects the fall secondary freshet discharge rate. The survey conducted on November 2008 started approximately two hours after the first low tide for this cycle.

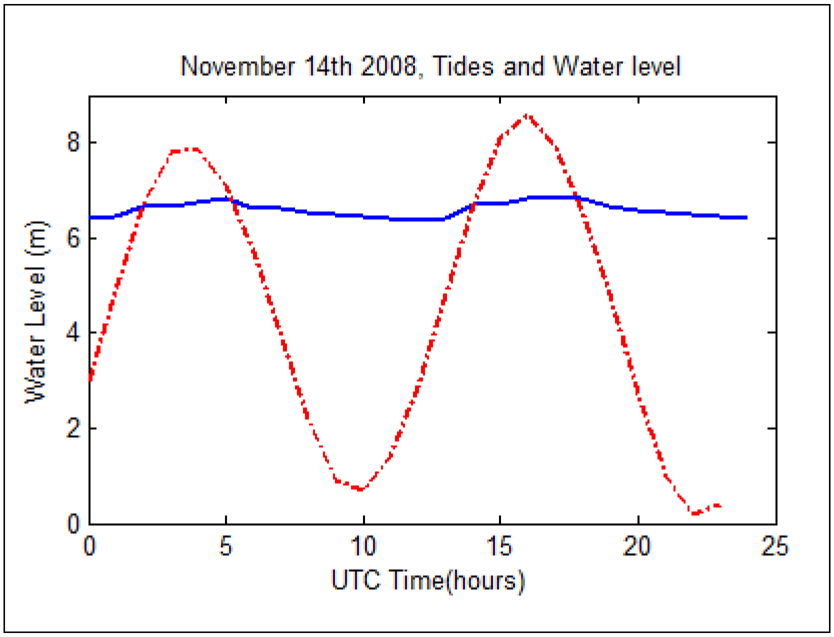


Figure 5.16: Showing the water level at Indiantown tide gauge (blue) w.r.t the tides (red) at the mouth of the Saint John Harbour on November 14th 2008. (Relative to chart datum).

The Fall freshet circulation patterns appear intermediate between the minimum discharge conditions of winter and summer and the larger Spring freshet. In this case the falls do reverse although for a shorter period and closer in time to high water. After the Falls reverse, the halocline gets flatter, but retains significant relief. The outflowing water is fresher although not truly fresh as it was in the Spring.

Unlike the Spring freshet, the suspended sediment levels are less elevated in the upper layer. But like the spring freshet, the highest suspended sediment concentrations occur in the lower layer which is present on the rising tide, but in this case best developed at high tide (see Figure 5.17).

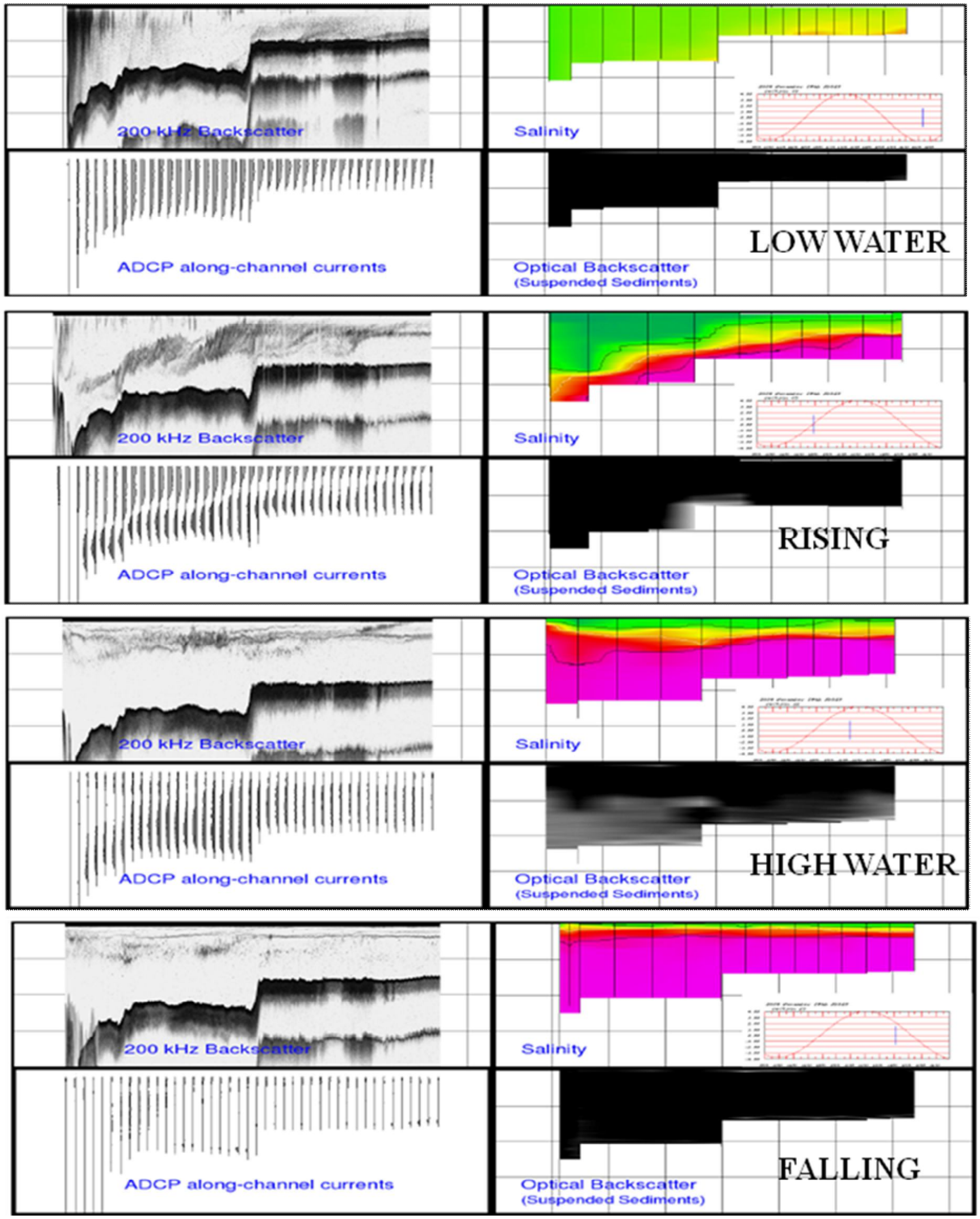


Figure 5.17: Showing the results of the longitudinal sections of the measurements; 200kHz acoustic backscatter, salinity, along-channel currents and optical backscatter for low tide, rising tide, high tide and falling tide for November 14th 2008 survey.

5.5.1 Zoom of the 200kHz acoustic imagery of the halocline during the fall freshet minimum.

Again the same 500m section is presented here of the acoustic scattering at the 200kHz at that location of the detailed profile analysis and the volume flux calculations.

At low water the nose of the salt wedge has retreated out of the field of view. On the rising tide, interfacial waves are clearly developed on the tilted halocline. At high water and on the falling tide, the suspected interfacial waves are far reduced compared to the spring freshet, but not absent like the winter and summer minimum conditions when a laminar layer is visible.

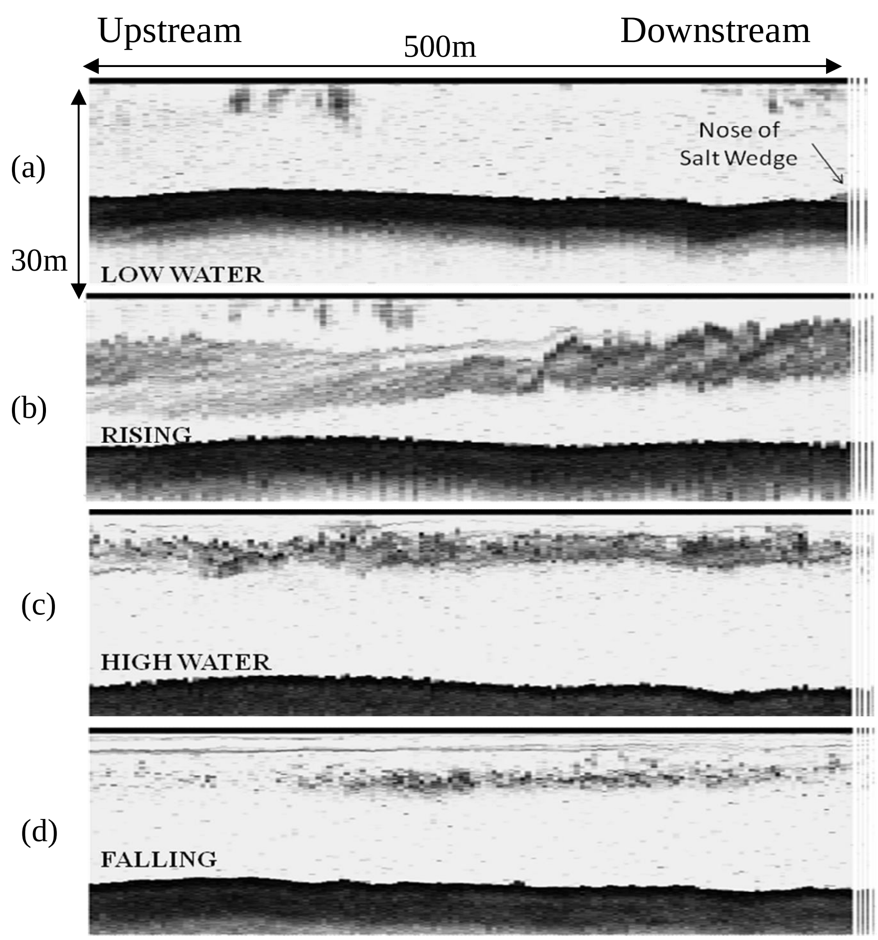


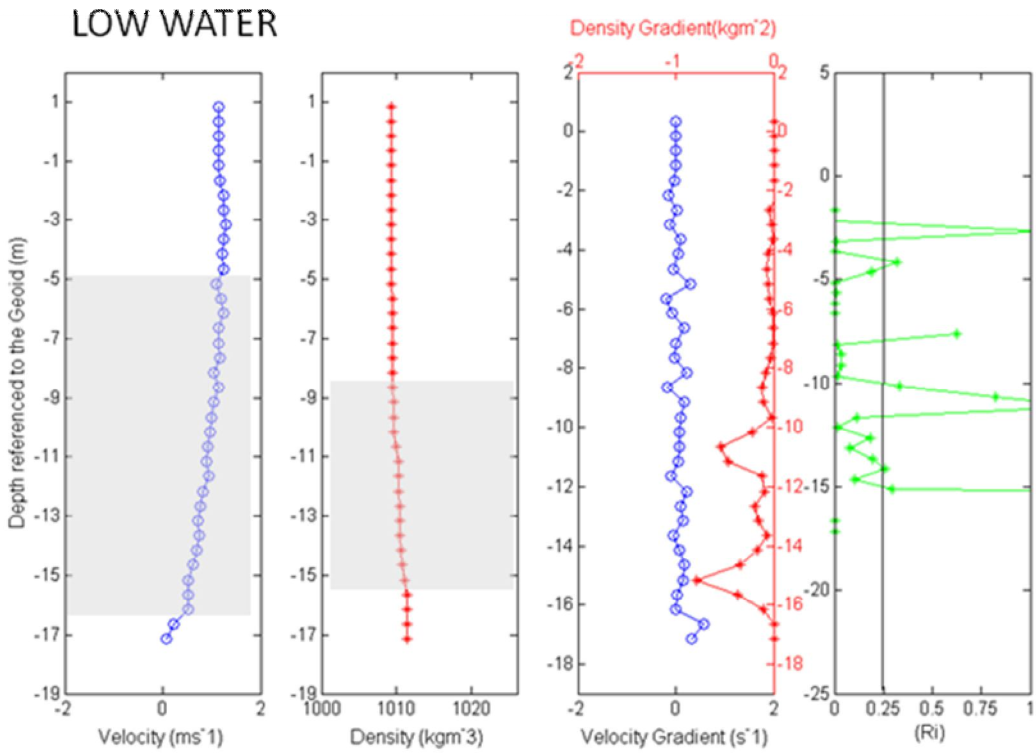
Figure 5.18: Showing the zoomed in images of the halocline for November 14th 2008. (a) Shows that the salt wedge is not in field of view. (b) Rising tide interfacial waves are best developed. (c) and (d) the high tide and falling tide the interfacial waves are still noticeable.

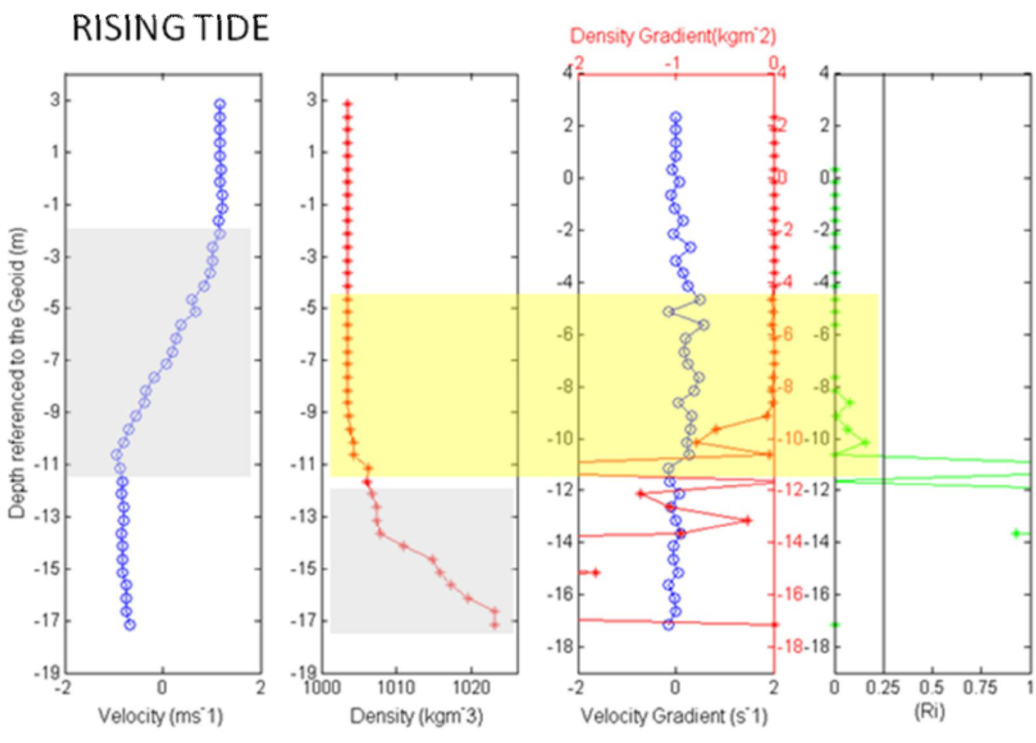
5.5.2 Velocity and Density structure at the cross-section location.

At low water, while the nose of the salt wedge has retreated, there is still a density gradient in the overlying brackish layer. A thick shear zone is developed in this. As this is all above the main salt water, no interfacial waves are visible.

On the rising tide, the current shear zone clearly lies above the main pycnocline. As before, while within the main pycnocline, the flow is stable at the top of the pycnocline, where the shear is highest, the Ri is <0.25 indicating that active mixing may be taking place. Again this suggests that they reflect entrainment of the lower salt water layer into the upper freshwater layer.

At high water and on the falling tide the thicknesses of both the shear zone and the pycnocline have been reduced. In both cases the flow density gradient suppresses mixing effectively, and the interfacial waves disappear (see Figure 5.20).


LOW WATER
Density Gradient(kgm^2)
Depth referenced to the Geoid (m)
Velocity (ms^1)
Density (kgm^3)
Velocity Gradient (s^1)
(Ri)


RISING TIDE
Density Gradient(kgm^2)
Depth referenced to the Geoid (m)
Velocity (ms^1)
Density (kgm^3)
Velocity Gradient (s^1)
(Ri)

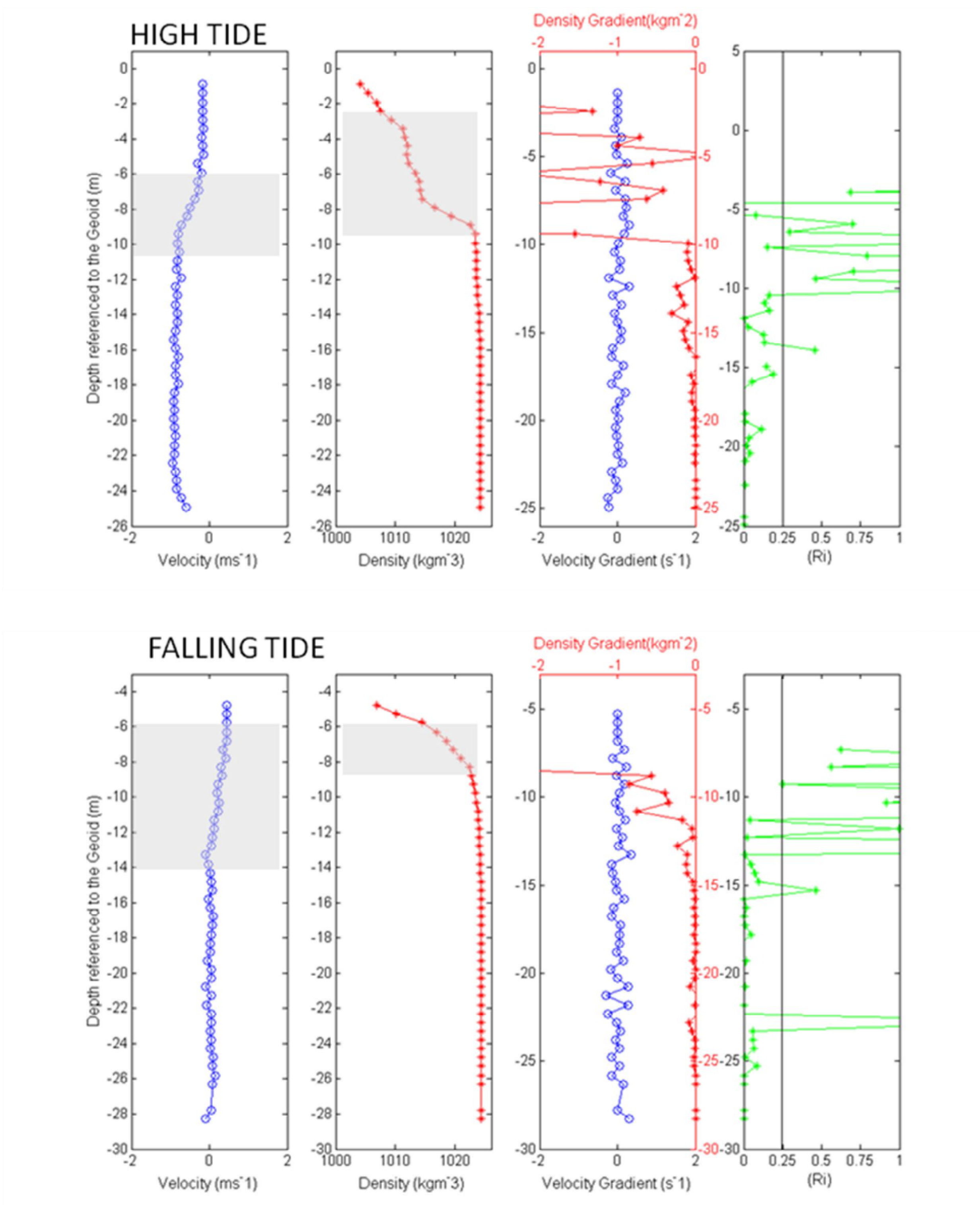


Figure 5.19: Showing the graphical results of the observed velocity and density profiles, density gradients, velocity gradients and the derived Ri numbers for low tide, rising tide, high tide and falling tide for November 14th 2008 survey.

5.6 Summary of Main Harbour Channel Circulation

The observations during the four flow regimes of the year indicate a common estuarine circulation pattern. The pattern however is modulated in a number of ways.

At all times of the year (assumed for June), the highest suspended sediment concentrations are always observed in the lower layer, either during the rising tide or at high tide. How significant this is in terms of mass flux, however, will depend on the volume flux in that lower salt layer.

The only time of the year when there are significant suspended sediment concentrations observed in the brackish or freshwater upper layer is during the Spring freshet.

The rising tide period is clearly the point in the tidal cycle where there is most entrainment of salt water into the upper layer. This is evidenced by the clear development of the Kelvin Helmholtz waves observed just above the main pycnocline. These waves develop best when the shear zone extends above the pycnocline.

During the Spring freshet, those interfacial waves are developed at all stages of the tide. For the other times of the year, they are absent at those other phases of the tide.

5.7 Courtenay Bay Channel Oceanographic Results

The following four figures illustrate representative sections along the Courtenay Bay channel for rising tide, high tide, falling tide and low tide respectively. Figures 5.20 5.21, 5.22 and 5.23 show the results for the surveys conducted during the winter minimum, spring freshet, summer minimum and fall freshet periods.

The flow is much thinner here than in the Main Harbour channel as it is constrained between ~5m depth at low water and ~11m at high water. With no significant freshwater influence at the upstream end, the current velocities are very low (in all cases <0.5m/s) and thus are poorly resolved by the underway ADCP.

In all cases at low tide the Bay is primarily full of fresh water (during the two freshet periods) or brackish water (during winter and summer minimums). The salt water penetration in the lower layer is seen on the rising tide but notably is not efficiently flushed out on the falling tide. At that time the pycnocline is tilted downward toward the sea, suggesting that while there is an outward seaward pressure gradient trying to eject the salt plug out of the Bay, it is not flushing efficiently possibly due to bed friction. This suggests that, without a strong river outflow, the salt plug that enters the Courtenay Bay channel is left to stagnate. If that salt plug enters with suspended sediment, it is thus likely to settle out before being withdrawn from the Bay.

The location and timing of the presence of the significant suspended sediments is notable. For the winter minimum and the fall freshet a clear inflow of suspended sediment occurs on the rising tide, entirely within the lower layer. Interestingly, the suspended sediment appears to enter the channel just downstream of the breakwater rather than from the southern end of the channel, suggesting that they are sourced from flow coming over the shallows (mud flats) to the eastern side of the breakwater.

In contrast, for the Spring freshet, the suspended sediments are also present in moderate levels in the upper freshwater layer. This occurs on the flood tide rather on the ebb suggesting that the Main Harbour channel upper freshwater layer is being pushed back into the Courtenay Bay channel. At this time of the year, the strongest suspended sediment signature is seen at the bottom of the tide, apparently being reinjected around the end of the breakwater in both the upper and lower layers.

The suspended sediment probe was broken for the summer minimum tidal cycle, thus there are no suspended sediment observations available for the June 2009 survey.

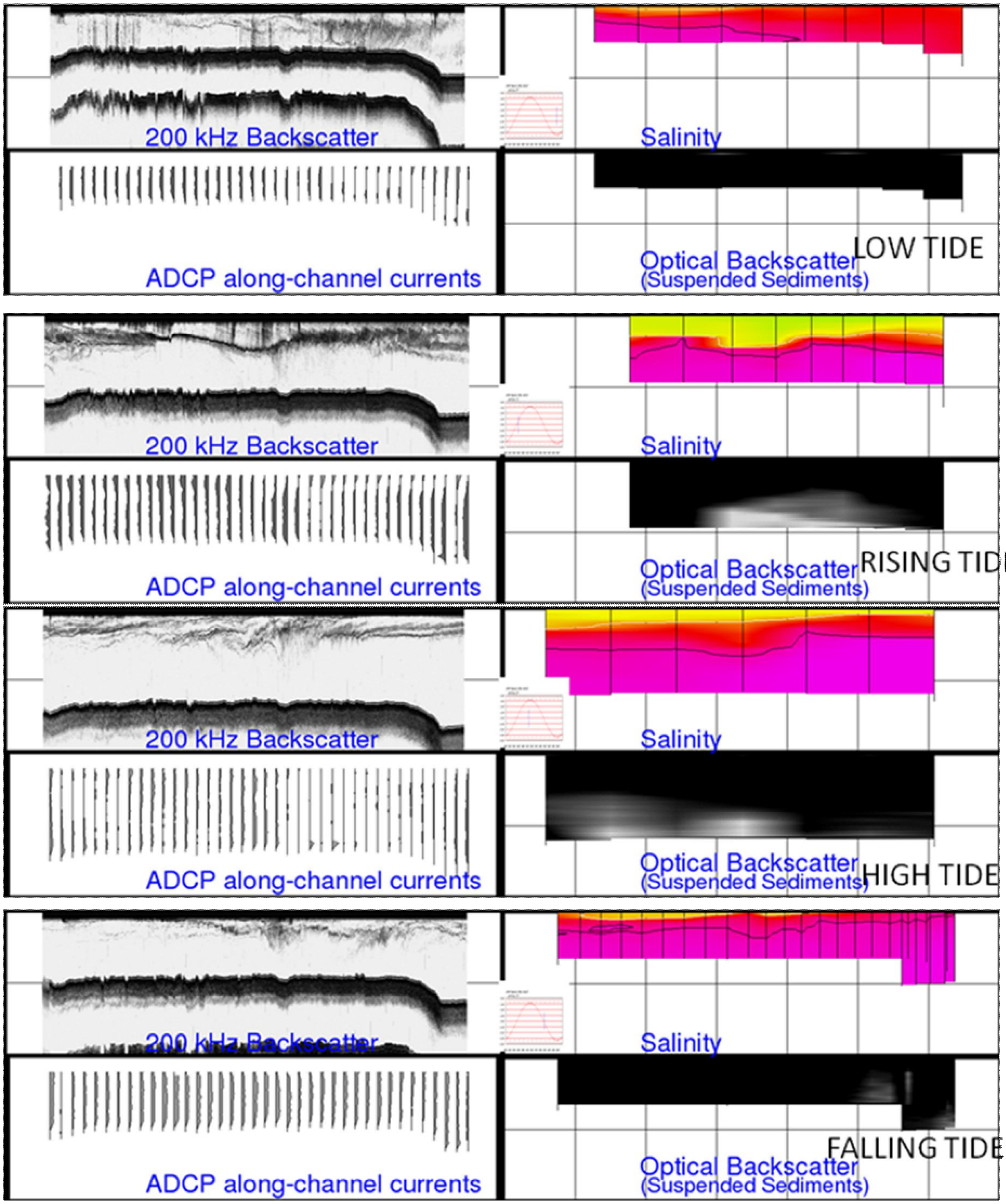


Figure 5.20: Showing the results of the longitudinal sections of the measurements; 200kHz acoustic backscatter, salinity, along-channel currents and optical backscatter for low tide, rising tide, high tide and falling tide for the Winter minimum, March 26th 2009 survey.

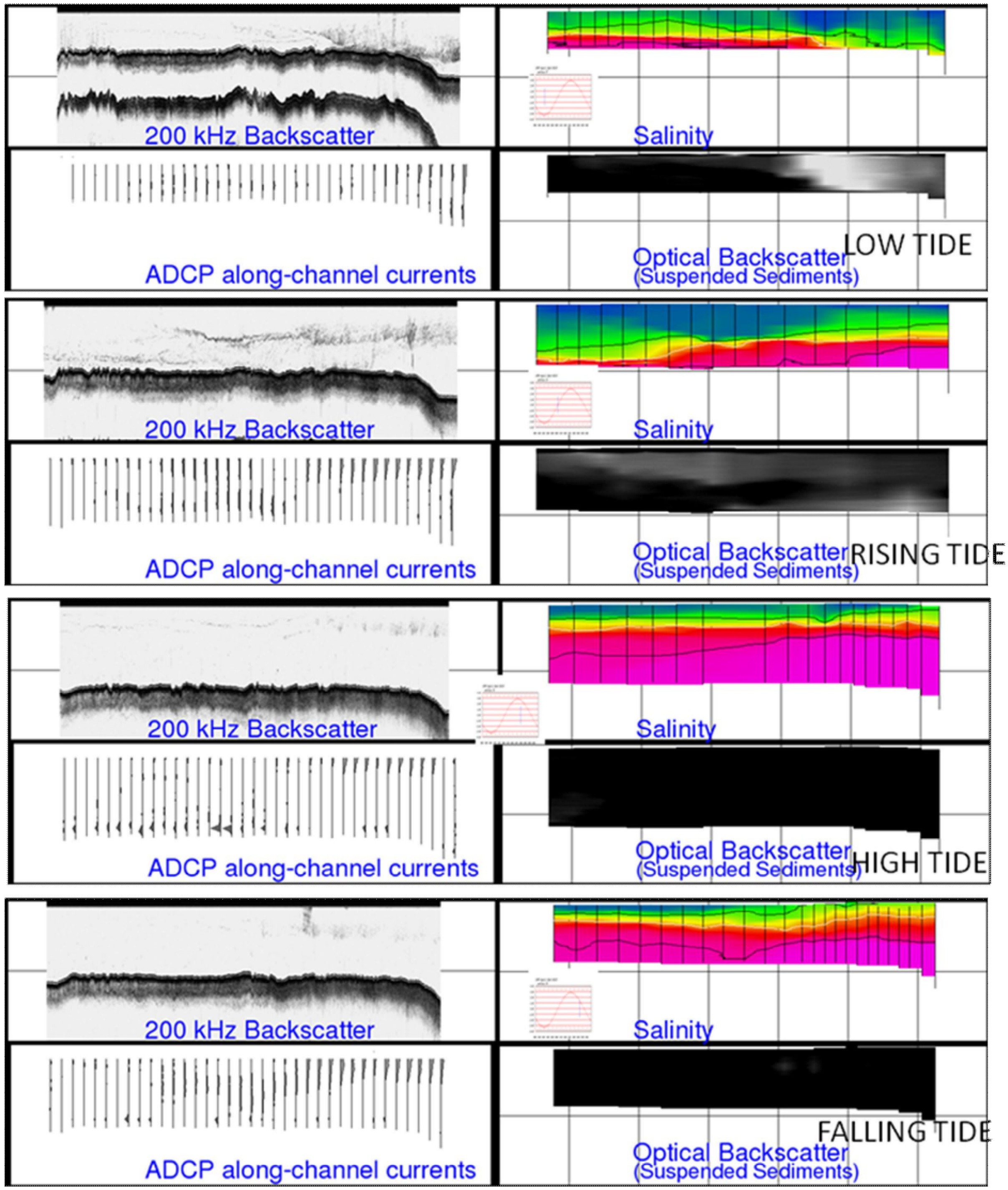


Figure 5.21: Showing the results of the longitudinal sections of the measurements; 200kHz acoustic backscatter, salinity, along-channel currents and optical backscatter backscatter for low tide, rising tide, high tide and falling tide for the Spring freshet April 22nd 2008 tidal cycle survey.

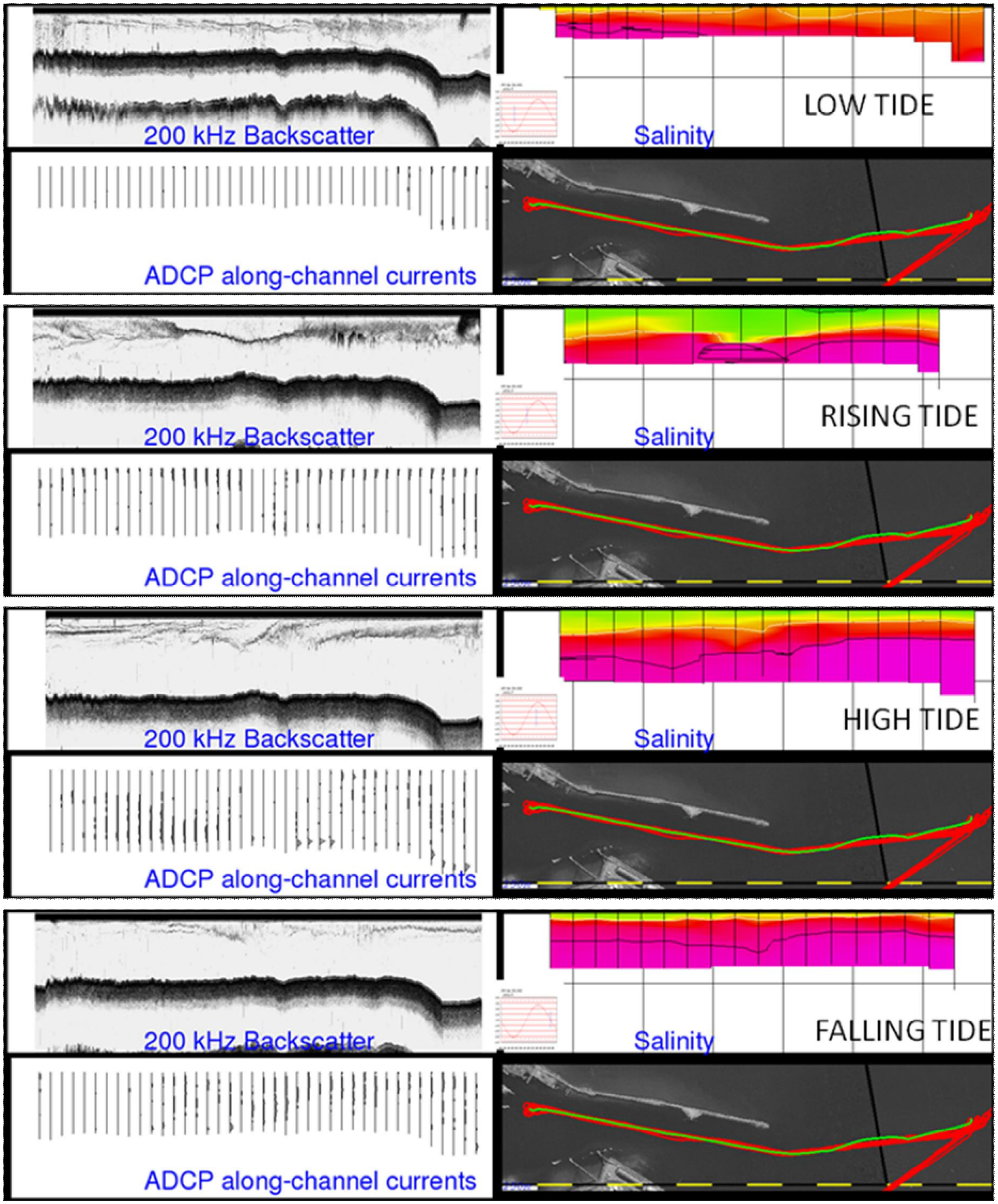


Figure 5.22: Showing the results of the longitudinal sections of the measurements; 200kHz acoustic backscatter, salinity, along-channel currents and optical backscatter backscatter for low tide, rising tide, high tide and falling tide for Summer minimum June 11th 2009 tidal cycle survey.

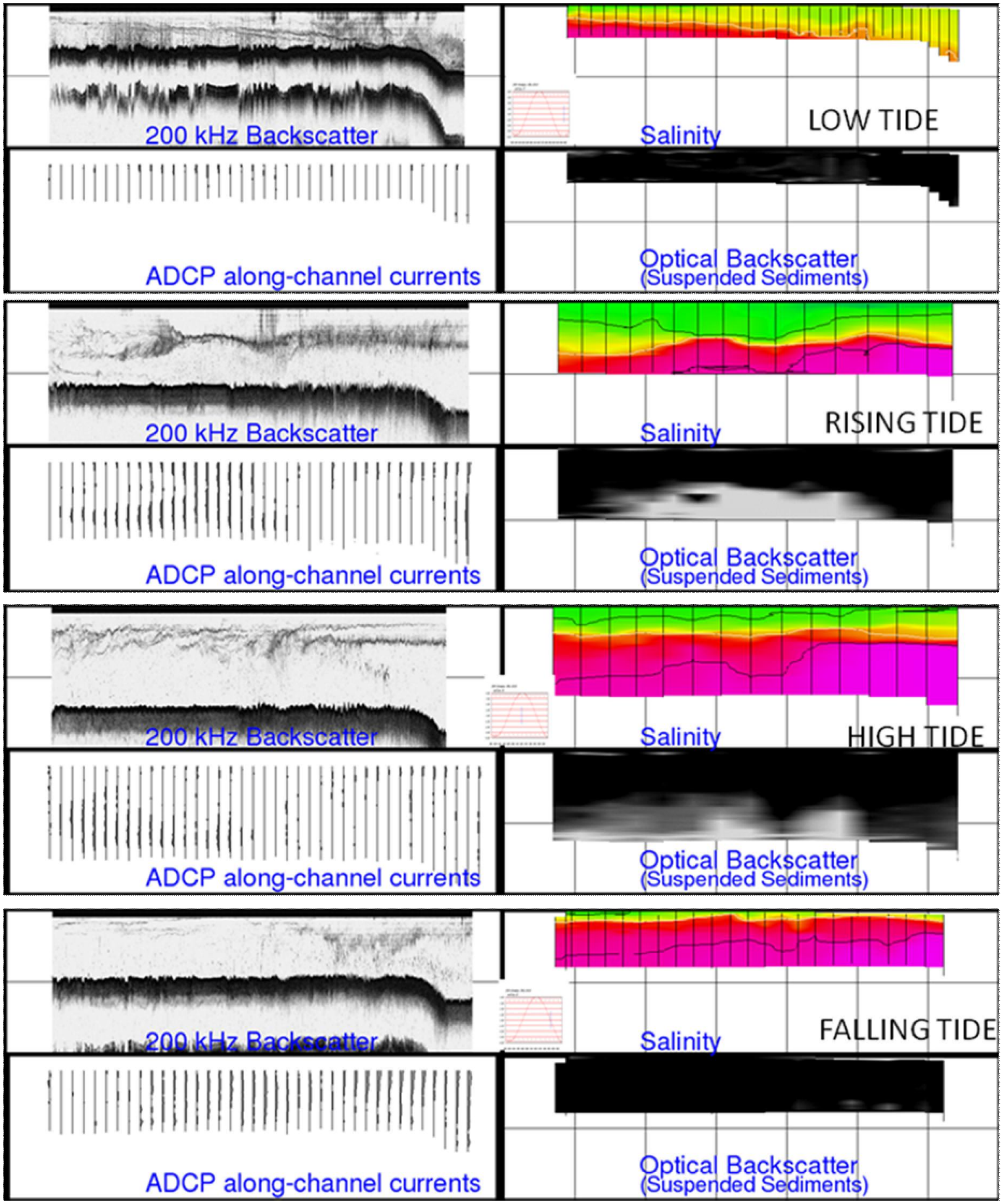


Figure 5.23: Showing the results of the longitudinal sections of the measurements; 200kHz acoustic backscatter, salinity, along-channel currents and optical backscatter. backscatter for low tide, rising tide, high tide and falling tide for the Fall freshet November 14th 2008 tidal cycle survey.

5.8 Summary of the Main Harbour Channel and Courtenay Bay Channel observations

In summary, the longitudinal sections within both the Main Harbour channel and Courtenay Bay illustrate that the suspended sediment concentrations are often highest in the lower saline layer. There is thus a significant movement of sediment coming into the two channels from offshore. In the upper layers, in contrast, there are generally weaker suspended sediment concentrations. Those are advected out of the harbour.

In order however to estimate the significance of the lower and upper layer sediment fluxes, we need to be able to estimate the total volume flux of water. In those layers over a tidal cycle, that flux, multiplied by the local suspended sediment concentration will allow us to estimate the total mass flux. The next section undertakes this.

5.9 Volume Flux Analysis in the Main Channel

In this study, the volumetric fluxes of water through the Main harbour channel were evaluated for the four oceanographic tidal cycles (12.42hrs each) conducted during the months of March, April, June and November. As mentioned in Section 4.5 the method used to quantify the volumetric fluxes, the separate layer fluxes and the sediment fluxes(defined by the isohaline conditions of less than 10‰, between 10‰ and 20‰ and greater than 20‰) all depend on the data collected as shown as part of the qualitative results in Section 5. The data collected along the Main Channel include an extensive set of velocity measurements from the ADCP as well as the salinity measurements and the optical backscatter results obtained from the MVP to quantify the cross-sectional analysis of the fluxes.

This cross-sectional analysis of the fluxes is thought to be a useful approach in determining the importance of the different transportation process through the cross section of the Main Channel in the harbour. This analysis which provides the magnitude and direction of the fluxes in and out of the Main Harbour Channel is the first step in understanding the physical factors contributing to the sediment distribution in the channel. By quantifying the fresh and salt water layer fluxes over a tidal cycle through the cross section chosen for the Main Channel harbour, it can be used to test whether the sediment flux in the lower saline layers are high enough to provide a significant effect on accumulation of sediments in the channel. This can assist in future observations and research since it is hypothesized that a significant fraction of the sediments are from offshore re-suspension.

As mentioned in section 4.1.3 the use of the field measurements of the currents' magnitudes and directions at the cross section has limitations associated with them (see section 4.1.3). The flux calculations determined in this section can be seen as estimates since there were several assumptions made to arrive at these values. Such assumptions included the following:

1. Since the ADCP velocity profile was taken at the approximate centre of the channel (following the longitudinal direction of the ship's transect), there were no velocity measurements taken across (east – west direction) the main channel

harbour. The depth averaged velocity measurements were hence assumed to be the same in the lateral direction across the channel for each depth interval.

2. As previously mentioned in section 4.1.3, the velocities have to be extrapolated to the water level upward to the surface and downward to the deepest depth in the cross-section which considered untested assumptions. This is particularly problematic for the March tidal cycle when the upper brackish layer is only on the order of 2m thick.

There are three types of fluxes being investigated, both instantaneously and over their respective tidal cycles during the different river level stages. Negative fluxes indicate that the flow is landward (into the harbour) and positive fluxes indicate that the flow is seaward (out of the harbour). These fluxes are quantified and represented graphically in the following sections as:

1. **Volumetric flux:** Gives an approximation of the depth averaged volumetric flow and its direction (incoming flow - outgoing flow) through the cross section for each profile. The graphs show this both tidally averaged as well as how it fluctuates over the tidal cycle.

2. **Layer Volumetric flux:** By first defining the salinity classes by the use of contours (less than 10‰, between 10‰ and 20‰ and greater than 20‰) of the through flow, one can assess the volumetric flow as the top fresh layer, middle mixed layer and the bottom saline layer either entering the harbour or exiting the harbour cross section.

3. **Sediment flux:** This combines the suspended sediment observations (observed from the optical backscatter) with the volume fluxes. An evaluation of the total sediment flux with the same salinity classes defined for the layer flux calculation (defined by the aforementioned salinity contours), during one tide cycle gives us an estimation of the amount of incoming and outgoing sediment though the cross section.

5.4.1 Flux Results - MARCH 2009: Winter Minimum

The March 26th 2009 results reflect the estimation of the fluxes during a period of low river discharge through the Reversing Falls into the Main Harbour Channel. The mean volumetric flow estimated through the channel cross section was estimated to be -211m^3s^{-1}. This estimation indicated that the flow averaged over the tidal cycle was dominant in the landward direction. (see Figure 5.24). This is actually unlikely and thus may reflect limitations in the method.

When the net volumetric flux graph is directly examined, the mean fluxes based on the isohalines categories of (less than 10‰, between 10‰ and 20‰ and greater than 20‰) were summarised in Table 5.1. The mean freshwater flow through the cross section resulted in a null value. This confirmed the qualitative descriptions shown in section 5.1.1 where the longitudinal sections indicate that the channel varies in salinity from greater than 10‰ to greater than 20‰ (i.e. there is no salinity characteristics of less than 10‰ at this time of the year). The mixed layer flow resulted in a mean seaward flow of 657m^3s^{-1} for the duration of the tidal cycle. The saline layer flow however was dominant in the landward direction with a magnitude of 868m^3s^{-1} (see Figure 5.25).

The net sediment flux was also calculated based on the aforementioned isohalines. The graph shows the summation of the amount of sediments passing through the cross section within the bounds of the isohalines. The tidally averaged sediment flux through the cross section shows that the sediments are approximately $-34 kgs^{-1}$ in the saline layer (greater than 20‰) in the landward direction (see Figure 5.26).

The minimum salinity observed during this tidal cycle was greater than 10‰, thus as a result of this there was a zero volumetric flux for the salinity class of less than 10‰ flux calculation. The brackish volumetric flux was less than the saline volumetric flux which resulted in a net flux into the harbour. The dominant source of sediment during the winter minimum observation is questionable but it shows that it could be resuspended sediments from outside the harbour.

Table 5.1: Showing a summary of the fluxes through the harbour cross-section for March 26^{th} 2009 oceanographic survey.

March 26th 2009	
Mean Volumetric Flow	$-211\ m^3s^{-1}$

Salinity Conditions	**Layer Volumetric Flux (m^3s^{-1})**
<10‰	0
>10‰ && <20‰	657
>20‰	-868

Salinity Conditions	**Sediment Flux (kgs^{-1})**
<10‰	0
>10‰ && <20‰	9
>20‰	-34

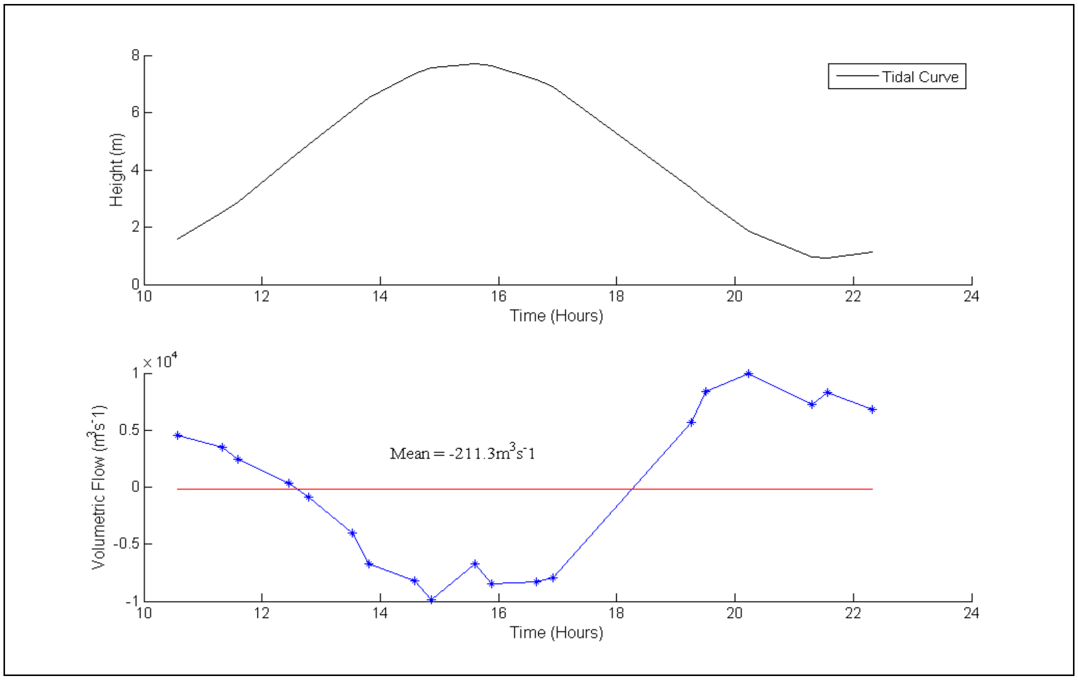


Figure 5.24: The instantaneous depth averaged Volumetric Flux over a single tidal cycle on March 26th 2009 (blue) and the mean Volumetric Flux (red).

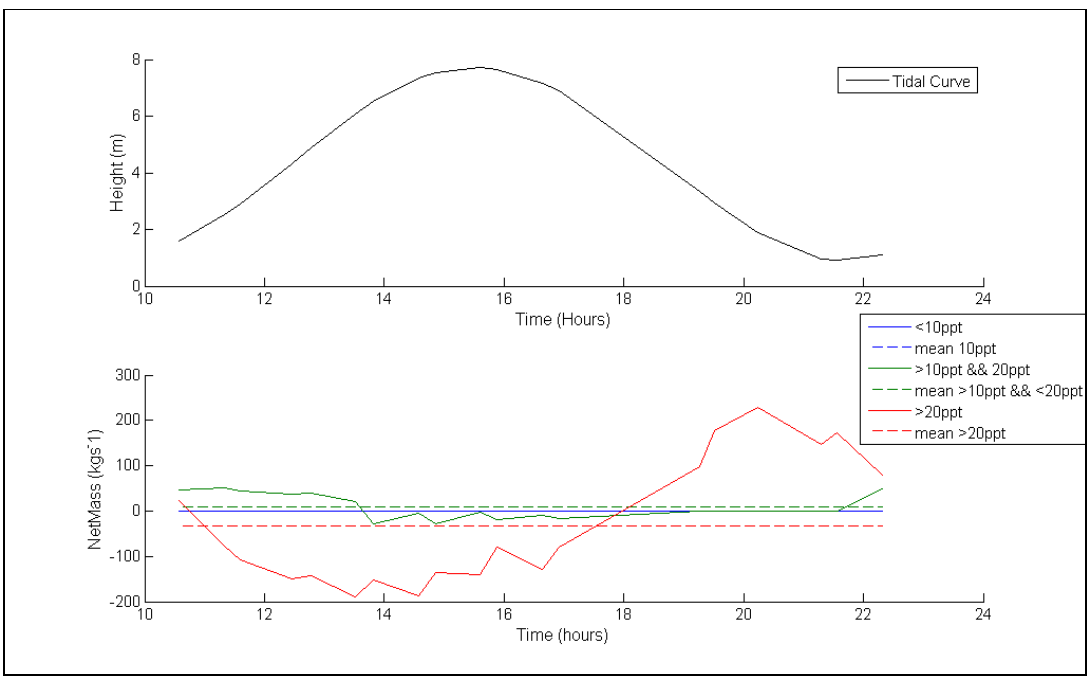


Figure 5.25: The tidally averaged Layer Volumetric Flow over a single tidal cycle on March 26th 2009 defined by less than 10‰, between 10‰ and 20‰ and greater than 20‰ isohalines along with their corresponding mean values over the tidal cycle.

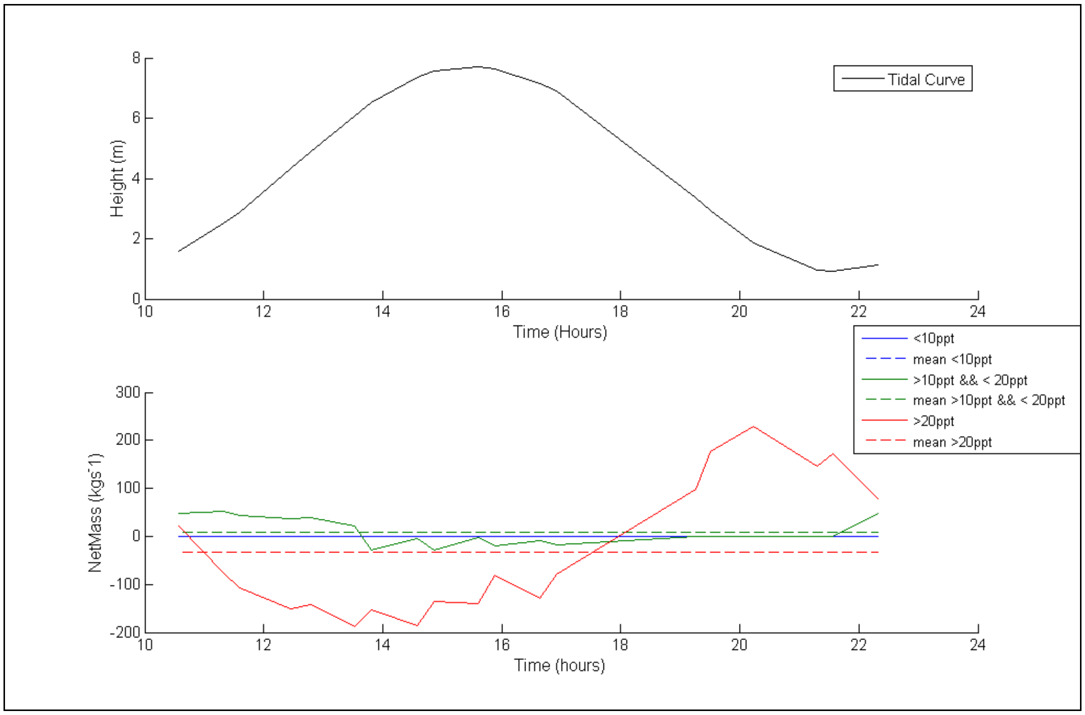


Figure 5.26: The tidally averaged Net Mass of sediments over the March 26th 2009 tidal cycle defined by the less than 10‰, between 10‰ and 20‰ and greater than 20‰ isohalines along with their corresponding mean values over the tidal cycle.

5.4.2 Flux Results - APRIL 22nd 2008 : Spring Freshet

Over the complete tidal cycle for the Spring freshet survey done on April 2008, the depth averaged mean volumetric flow through the cross section in the Main Channel harbour was calculated to be $4704m^3s^{-1}$. This estimation indicated that the mean flow averaged over the tidal cycle was strongly dominant in the seaward direction which was expected because the flow during the spring freshet is always in the seaward direction. This confirms that the net freshwater discharge through the Reversing Falls is greater than the net tidal inflow from the Bay of Fundy. The freshwater discharge in the Main Channel is so large that it suppresses the tidal inflow, creating a residual flow in the upper layer (in the seaward direction). Figure 5.27 shows that the flow is in the seaward direction (positive values) at all stages of the tide, implying that there is no reversal of the flow during the Spring freshet.

For reasons not well understood a bottom tracking velocity bias is present just in the April 2008 data. The net result is that velocities calculated when steaming upstream and downstream could mismatch by a fixed amount. This was therefore quantified and the biased anomaly was removed. (see Figure 5.28).

When the net volumetric flux graph is closely examined, the mean fluxes based on the isohalines of (less than 10‰, between 10‰ and 20‰ and greater than 20‰) are summarised as in Table 5.2. The mean freshwater flow through the cross section resulted in a value of 5156 m^3s^{-1}. The mixed layer resulted in a very low mean seaward flow of $230m^3s^{-1}$ for the duration of the tidal cycle. The saline layer flow however was dominant in the landward direction with a magnitude of $682m^3s^{-1}$ (see Figure 5.29). The ratio of the freshwater flux and the saline bottom layer flux was in the order of 7:1. This implies that $1/7^{th}$ of the outflow is derived by entrainment from the lower layer.

The tidally averaged sediment flux was also calculated based on the aforementioned isohalines. For each velocity profile the graph shows the summation of the amount of sediments passing through the cross section within the bounds of the isohalines. The tidally averaged sediment flux through the cross section shows that the sediments are approximately $166kgs^{-1}$ in the freshwater layer (less than 10‰) in the seaward direction, $6kgs^{-1}$ in the mixed layer and $33kgs^{-1}$ landward from the saline layer moving into the harbour. (see Figure 5.30). This proves that there are more sediments moving outwards through the harbour in both the fresh water layer and the brackish layer than the landward flow of saline water. Even though there are very high suspended sediments in the lower layer carrying sediments with it into the harbour, the flow is not moving fast. Thus the river is the dominant source of sediments at this time of the year.

Table 5.2: Showing a summary of the fluxes through the harbour cross-section for March 26th 2009 oceanographic survey.

April 22nd 2008	
Mean Volumetric Flow	4704 m^3s^{-1}

Salinity Condition	**Layer Volumetric Flux (m^3s^{-1})**
<10‰	5156
>10‰ && <20‰	230
>20‰	-682

Salinity Condition	**Sediment Flux (kgs^{-1})**
<10‰	166
>10‰ && <20‰	6
>20‰	-33

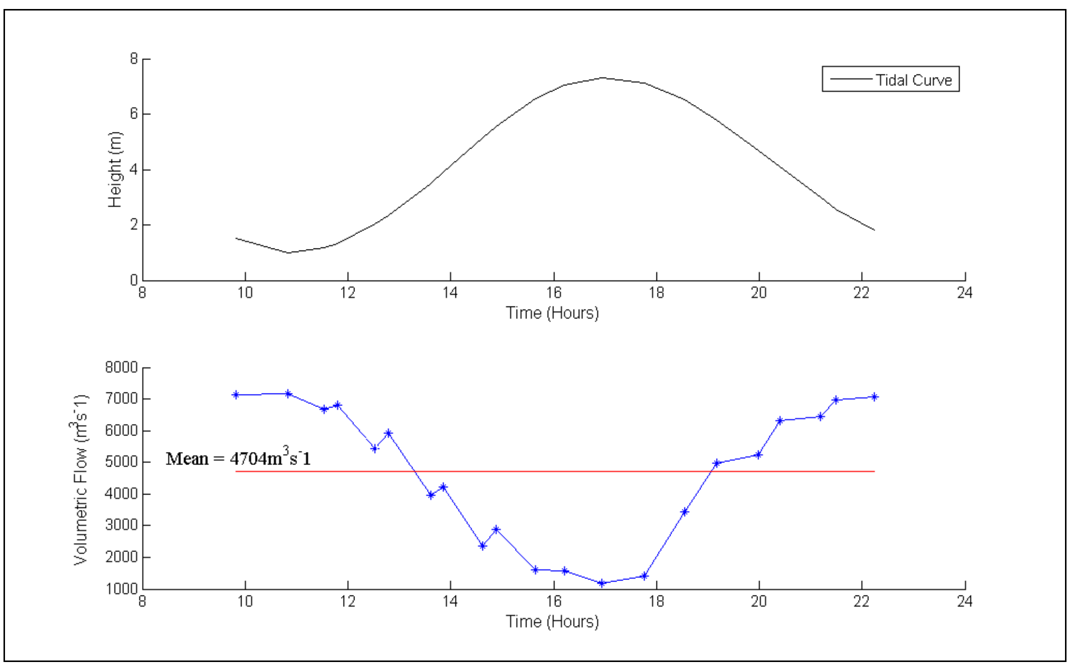


Figure 5.27: The instantaneous depth averaged volumetric flux over a single tidal cycle on April 22nd 2008 (blue) and the mean volumetric flux (red).

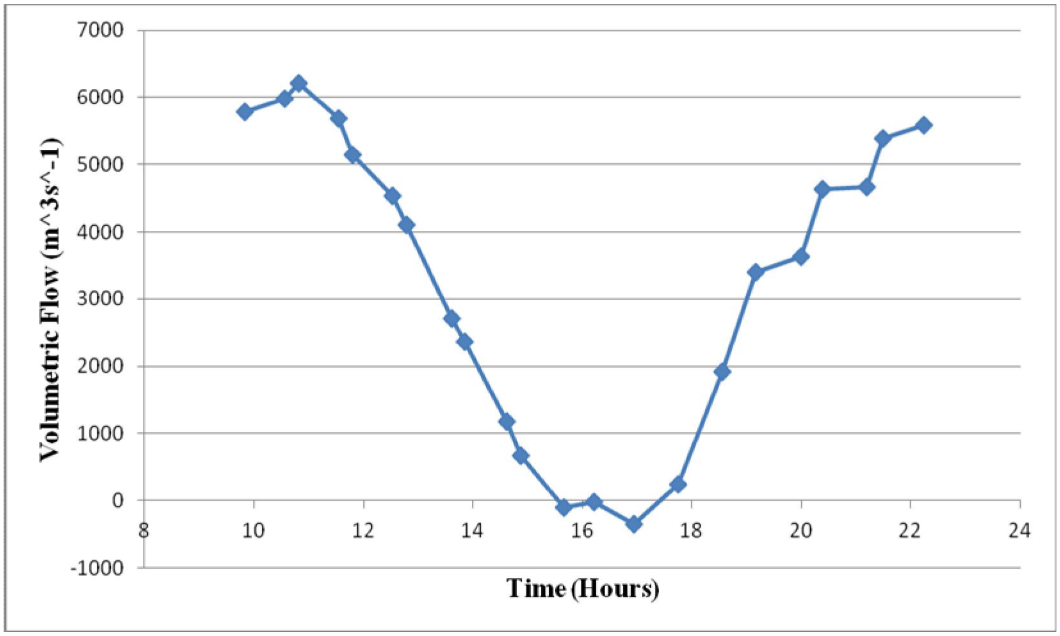


Figure 5.28: Showing the corrected graph of the instantaneous depth-averaged Volumetric Flux over a single tidal cycle on April 22nd 2008.

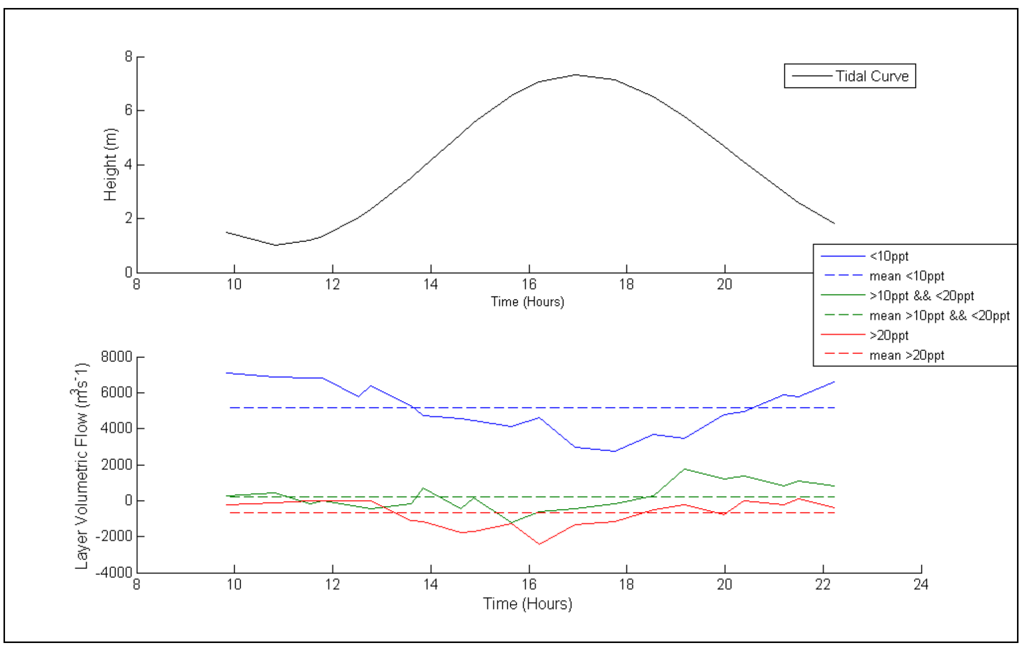


Figure 5.29: Showing the depth averaged Layer Volumetric Flow over a single tidal cycle on April 22nd 2008 defined by the less than 10‰, between 10‰ and 20‰ and greater than 20‰ sohalines along with their corresponding mean values over the tidal cycle.

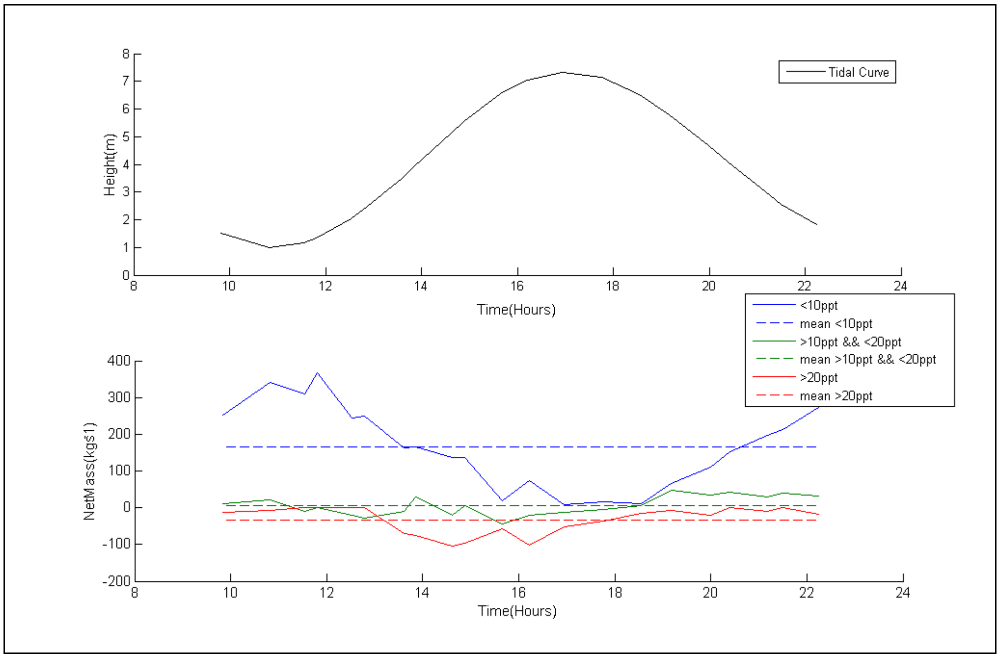


Figure 5.30: Showing the variation Net Mass of sediments over the tidal cycle for the April 22nd 2008 observations defined by the less than 10‰, between 10‰ and 20‰ and greater than 20‰ isohalines along with their corresponding mean values over the tidal cycle.

5.4.3 Flux Results - JUNE 11th 2009 : Summer Minimum

The June 11th 2009 survey reflects the estimation of the fluxes during a period of low river discharge during the summer. The proxy for discharge is the tidally average river heights at Indiantown (see Figure 2.13) which show that river discharge for June is slightly higher than the winter minimum in March. The mean volumetric flow estimated through the channel cross section was estimated to be a mere $760m^3s^{-1}$ (see Figure 5.31).

The mean fluxes based on the isohalines of less than 10‰, between 10‰ and 20‰ and greater than 20‰) are summarised as in Table 5.3. The mean freshwater flow through the cross section resulted in a low estimation of $293m^3s^{-1}$ because during the summer minimum discharge period, the outward flow is mainly brackish with a mean flow of 612m^3s^{-1} for the duration of the tidal cycle. The saline layer flow resulted in a landward directed flow of magnitude of 145m^3s^{-1} (see Figure 5.32). The ratio of the outward flow and saline flow through the cross section is 6:1. This implies that approximately 1/6th of the outflow is derived by entrainment from the lower saline layer.

The sediment fluxes for the June 11th 2009 survey could not be calculated because the OBS sensor was broken and therefore no OBS observations were collected during this survey.

Table 5.3 : Showing a summary of the fluxes through the harbour cross-section for June 11th 2009 oceanographic survey

June 11th 2009	
Mean Volumetric Flow	760 m^3s^{-1}

Salinity Condition	**Salt Volumetric Flux (m^3s^{-1})**
<10‰	293
>10‰ && <20‰	612
>20‰	-145

Salinity Condition	**Sediment Flux (kgs^{-1})**
<10‰	N/A
>10‰ && <20‰	N/A
>20‰	N/A

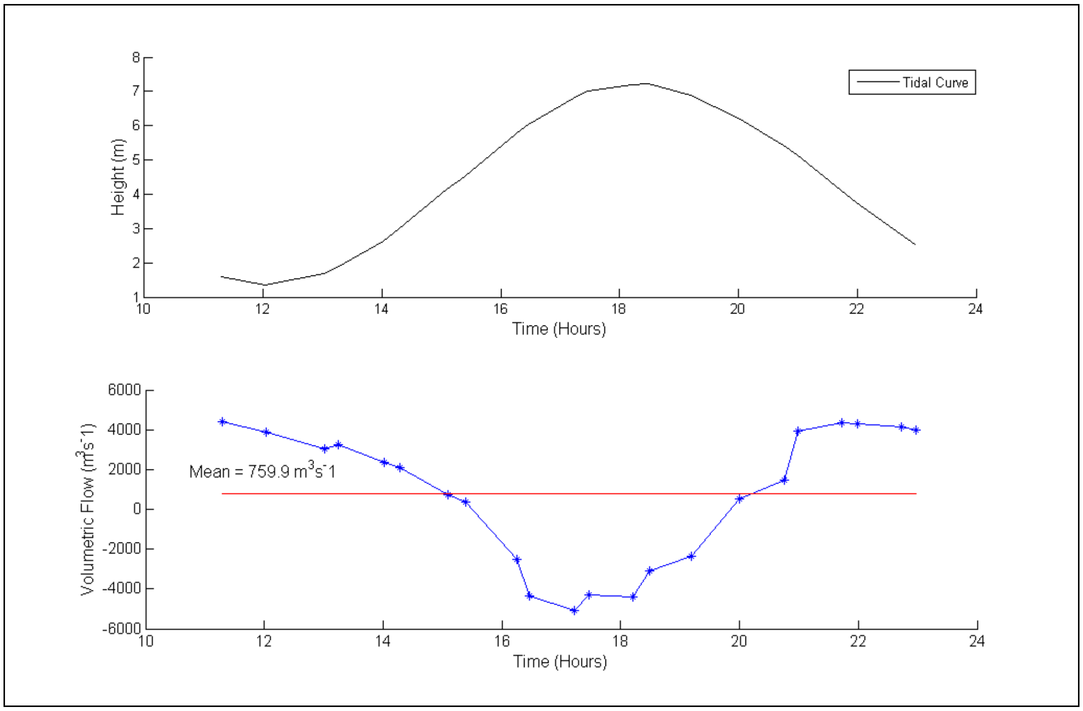


Figure 5.31: Showing the depth averaged volumetric flux over a single tidal cycle on June 11th 2009 (blue) and the mean volumetric flux (red).

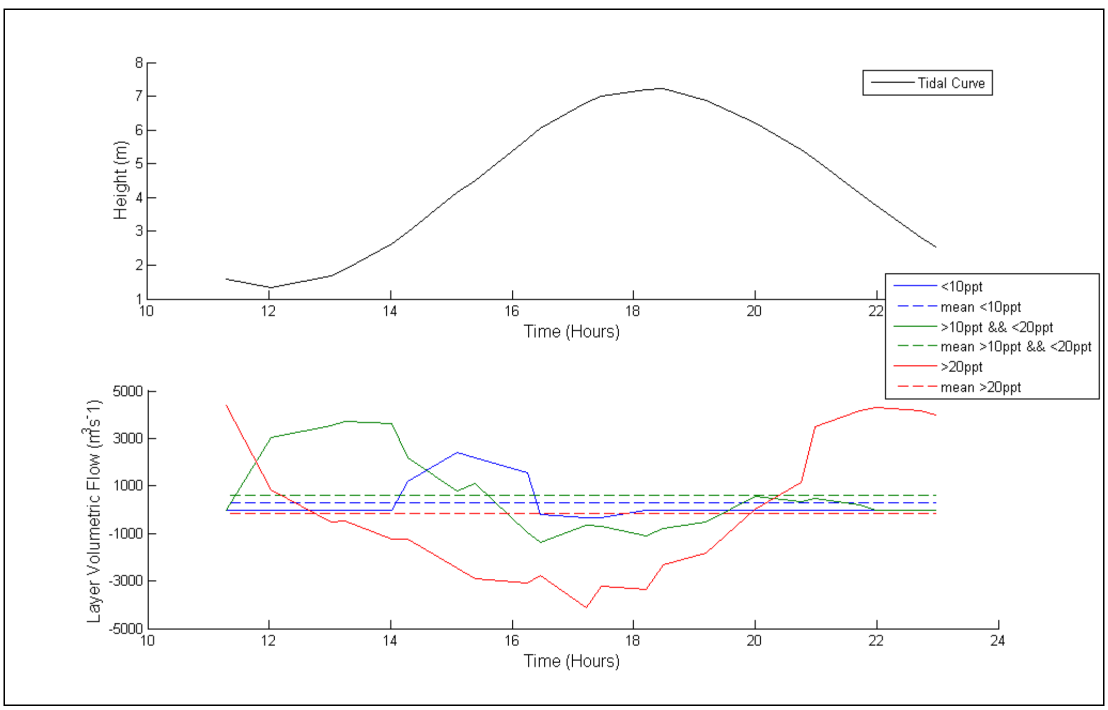


Figure 5.32: Showing the variation in Layer Volumetric Flow within the three main saline zones over a single tidal cycle on June 11th 2009 defined by the less than 10‰, between 10‰ and 20‰ and greater than 20‰ isohalines along with their corresponding mean values over the tidal cycle.

5.4.4 Flux Results – NOVEMBER 14th 2008 : Fall Freshet

For the Fall freshet survey done on November 14th 2008, the tidally averaged mean volumetric flow through the cross section in the Main Channel harbour was estimated to be 1650m^3s^{-1}. This estimation indicated that the mean flow averaged over the tidal cycle was predominantly in the seaward direction. (see Figure 5.32).

The mean fluxes based on the isohalines of (less than 10‰, between 10‰ and 20‰ and greater than 20‰) are summarised as in Table 5.4. The mean freshwater flow through the cross section resulted in a seaward flow of 857m^3s^{-1}. The mixed layer resulted in a mean seaward flow of similar magnitude 985m^3s^{-1} for the duration of the tidal cycle. The saline layer flow however was dominant in the landward direction with a magnitude of 192m^3s^{-1} (see Figure 5.33). The ratio of the outward flow and the inward moving flow (saline bottom layer flux) was in the order of 9:1. This implies that the entrainment rate for the November freshet is approximately 1/9th of the outflow is derived by entrainment from the lower layer.

The tidally averaged sediment flux was also calculated based on the aforementioned isohalines. For each velocity profile the graph shows the summation of the amount of sediments passing through the cross section within the bounds of the isohalines. The tidally averaged sediment flux through the cross section shows that the sediments are in order of 24 kgs^{-1} in the freshwater layer (less than 10‰) in the seaward direction, 23 kgs^{-1} in the mixed layer and -18 kgs^{-1} input the saline layer moving into the harbour (see Figure 5.34). Therefore the net sediment transport during the Fall freshet observations was an export of sediments in the upper and middle layers. Although the suspended sediments in the lower saline layer are in the same order as the upper and middle layers, the volume flux dominates in the upper layers. This proves that during the Fall freshet discharge period, the dominant source of sediments in the harbour is derived from the river.

Table 5.4: Showing a summary of the fluxes through the harbour cross-section for June 11th 2009 oceanographic survey.

November 14th 2008	
Mean Volumetric Flow	1650 m^3s^{-1}

Salinity Condition	**Layer Volumetric Flux (m^3s^{-1})**
<10‰	857
>10‰ && <20‰	985
>20‰	-192

Salinity Condition	**Sediment Flux (kgs^{-1})**
<10‰	24
>10‰ && <20‰	23
>20‰	-18

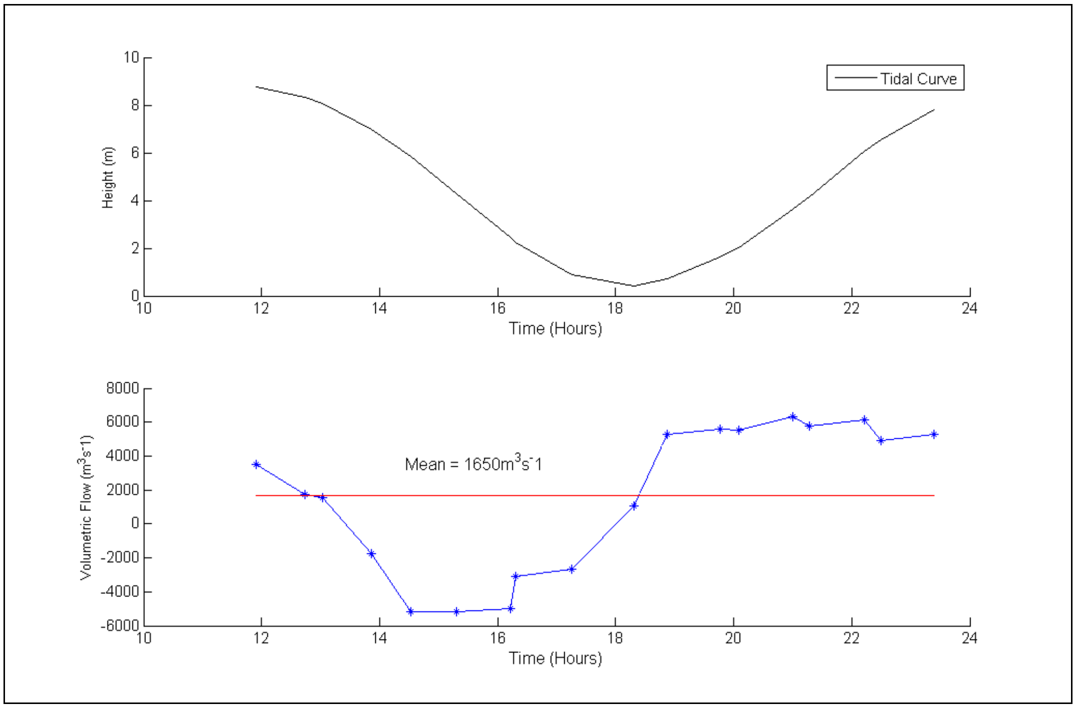


Figure 5.33: Showing the Volumetric Flux over a single tidal cycle on November 14th 2008 (blue) and the mean Volumetric Flux (red).

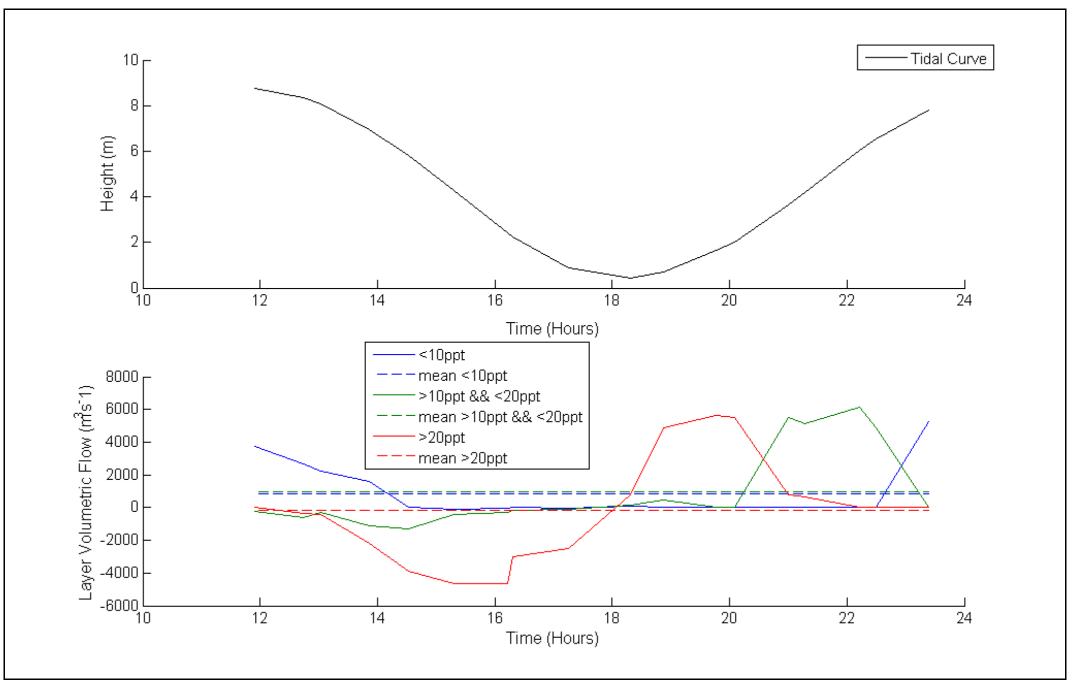


Figure 5.34: Showing the variation in Layer Volumetric Flow within the three main saline zones over a single tidal cycle on November 14th 2008 defined by the less than 10‰, between 10‰ and 20‰ and greater than 20‰ isohalines along with their corresponding mean values over the tidal cycle.

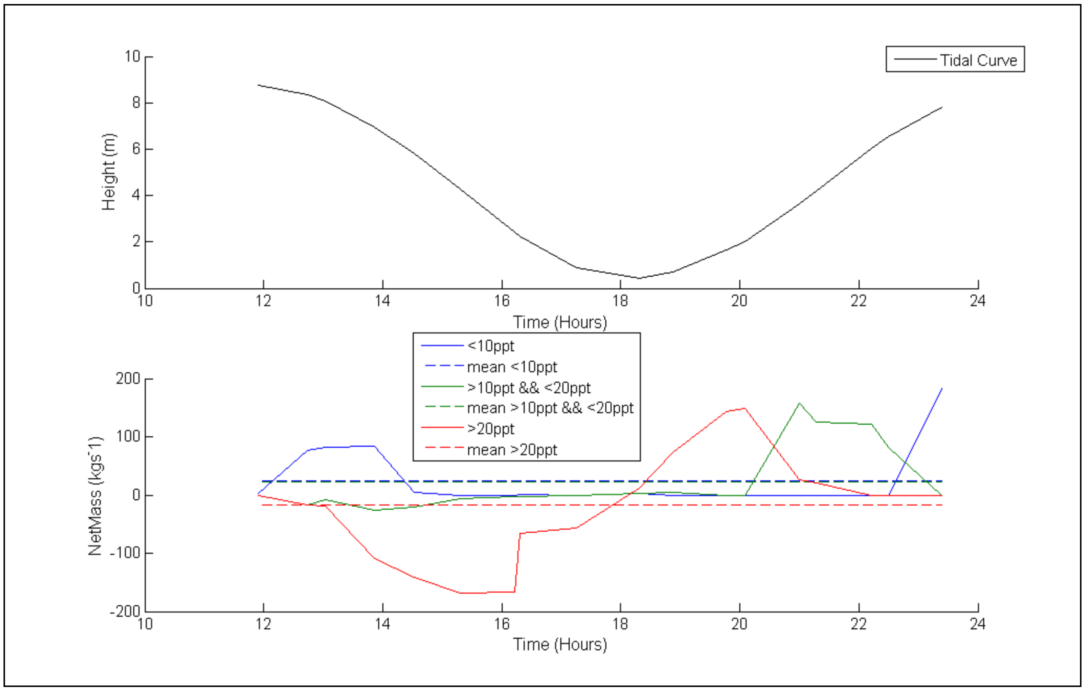


Figure 5.35: Showing the tidally averaged Net Mass of sediments over the November 14th 2008 tidal cycle defined by the less than 10‰, between 10‰ and 20‰ and greater than 20‰ isohalines along with their corresponding mean values over the tidal cycle.

Chapter 6: CONCLUSIONS AND RECOMMENDATIONS

To present a qualitative description of the seasonal and tidal variations of the estuarine circulation of the Port of Saint John, field data were collected at different times of the year for complete 12.42hr tidal cycles to capture the changes which take place in the Main Harbour and Courtenay Bay. It's important to understand the hydrodynamics of the Port because the estuarine circulation and the interaction and mixing between the freshwater from the Saint John River and the tidal influx of salt water from the Bay of Fundy has an impact on suspended sediments that are retained or flushed out from the harbour.

6.1 Main Harbour Channel

To estimate the mixing between the fresh water and salt water in the Main Harbour channel, the appearance of interfacial waves must be examined. There were two ways in which the development of interfacial waves was identified in this project:

1. Qualitatively by the use of the 200kHz acoustic imagery to visualise the variation of the pycnocline and the evolution of the KH waves by directly observing the image.

2. Quantitatively by graphically representing the individual velocity and density profiles in order to highlight the zones of velocity shear and density gradient. By comparing the magnitude of the velocity shear and the density gradients in the flow, the results indicate whether or not the shear is high enough to promote breakdown of the pycnocline and hence determine by examining the gradient Richardson number if mixing between the upper and lower layers are possible.

It is important to estimate the magnitude and timing of the mixing that is taking place between the salt and fresh water in the Main Channel because this is one the processes that affects the exchange of salt and suspended sediments between the upper and lower layers. In the Main harbour channel, regardless of the freshwater discharge period, these interfacial waves are best developed on the rising tide. This corresponds to when the velocity shear zone extends above the pycnocline. However, during the Spring freshet when the discharge is highest, interfacial waves are developed on the rising tide as well as the low, high and falling tide. At other times of the year they are absent at the other stages of the tide.

Although the Main Channel exhibits the same gross estuarine circulation year round, there are seasonal differences between the volume fluxes in the upper and lower layers. Implementation of the method of calculating the volume fluxes is important because it aids in determining how significant the mass fluxes are in each of the layers since the highest suspended sediments are observed in the lower saline layer.

6.1.2 For low river discharge rates:

6.1.2.1 March 26th 2009

The winter minimum observations showed that there are errors associated with the surface volumetric flux. The surface layer in the March tidal cycle is very thin and this provides a challenge for the ADCP to resolve since the first good measurement is approximately 2m below the surface. Therefore the upward extrapolation of the velocity profiles may not be accurate enough to eliminate this error and capture the true volumetric flux in surface layer.

The lower saline layer shows the influx of suspended sediments; either from outside of the harbour or the possibility of the harbour bottom sediments being resuspended on the rising tide.

6.1.2.2 June 11th 2009

In June the mean volumetric flux was closely related to the weak river discharge period. The volumetric fluxes in the upper and middle brackish layers are dominant in the seaward direction. Unfortunately, since there were no suspended sediment concentrations observations, one cannot determine the net direction of the sediment flux.

6.1.3 For high river discharge rates:

6.1.3.1 April 22nd 2008

The lower saline layer has the highest suspended sediment concentrations of all phases of the tides discussed. During the Spring freshet period when the river discharge is higher than any other times of the year, the net mass flux in the lower layer is smaller than the surface mass flux seaward. The river is the dominant source of sediments in the Spring freshet periods.

6.1.3.2 November 2008

The November freshet observations show that the net volumetric flux is in the seaward direction. Even though the net suspended sediments are high in the lower saline layer, there is a net export of sediments from the harbour because the volume flux in the upper and middle layer dominates in the seaward direction. During the high river discharge periods, the river is the main source of sediments.

6.2 Courtenay Bay

Courtenay Bay's circulation, which is quite different from The Main Harbour Channel, revealed very low current activity in the channel resulting from the lack of freshwater entering Courtenay Bay channel.

6.2.1 For low river discharge rates: June and March

Courtenay Bay is primarily full of brackish water during the winter and summer minimum discharge periods. The salt water penetration on the rising tide brings an inflow of suspended sediments in the lower saline layer. The suspended sediments which enter the channel are observed just downstream of the breakwater structure which suggests that the lower saline sediment inflow is coming over the shallows from the eastern end of the breakwater. The saline layer is not efficiently flushed out of the harbour because there is no significant source of freshwater for effective flushing. Therefore the sediments entering on the rising tide settled out before they could withdraw from the harbour during the falling tide.

6.2.2 For high river discharge rates: April and November

For the high river discharge periods, the strongest suspended sediment signature is seen in the lower saline layer on the rising tide. During the Fall freshet the suspended sediments which enter the channel are observed just downstream of the breakwater structure which again suggests that the lower saline sediment inflow is coming over the shallows from the eastern end of the breakwater.

During the Spring freshet the moderate levels of suspended sediments are seen in the upper freshwater layer on the rising tide which indicate that the upper freshwater layer from the Main Channel is being pushed back into Courtenay Bay. At rising tide the suspended sediments are being reinjected in both the upper and lower layers.

It can be concluded that the main mechanisms that contributes to the high sedimentation rates in Courtenay Bay is the salt water plug that gets left behind at the head of the channel. Without efficient flushing, the sediments in the saline layer are left to settle after every high water. Another important factor is the source of sediments from the eastern end of the breakwater that enters the channel.

It is important to emphasize that the estuarine circulation observations and estimated volume fluxes are representative for only four tidal cycle surveys. To observe the circulation patterns in the harbour and to determine a long term trend, continuous monitoring of the currents in the Main Harbour Channel and Courtenay Bay Channel is therefore necessary. These long term averages would aid in fully understanding if there are any changes in the seasonal trends of the volume fluxes especially in the Main Harbour Channel.

For the continuation of the Saint John Harbour collaborative project, there are two bottom mounted ADCP's in the harbour, one is located close to the location where the cross-sectional fluxes were determined for this project. Another has also been placed in Courtenay Bay near the edge of the breakwater structure to monitor the currents and hence the circulation patterns around the edge of the breakwater. These have been strategically placed to capture the seasonal and tidal variations of the currents for a period of eight months (from November 2011 to June 2012).

As part of the end goal, a hydrodynamic numerical model is currently being developed by research associates Dr. Susan Haigh and Ian Church in the Ocean Mapping Group at the University of New Brunswick. The model will be used to do simulations coinciding with the observational data used in this thesis research. The use of the local field data will be used to validate the model simulations for the hydrodynamic circulation and harbour sedimentation problems considered. In the future, all the information collected as part of this greater collaborative research, such as the role of offshore resuspension, density current intrusions, statistical analysis of seasonal river discharge and sediment concentration loads will be integrated to produce a predictive model used to reliably forecast siltation rates in the Port of Saint John.

REFERENCES

Ayub,A., Lemckert,C.J., Dunn,R.J.K, (2010) “Salt Fluxes within a very shallow Sub-tropical estuary” Journal of Coastal Research, Vol(26), No.3, pp436-443.

Baird, W.F. and Associates Coastal Engineers Ltd (1987). “Evaluation of the sedimentation processes in the Saint John Harbour/Courtenay Bay, New Brunswick, Canada

Cameron, W.M. and D.W. Pritchard (1963). The Sea Vol 2, John Wiley and Sons, New York, pp 306-324

Commandeur, S. (Unpublished). “Assessment of inter-annual and inter-seasonal seabed topography change in Port of Saint John, New Brunswick” Unpublished M.Sc.E. thesis, Department of Geodesy and Geomatics Engineering University of New Brunswick, Fredericton, N.B., Canada.

Components of MVP-30 [Online] http://www.brooke-ocean.com

Delpeche, N. (2004). “Observations of advection and turbulent interfacial mixing in the Saint John River Estuary, New Brunswick Canada, MScE. thesis, Department of Geodesy and Geomatics Engineering, University of New Brunswick, Fredericton, N.B., pp299.

Department of Fisheries and Oceans Canada, 2002

Department of the Army US Corps of Engineers (1991). Engineering and Design – Tidal Hydraulics Engineer Manual No. 1110-2-1607 15

DredgingToday.com Canada, 2011: “Port of Saint John Dredging Study Under Way”, written by Sandra Davis. Posted Jan 27th, 2011.

Dyer, K.R (1997). Estuaries a Physical Introduction 2nd ed., John Wiley & Sons Ltd, New York.

Krone, R.B and Einstein, A.H Einstein. “Estuarial Sediment Transport Patterns” Journal of Hydraulics Division, American Society of Civil Engineers March, 1961.

Environment Canada. (2009). Climate data online and Climate data Normal and Averages for New Brunswick at Saint John A, [On-line] : Multiple access between 2009 -2011

Fisheries and Oceans Canada (2002). “DFO Classification of Maritime Inlets” Resources.” [On-line] 10 November 2005. http://www2.mar.dfo-mpo.gc.ca/science/ocean/ceice/ceice.html

Godin, G. (1991). “Tidal Hydraulics of Saint John River.” Journal of Waterway, Port, Coastal and Ocean Engineering, Vol. 117, No. 1, pp 19-28.

Greenberg, D.A. (1979) "A numerical model investigation of tidal phenomena in the Bay of Fundy and Gulf of Maine". Marine Geodesy, 2, pp 161-187

Hachey,H.B. (1939). “Hydrographic Features of the Waters of Saint John Harbour.” Journal of the Fisheries Research Board of Canada, 1939, 4b:(5), pp 424-440

Hare,F., Dikison,R.B.B and Ismail,S. (2007) “Variations of Climate and Streamflow over the Saint John Basin since 1872”. The 9th Workshop on River Ice, Sept 24-26th

Hughes Clarke, 2008. Satellite Image taken from lectures.

Hughes Clarke, J.E and S.P. Haigh (2005). “Observations and Interpretation of Mixing and Exchange Over A Sill At the Mouth of the Saint John River Estuary.” 2nd CSCE Speciality Conference on Coastal, Estuary and Offshore Engineering.

HYDAT -Environnent Canada (2010). [Online] http://www.ec.gc.ca/rhc-wsc/default.asp?lang=En&n=9018B5EC-1

Leys,V (2007). “3D Flow and Sediment Transport Modelling at the Reversing Falls – Saint John, New Brunswick” CBL Limited Consulting Engineers.

Matheron, D (2010). “Sedimentation patterns and inferred dynamics in Saint John Harbour” M.Sc.E. thesis, Department of Civil Engineering, University of New Brunswick, Fredericton, N.B., Canada, 154pp.

Metcalfe, C., C., M.J Dadswell, G.F. Gillis, M.L.H Thomas (1976). “Physical, chemical and biological parameters of the Saint John River Estuary, New Brunswick, Canada” Department of the Environment Fisheries and Marine Service. Technical Report No 686.

Muste,M., Spasojevic, M. (2004). “Practical aspects of ADCP data use for quantification of mean river flow characteristics; Part I: moving-vessel measurements.” Flow measurement and Instrumentation. Vol15, pp1-16.

Natural Resources Canada, (2004). Optical Backscatter calibration data. Personal communication by email forwarded from Hughes Clarke, J.H.: jhc@omg.unb.ca

Neu,H.A. “Hydrographic Survey of Saint John Harbour, N.B.” MH-97, National Research Council of Canada, No. 607, Ottawa. 1960

Parrott, D. R., Cranston, R. E., Li, M. Z., Parsons M. B., and Kostylev, V., 2002. Monitoring and evaluation of conditions at the Black Point offshore disposal site. Technical Report submitted to Environment Canada. 167. p

RD Instruments. (1996). Acoustic Doppler Current Profiler: Principles of Operation. 2nd Edition.

Saint John River Atlas, [Online] http://cri.nbwaters.unb.ca/sjratlas/site/index.castle

Teledyne RD Instruments [Online] http://www.rdinstruments.com

Trites, R.W. (1959). “An Oceanographic and Biological Reconaissance of Kennebecasis Bay and the Saint John River Estuary.” Journal of Fisheries Research Board Canada. Vol(17)3.

Uncles, R.J. and Jordan, M.B. (1979). “Residual fluxes of water and salt at two stations in the Severn estuary” Estuarine Coastal Marne Science, Vol 9, pp 287-302

BIBLIOGRAPHY

Bowden, K.F., (1963). ‘Tidal Mixing processes in a tidal estuary” International Journal of Air Water Pollution, Vol7, pp343-356.

Desplanque,C. and Mossman,D. (2004). “Tides and their seminal impact on the geology, geography, history, and socio-economics of the Bay of Fundy, eastern Canada. Journal of Atlantic Geology, North America, Vol 40, pp 66-130. [Online]. http://journals.hil.unb.ca/index.php/ag/article/view/729/1085.

Dyer, K.R (1973). Estuaries a Physical Introduction. 1st ed., John Wiley & Sons Ltd, New York.

Dyer,K.R., (1974) “The salt balance in stratified estuaries”, Estuarine Coastal Marine Science, Vol 2, pp 273-281.

Fischer, H.B. (1972), Mass transport mechanisms in partially stratified estuaries. Journal of Fluid Mechanics, Vol 53, pp. 671–687.

Geyer,W.R., and Smith, J.D.,(1987). “Shear instability in a highly stratified estuary” Journal of Physical Oceanography, Vol 19 pp 1060-1072.

Hachey, H.B. (1935). “Tidal Mixing in an Estuary’ Journal of Biological Board of Canada” Vol 1 (3), pp 171-178.

Kjerfve, B. “Measurement and analysis of water current, temperature, salinity and density” In Press in Estuarine Hydrography and sedimentation, K.R Dyer, ed, Cambridge University Press, Cambridge, UK, pp230.

Kjerfve, B. and Prochl, J.A. (1979). “Velocity variability in a cross-section of a well mixed estuary” Journal of Marine Research, Vol 37, 3, pp 409-418.

Li, Michael Z., Parrott, D. Russell, Yang, Zongyan, 2009. Sediment Stability and Dispersion at the Black Point Offshore Disposal Site, Saint John Harbour, New Brunswick, Canada. Journal of Coastal Research. Vol. 25, No. 4

Wind Statistics and Maps for Saint John Airport (2010). [Online] January, 2011 http://www.windfinder.com/windstats/windstatistic_map_canada_east_11.htm

Winterwerp, J. C.(2005). "Reducing harbour siltation. I: Methodology". Journal of Waterway, Port, Coastal and Ocean Engineering. Vol. 131, No. 6, pp.258-266

APPENDIX I

Website of all tidal cycles images - Data sets include the raw MVP, ADCP, 200kHz

http://www.omg.unb.ca/PSJ_project/

APPENDIX II

Refer to website (http://www.omg.unb.ca/PSJ_project/) for the following results:

Results of all the Ri sections for all stages of the tide for March 26th 2009.

Results of all the Ri sections for all stages of the tide for April 22nd 2008.

Results of all the Ri sections for all stages of the tide for June 11th 2009.

Results of all the Ri sections for all stages of the tide for November 14th 2008.