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Seasonal and Tidal Variations of Sediment Transport Patterns in the Saint John Inner Harbour, New Brunswick

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Abstract: The Saint John Harbour is located along the Bay of Fundy in southern New Brunswick and serves as the primary outlet for the Saint John River. Sediment movement within the Saint John Harbour is a concern from both an ecological and operational perspective. Seasonal measurements of current velocity and suspended sediment concentration (SSC) have been obtained by deploying two acoustic Doppler current profilers (ADCPs) in the inner harbour. ADCP observations spanned several months and were nearly continuous, thus allowing for an in-depth analysis of meteorological and tidal influences on observed hydrodynamics. A comparative assessment was conducted for spring and neap tides, storm surges, and changes in fluvial input. It was observed at both deployment locations that the intruding salt wedge frequently contained high SSC. The salt wedge is believed to be a major contributor of sediment accretion in the inner harbour, particularly during winter storm surges when river discharge is reduced. The Courtenay Bay Channel was observed to be more sensitive to river level, with only winter storms resulting in a landward average sediment flux. Observations made near Courtenay Bay Channel also suggested the presence of a cross channel flow pattern from an adjacent inter-tidal mudflat. This cross channel flow was only observed during spring freshet conditions and contained high SSC. Hydrodynamic observations from the study were compared with published estuarine theory. Results of the study will help to further define hydrodynamic processes in the Saint John Harbour.

1 Introduction

Macrotidal and hypertidal estuaries are defined as those having a tidal range >4 m and >6m, respectively (Davies 1964). Examples of macrotidal and hypertidal estuaries include the Bay of Fundy, Canada; Tay, Scotland; Gironde, France; and the Rios Gallegos, Argentina. Macrotidal and hypertidal estuaries are of particular research interest because they are among the least studied in the literature (Perillo 1995).

After reviewing historical definitions of estuaries, Perillo (1995) formulated the following definition:

> "An estuary is a semi-enclosed body of water that extends to the effective limit of tidal influence, within which sea water entering from one or more free connections with the open sea, or any other saline coastal body of water, is significantly diluted with fresh water derived from land drainage ..."

This deliberately constructed definition clearly highlights the mixing of salt and fresh water as an essential attribute of any estuary. Perillo (1995) goes on to suggest that density structures in an estuary may exist as either highly stratified (salt wedge type), partially stratified or well mixed. Classification of estuaries by stratification is not absolute and instead forms a spectrum whereby an estuary may exhibit characteristics of more than one type under different conditions.

A partially mixed or partially stratified estuary has a similar structure to the highly stratified case but with a more gradual density gradient through the water column. The position of the salt wedge oscillates landward and seaward with the tidal period. This movement creates friction with the sea bed increasing turbulence in the bottom layer which promotes mixing within the water column (Dyer 1997). This mixing contributes to the creation of a less defined halocline which is typical of partially stratified estuaries (Dyer 1995).

Sediment circulation within an estuary is contingent on the type of sediments and the hydrodynamic regime within the estuary. Of particular relevance to a macrotidal, partially stratified estuary is the concept of the turbidity maximum (TM). The TM is a location within the estuary where suspended sediment concentrations (SSC) are greater than either the fresh or salt water inputs (Dyer 1997). A TM occurs due to a combination of tidal pumping, vertical gravitational circulation and sediment dynamics (Officer 1981). Figure 1 shows the effects of gravitational circulation and the resulting TM near the upper limit of salt water intrusion. Landward flow in the lower salt wedge (flood tide) is required for gravitational circulation to occur.

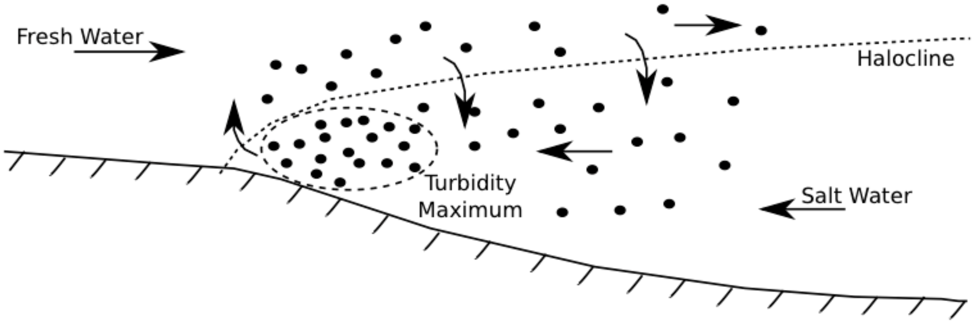

Figure 1: Graphical Depiction of Vertical Gravitational Circulation (adapted from Dyer (1995))

TMs have been studied and described in great detail for the Gironde (Allen 1973, Allen et al. 1980) and Tamar (McCabe 1992) estuaries. These studies found that the position of the TM was particularly responsive to variability in tidal range (ie. neap and spring tides), and fluctuations in fresh water input. Allen et al (1980) also found that the suspended sediment concentration of the TM was greater during spring tides than for neap tides. These studies highlight the response of TMs to the variable flow patterns typical of partially stratified estuaries.

By collecting hydrodynamic data over large timescales, sediment circulation patterns within an estuary may be investigated. In particular, seasonal and tidal variations of hydrodynamic behavior and sediment circulation may be analyzed. Instrumentation has been deployed in the Saint John Inner Harbour to collect relevant hydrodynamic data. The purposes of this work are to: a) collect data to assist in the future development of a baroclinic hydrodynamic model of the harbour, b) offer insight into the management of harbor dredging activities and, c) contribute to the larger body of estuarine research.

2 Description of Study Area

The Saint John Harbour is located in southern New Brunswick adjacent to the Bay of Fundy as shown in Figure 2. Commercial and industrial operations rely on the Saint John Harbour, making the waterway of great economic significance for the province of New Brunswick. The accretion of sediment within the port’s navigational channels impedes shipping access and therefore requires annual dredging (SJPA 2010). An enhanced understanding of sedimentation mechanisms would allow for better prediction of dredging requirements. Such foresight would improve budgetary planning and offer considerable operational benefits for all users of port facilities.

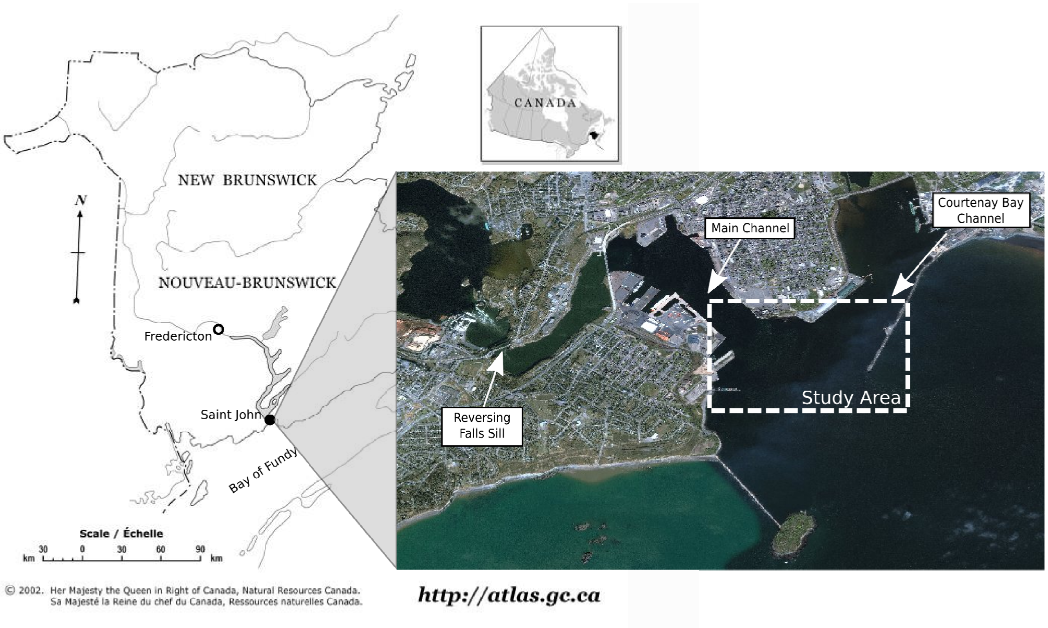

Figure 2: Saint John Inner Harbour and Study Area Location

Combined with tidal inputs from the Bay of Fundy, the harbour serves as the primary outlet for the Saint John River which has a total catchment area of approximately 55,000 km^2 (Metcalfe 1976, Neu 1960). Much of this drainage area is located in north-western New Brunswick as well as regions of Quebec and Maine, U.S.A (Metcalfe 1976). According to Neu (1960), Saint John River discharge is seasonally variable with a mean value of 690 m^3/s but can be as high as 6,900 m^3/s during spring freshet discharge. The river level is controlled by several dams; the most downstream is the Macequac Dam located approximately 120 km upstream of the Saint John Harbour. Near the river mouth, flow into the harbour is restricted by a sill located immediately downstream of the well-known Reversing Falls (shown in Figure 2). According to Trites (1960), the Reversing Falls sill has a depth of 5 m, and severely limits the seaward and landward exchange of water during a tidal cycle. This restriction of flow is evident given that the mean tidal range in the harbour is approximately 6.4 m, while in nearby Indiantown, upstream of the sill, the maximum tide range observed is typically 0.7 m (Metcalfe 1976).

The analysis presented in this study will focus exclusively on the lower reaches of the estuary downstream of the Reversing Falls sill. On the seaward side of sill, the harbour is subject to a maximum spring tidal range of 8.8 m and a minimum neap range of 4.5 m (Neu 1960). According to Neu (1960), these exceptionally large tide ranges are the result of near resonation with the physical dimensions of the Bay of Fundy. The primary tidal constituent in the harbour is the semi-diurnal M_2 tidal constituent (Godin 1991). The harbour experiences a full tide cycle every 12.42 hours (Greenberg 1979).

The Saint John Harbour is subject to storm surges, tidal variation and seasonal increases in freshwater input during spring freshet periods. Several studies have been conducted to further quantify and describe this variability. Higgins et al. (2011) investigated hydrological inputs (precipitation, snow melt, river level, etc.) and the corresponding variations in SSC in the Kennebecasis River, a tributary of the Saint John River. Toodesh (2012) found that both the tidal range and the river level influence the state of the Saint John Harbour which exhibits characteristics of both a stratified and partially stratified estuary. Furthermore, Matheron (2010) conducted a detailed analysis of harbour sediments, investigating both bed load and suspended sediment grain size and geological composition. The analysis established that both cohesive and non-cohesive sediments are present in the harbour.

Observations made by Matheron (2010) and Toodesh (2012) in the Saint John Inner Harbour suggest that the harbour exhibits characteristics of both a partially mixed and/or stratified estuary. These observations have also been supported in the upper reaches of the estuary by Delpeche (2007). Under these conditions a salt water wedge oscillates landward and seaward with the tide and is overlain by a brackish layer of river discharge. Salinity values in the salt wedge are typically around 30 $^{0}/_{00}$, while at the surface salinity values of between 15 – 20 $^{0}/_{00}$ have been observed (Delpeche 2007). The brackishness of the surface layer suggests that some combination of turbulent mixing and/or entrainment is taking place and the estuary is frequently in the partially stratified condition.

3 Data Collection

Hydrodynamic data have been collected in fifteen minute intervals at two locations within the Saint John Inner Harbour. These data have been collected by deploying two acoustic Doppler current profilers (ADCPs). The following section will offer a technical background of the equipment used, and describe the computational and field procedures employed throughout the study.

3.1 Acoustic Doppler Current Profilers

The Workhorse Sentinel is a broadband ADCP unit manufactured by Teledyne RD Instruments (TRDI). The Workhorse model is well-suited for bottom-mounted, sustained sampling durations. Figure 3 shows the unit in the standalone configuration and embedded inside of a trawl-resistant bottom mount prior to deployment.

What distinguishes ADCPs from conventional current meters is the ability to collect current velocity data over an entire water profile. This is achieved by dividing the water profile into depth cells and measuring an average velocity reading for the each depth cell. However, due to errors associated with ADCP operation, data from the near-surface and near-bottom portion of the water column are excluded. As a result, the upper 6% of the water column and between 0.5 and 0.9 m (depending on ADCP frequency) above the ADCP were excluded from measurement. Near-surface error is due to interference from the water surface, and near-bottom error is caused by near-transducer ringing (TRDI 2011).

Figure 3: Workhorse Sentinel in standalone (left), and bottom-mounted (right) configurations (TRDI 2011)

In addition to velocity measurement, ADCPs also have the ability to measure acoustical backscatter (ABS) at each depth cell throughout the water column. The strength of the return signal is used to measure ABS intensity. This is a useful feature as ABS can serve as an indication of scatterer concentration in the water column (Deines 1999). A number of studies have used ADCP measurement of ABS to estimate SSC in estuarine environments (Poerbandono and Mayerle 2003, Kim and Voulgaris 2003, Bartholoma et al. 2009). For this study, the estimation of SSC from ABS measurement has been derived using a modified version of the sonar equation developed by Deines (1999). Water profile samples at each deployment location were also analyzed for total suspended solids to develop the relationship between ABS and SSC at each location.

3.2 ADCP Deployments

The 600 kHz ADCP unit was deployed in the Main Channel, and the 1200 kHz unit in the Courtenay Bay Channel. The approximate deployment locations for each unit are shown in Figure 4. The Courtenay Bay Channel unit needed to be relocated twice during the entire 233 day deployment (September 2011 – May 2012). Connection to the Main Channel unit was lost during recovery efforts approximately 133 days after the initial deployment (November 2011 – March 2012). Data were regularly downloaded during each deployment via a unit-to-shore cable connection. Unfortunately, data collection from the Main Channel unit ceased after March 13, 2012.

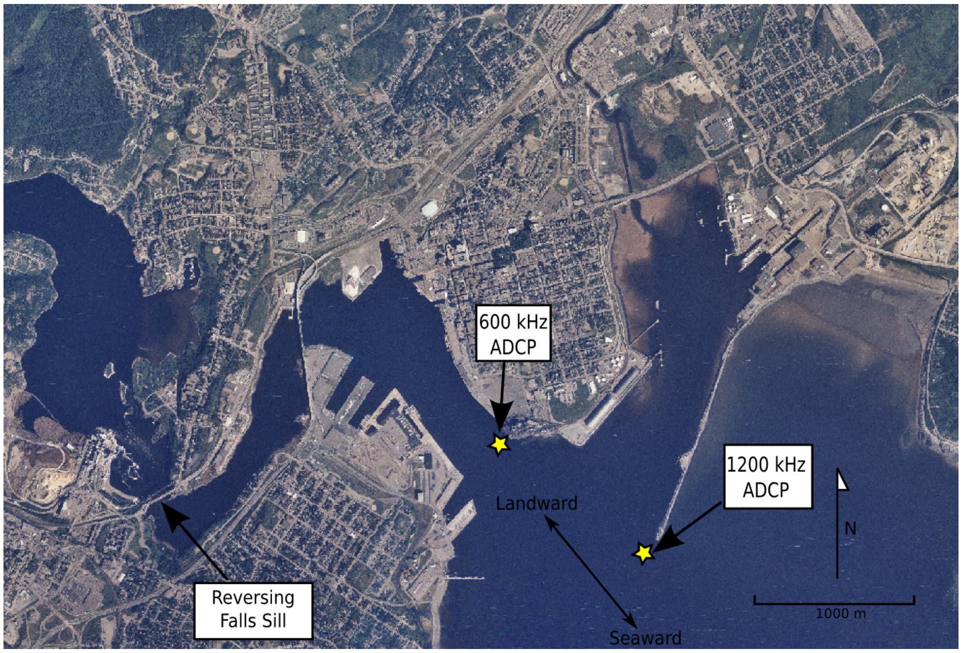

Figure 4: ADCP Deployment Locations in Main Channel and Courtenay Bay

3.3 Data Processing

Channel cross section profiles collected during a 2008 bathymetric survey were provided by the University of New Brunswick's (UNB) Ocean Mapping Group. These profiles were combined with the relevant ADCP data to estimate volumetric flow and sediment mass flux through an approximate channel cross section at each deployment location. Two components of the current velocity were used for the analysis: along channel (axis parallel to the alignment of each channel), and across channel (axis perpendicular to the channel alignment). Methods used by Toodesh (2012) were followed closely and a polynomial function was fitted to each cross section in order to smooth the profile. The corresponding area for each ADCP bin was determined by iteratively moving a boundary function from the first recorded bin to the surface in steps equal to the bin size.

Once the flow area values were obtained it was possible to use the along channel velocities and SSC data to determine the flow rate and sediment mass flux for each channel. Equations 1 and 2 were used iteratively to determine the average volumetric flow through each bin, Q_{bin}, and sediment mass flux, F_{bin}, through each depth cell for each time step in the sampling period. A_{bin} and v_{bin} are the depth cell area and velocity values, respectively. SSC_{bin} is the estimated SSC value for each bin.

[1] $Q_{bin} = v_{bin} A_{bin}$

[2] $F_{bin} = Q_{bin} SSC_{bin}$

4 Results

The focus of the study is to investigate factors and events spanning multiple tide cycles and the effect on hydrodynamic conditions in the Saint John Inner Harbour. For each deployment location a baseline condition will be presented graphically to provide context for ADCP observations. A plot of estimated net sediment mass flux for each deployment will also be presented.

4.1 Main Channel

Given that the Main Channel ADCP deployment duration spans many tidal cycles (~ 250), unique insight into the effects of meteorological and tidal factors on inner harbour hydrodynamics is possible. For the duration of data collection in the Main Channel, the average tide range and river level were approximately 6.2 m and 5.6 m, respectively. The tide cycle occurring on November 10, 2011 was identified as being a “typical” tide cycle in the harbour. Figure 7 depicts the along and across channel current magnitude and SSC at the Main Channel deployment location for November 10, 2011.

Figure 8 below shows river level (right), and net sediment flux (left) for the entire observation period. To assist in identifying patterns in the data, Figure 8 (left) compiles the net sediment flux results, with the vertical lines denoting storm surges encountered during the observation period. Data corresponding to approximate spring and neap tide cycles are also colour coded. Note in Figure 8 (left), that positive values represent a net seaward movement of sediment, and negative values represent a net landward movement of sediment.

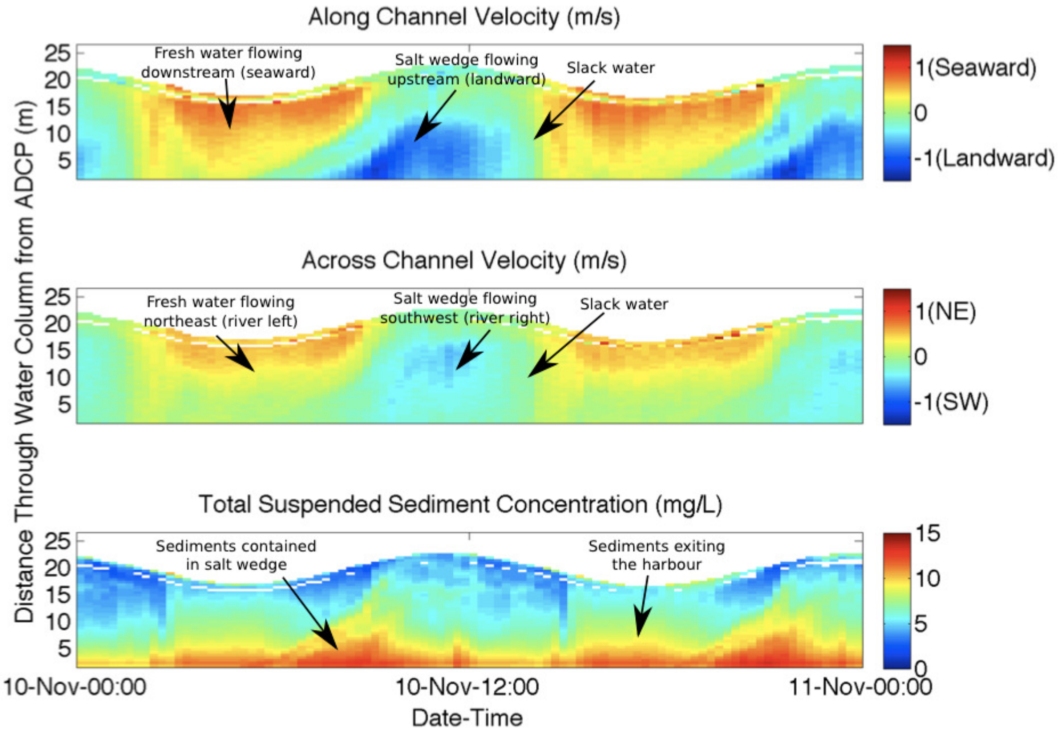

Figure 5: Along and Across Channel Current Magnitude and SSC at the Main Channel Deployment Locaiton for November 10, 2011

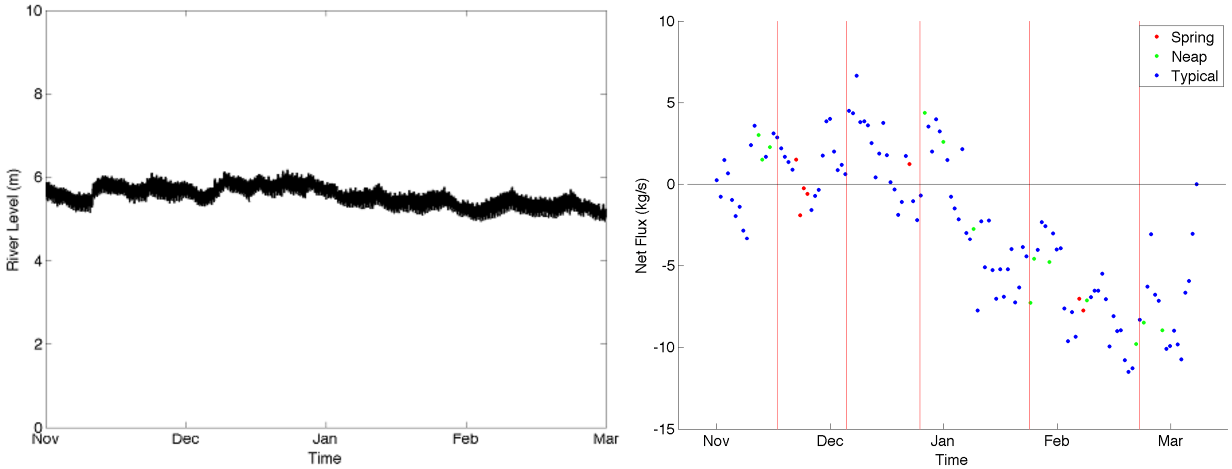

Figure 6: River Level (Right), and Net Sediment Flux for the Entire Main Channel Deployment Duration (Left)

4.2 Courtenay Bay Channel

Similar to Main Channel results, the Courtenay Bay unit offers a unique insight into the effect of meteorological and tidal factors on inner harbour hydrodynamics. The river level fell slightly between January and March but then increased substantially during the spring freshet beginning in March, reaching a peak of 7.6 m. The baseline condition presented in Figure 9 was recorded on January 1, 2012 and represents typical conditions at the Courtenay Bay deployment location.

Similar to the results presented for the Main Channel, Figure 10 shows river level (right), and net sediment flux (left) for the entire observation period. Storm surges (vertical lines) and spring and neap tide cycles have again been highlighted for comparison.

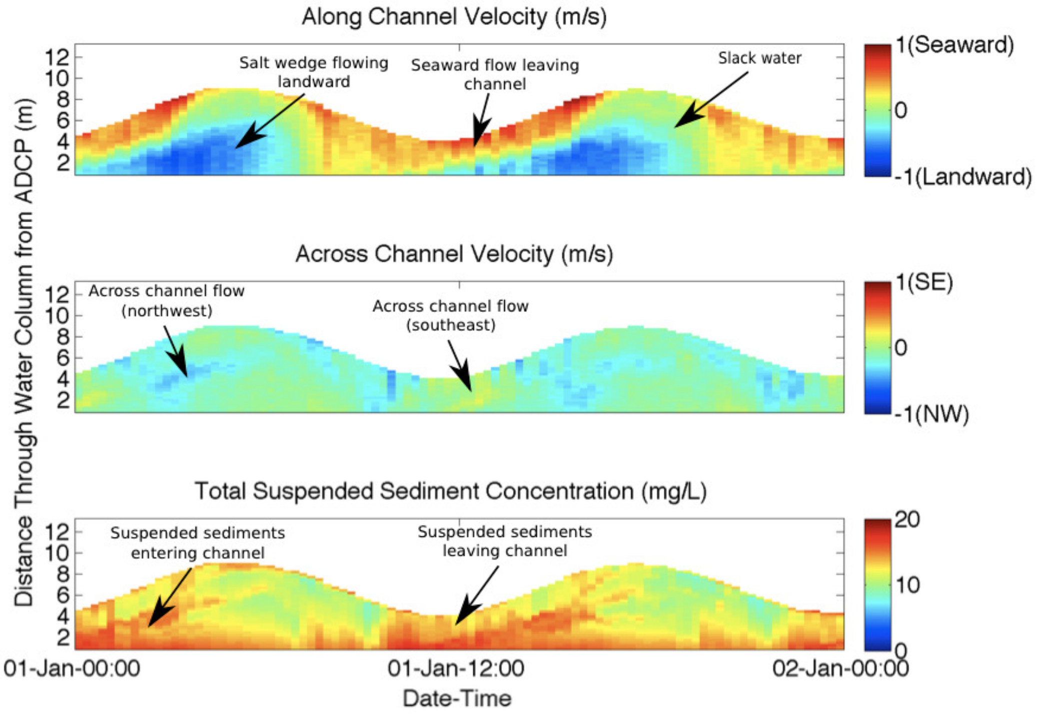

Figure 7: Along and Across Channel Current Magnitude and SSC at the Courtenay Bay Channel Deployment Location for January 1, 2012

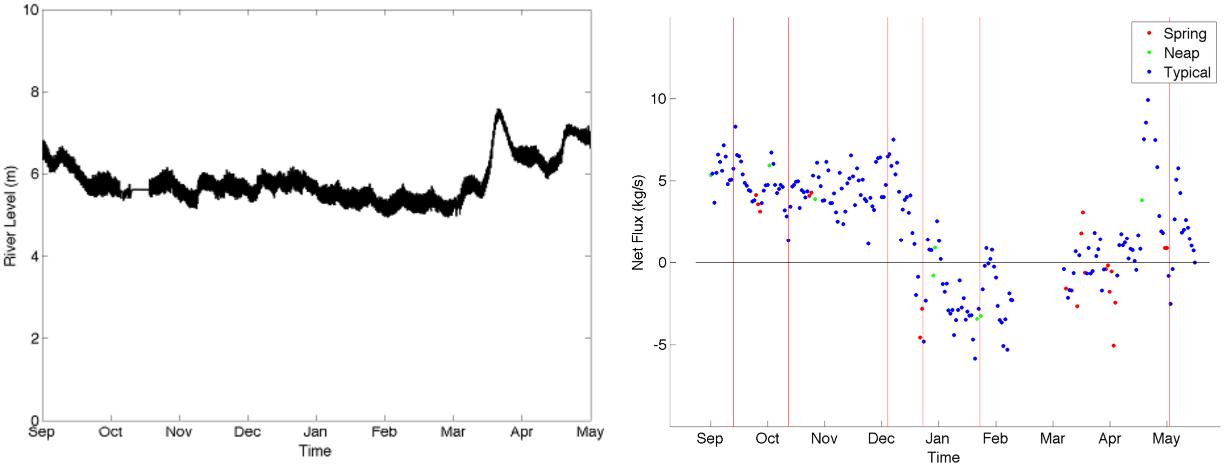

Figure 8: River Level (right), and Net Sediment Flux for the Entire Courtenay Bay Deployment Duration (Left)

5 Hydrodynamic Summary

5.1 Main Channel

The ADCP data collected in the Main Channel suggests high SSC in the lower saline wedge than in the upper brackish layer. ADCP observations ceased before spring freshet conditions began, when SSC in the upper layer is believed to contain the dominant SSC load as observed by Toodesh (2012). Due to the high velocities during spring freshet periods, it is supposed that this high SSC load is kept in suspension and deposited in the outer harbour where rapidly increasing flow area acts to decrease velocity. As a result of this annual freshwater flushing, the Main Channel is not typically dredged to the same extent as the Courtenay Bay Channel. The observations made in this study suggest that sediments enter the Main Channel via the lower salt wedge during winter months when river level is comparatively low. These sediments are then presumably flushed out during spring freshet discharge.

Figure 7 shows a disproportionately sensitive response in sediment flux to variation in river level (note that river level decreased by 0.8 m in late winter months). The influence of river level was apparent during storm surges. The storm event in late February resulted in the highest mean landward flux of sediment (-5.6 kg/s). In essence, a small change in river level (+/- 1 m) can vastly change the extent to which tidal intrusion affects sediment circulation in the Main Channel. These observations may be linked to the concept of the turbidity maximum. According to Dyer (1997), the TM tends to be pushed seaward during times of high river discharge lessening the amount of SSC entering the estuary. Conversely, at time of low river discharge and high tide range, such as spring tides or storm surges, the TM is able to progress further toward the head of the estuary, increasing landward sediment flux. ADCP data collected in the Main Channel suggest that this behaviour is occurring in the Saint John Harbour.

5.2 Courtenay Bay Channel

The Courtenay Bay Channel is typically dredged to a much larger extent than the Main Channel. This variation is largely due to the lack of freshwater flushing in Courtenay Bay. A similar SSC profile distribution was observed in Courtenay Bay with the lower salt wedge containing relatively high SSC. However, due to the lack of annual freshwater flushing, sediment accretion in Courtenay Bay is more pronounced and problematic for maintaining adequate draft for channel navigation.

Similar to the Main Channel, salt wedge intrusion was more pronounced during periods of low river discharge in late winter months (see Figure 8). This phenomenon was consistent for storm surges, as well as spring and neap tides. Similarly, there was also an increase in mean landward sediment flux during periods of low river flow.

Of note during high river discharge periods, is the increase in SSC throughout the water column, as well as a considerable cross channel velocity component at ebb tide. On the ebb tide and at low water there is a spike in SSC throughout the water column. This also coincides with a considerable north-westerly flow component (0.5 – 1 m/s) passing across the head of the breakwater toward the mouth of the channel. Bathymetric observations by UNB's Ocean Mapping Group undertaken in spring 2008 have suggested that there may be a cross channel flow component originating from the adjacent intertidal mudflat (see Figure 9). ADCP observations seem to support this observation; however, the phenomenon was only apparent during periods of high river discharge.

Higgins (2011) found a significant correlation between dredge volumes in the harbour and mean water level (coefficient of determination (r^2) = 0.63) and total annual river flow (r^2 = 0.73) in the Kennebecasis River. The cross channel contribution of sediment agrees with the work of Higgins (2011) since the cross channel flow seems to be exacerbated by high river discharge. Moreover, it was found that the sediment flux due to this cross channel effect can be significant and resulted in a mean sediment flux of 11 kg/s toward the channel – which is the greatest flux value observed at Courtenay Bay.

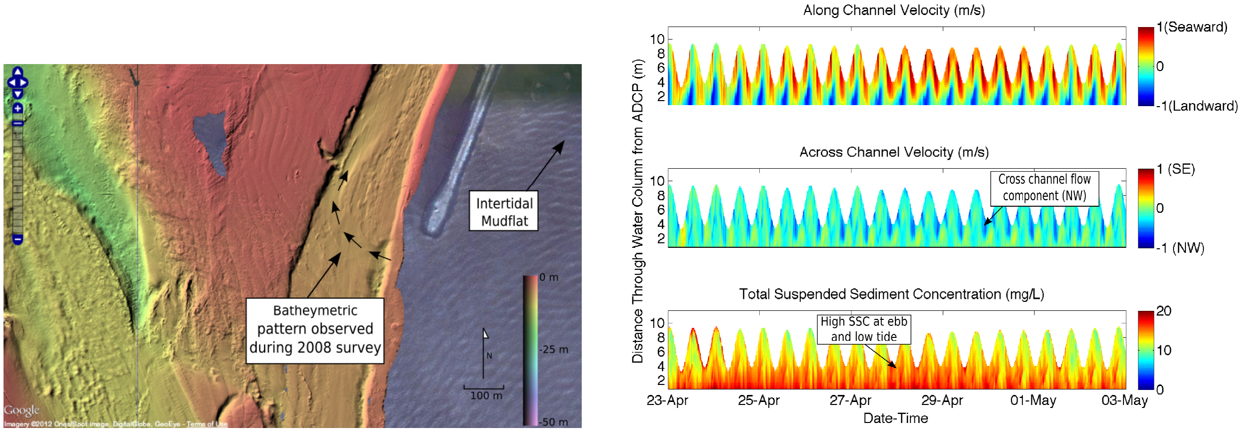

Figure 9: Courtenay Bay Channel Deployment Location 2008 Bathymetry with Annotated Cross Channel Flow Pattern (Right), and Associated ADCP Results (Left)

6 Conclusions

Observations made during atypical seasonal events such as spring tides, storm surges and high river discharge were of particular interest throughout the duration of this study. By evaluating ADCP observations, several hypotheses relating to sediment circulation have been presented to further define hydrodynamic processes in the harbour.

Some of the largest contributions of landward sediment flux in the Main Channel were observed during storm surges and spring tides in late winter months. This increased flux corresponded with low river levels and is believed to permit increased tidal progression toward the head of the estuary, carrying with it high levels of SSC. This phenomenon suggests the presence of a TM which oscillates with tidal action and increasing/decreasing river level. Despite this increase of sediment entering the harbour, it is believed that annual freshwater flushing during spring freshet periods protects the Main Channel from heavy sediment accretion.

The Courtenay Bay Channel represents a more complex hydrodynamic environment. Although similar patterns for the Main Channel have been observed at Courtenay Bay, the levels of landward sediment flux in the salt wedge were less significant. It is believed that a cross channel flow component from an adjacent intertidal mudflat may be a large contributor of sediments entering the channel. A strong cross channel flow component has been observed during the spring freshet period containing elevated SSC.

The study has helped to improve the understanding of hydrodynamics in the Saint John Harbour, particularly over large seasonal timescales. It is hoped that this research will assist in the planning of harbour dredging activities, and contribute to the larger body of academic work relating to the Saint John Harbour. While this study focused solely on the Saint John Harbour area, it would be possible to relate the methodology and findings presented here to other similar studies investigating hydrodynamics in estuarine environments.

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