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OBSERVATIONS AND INTERPRETATION OF MIXING AND EXCHANGE OVER A SILL AT THE MOUTH OF THE SAINT JOHN RIVER ESTUARY

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ABSTRACT: Upstream of the Reversing Falls, at the mouth of the Saint John River, the estuary is partitioned into a fjord-like body of water (the Kennebecasis) and the main river. At the point of convergence of these two water bodies (Grand Bay), lies a shallow sill that controls the mixing and exchange of the salt and fresh water and thus ultimately the renewal of the lower saline waters upstream.

High resolution multibeam bathymetric surveys of the sill top and flanks reveal erosive morphology indicating that the mixing is being focused and enhanced in narrow channels over the sill. The depth range and distribution of the channels indicate that they are being eroded by hyperpycnal flows unrelated to the main surface freshwater discharge. Scour morphology indicate that the erosion is predominantly due to upstream flow. ADCP current and CTD measurements within and across these channels clearly indicate that they are active today during the low river discharge periods. By acquiring spatially dense current and CTD information along a series of specific cross-sections over successive tidal cycles, a detailed picture has been built up of the mechanisms of mixing and exchange. By imaging the volume acoustic backscatter within the water column, the details on the mixing at the interface are examined.

The diluted salt water actually penetrates another 20 miles beyond the sill up the main river. The replenishment of the lower salt layer however, is interrupted by exchange over the sill, occurring only discontinuously during neap tides. Imaging the intrusion on spring tides indicates that during the ebb, the lower salt layer is, at times less than a metre thick. The intrusion into the Kennebecasis, which occurs primarily during spring tides occurs as a bore that propagates along the interface between the relatively stagnant deep salt water and the overlying fresh water. The observations are used as both boundary conditions and control for a 3D baroclinic hydrodynamic model of the sill area (Haigh and Hughes Clarke, this volume).

1. INTRODUCTION

The Saint John River is the largest contributor (~60%) of fresh water into the Gulf of Maine Basin. The watershed of the Saint John includes western and northern New Brunswick together with extensive parts of north east Maine and adjoining Quebec. The river flows into the Bay of Fundy at Saint John where locally tides exceed 7 metres close to the mouth. Because of the main topographic restriction of the Reversing Falls (Hachey 1935), however, the tidal ranges in the estuary upstream are generally less than 0.5m.

The restriction at the Reversing Falls causes currents in excess of 10 knots at the sill and almost completely homogenizes the incoming flow, resulting in intruding water having a characterstic salinity signature of ~23-26 ppt rather than the 31ppt associated with the main bay offshore (Trites 1960 and

Neu 1960). It is this brackish water which then intrudes further upstream into the estuary system. About 6 km upstream of the Reversing Falls, the flow comes out of a 30-50m deep gorge into the regionally shallower (<15m) Grand Bay, Boars Head Sill area (Figure 1). The oceanographic characteristics of the both the upstream river estuary (the Westfield Channel and Long Reach) and the adjacent Kennebecasis Fjord are determined by the volume and extent of dilution of the saline waters as they pass over this second sill. This paper focuses on the geomorphic and oceanographic evidence for mixing of the saline and fresh water over the sill in the Grand Bay area.

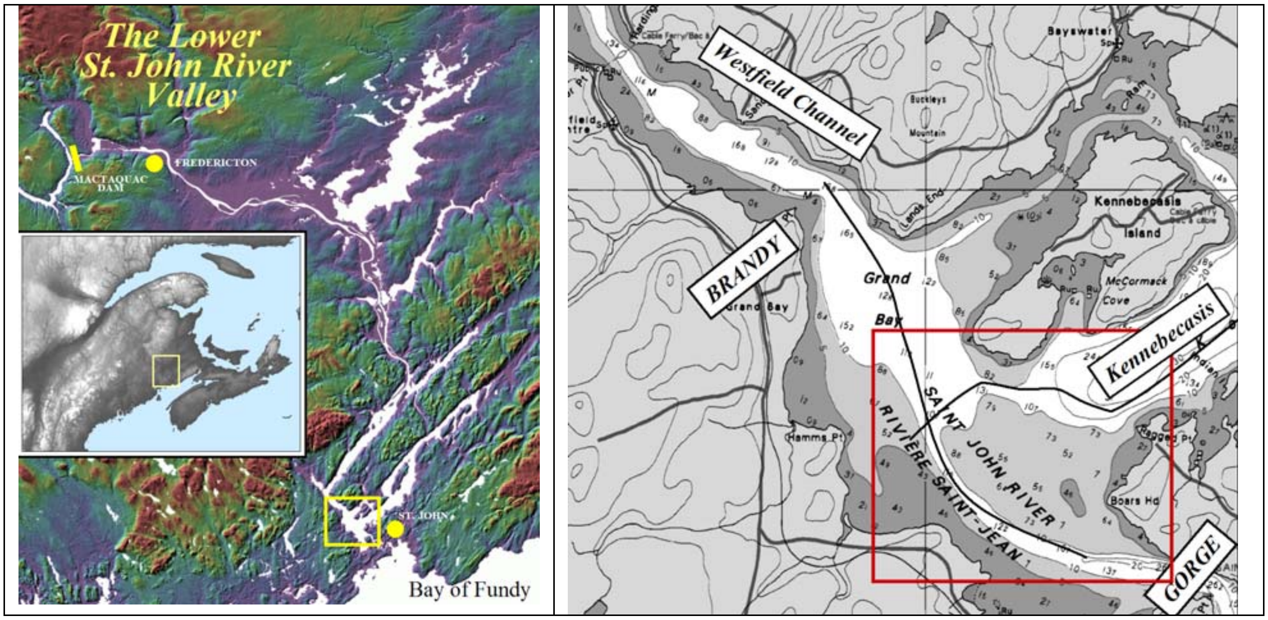

Figure 1. Left : showing the lower Saint John River system with inset of study area. Right: CHS chart 4116, showing major geographic features with inset of detailed mapping region (Figure 2).

The oceanographic attributes of any estuary depend upon a balance of the fresh water input, the tidal activity and the constraining morphology. Those estuaries with sills (shallow bathymetric barriers), are known to exhibit unique characteristics related to the restrictions on exchange of the deeper denser watermasses. Well documented studies of the Knight Inlet Sill (Farmer and Smith 1980, Klymak and Gregg 2001) and the sills enclosing the Puget Sound estuary system (Lavelle et al. 1991) have been published. Those sills restrict the deep water exchange, but significantly lie well below the average depth of the main pycnocline. The dynamics of those sill have generally been modelled on the basis of two layer flows (Farmer and Armi 1986).

In contrast to the deeper Knight Inlet and Puget Sound Sills, the Boars Head Sill lies at or above the mean level of the pycnocline. Thus the presence of saline water on the top of the sill is transient. Indeed during periods of high river discharge, the sill top is never exposed to the saline waters at all. During low discharge periods (summer low rainfalls and winter under the ice), the tidal fluctuations of the inflow over the Reversing Falls are just enough to intermittently lift the pycnocline over the top of the sill. Based on observed replenishment of the deeper Kennebecasis, these overflow events appear to occur only on spring tides (Trites 1960). This is in direct contrast to the Puget Sound Sills, where, as the sill never physically blocks the flow, it actually allows more exchange of deeper waters during neap tides when the pycnocline is less disturbed (Geyer and Cannon 1982).

2. SCIENTIFIC OBJECTIVES

The aim of this research program is to relate the circulation pattern over the Boars Head Sill in the lower end of the Saint John River estuary to new high resolution bathymetric mapping that has revealed clear evidence of focussed channelized scour. Whilst the new research results presented herein focus on the likely oceanographic driving forces, the underlying funded requirement was to better understand the variability in sound speed (controlled in turn by the same oceanography) for the purpose of accurate hydrographic survey.

3. MORPHOLOGY OF GRAND BAY SILL

The presence of a sill in Grand Bay has long been established. The original bathymetric survey was based on a 1930's lead line survey. Whilst the original sounding sheet did indicate a series of apparently isolated depressions across the sill, the soundings were so sparse that the continuous nature of the depressions could not be construed. Indeed the transfer to a metric edition of the chart further generalized the apparent bathymetric features losing even that sparse detail. In 1980's a single beam sparse survey identified further depressions (Torrie 1985). Based on these slightly denser soundings, it was speculated that the sill might have eroded since the 1930's although the reason for erosion was not recognised to be current related. In 2000, the first multibeam survey was conducted of the western end of the Kennebecasis Fjord Basin and recognised for the first time that sill top channels drained into the fjord. In 2001, 2002, 2003 and 2004 successive multibeam deployments have built up a detailed picture of the morphology of the sill and are presented herein.

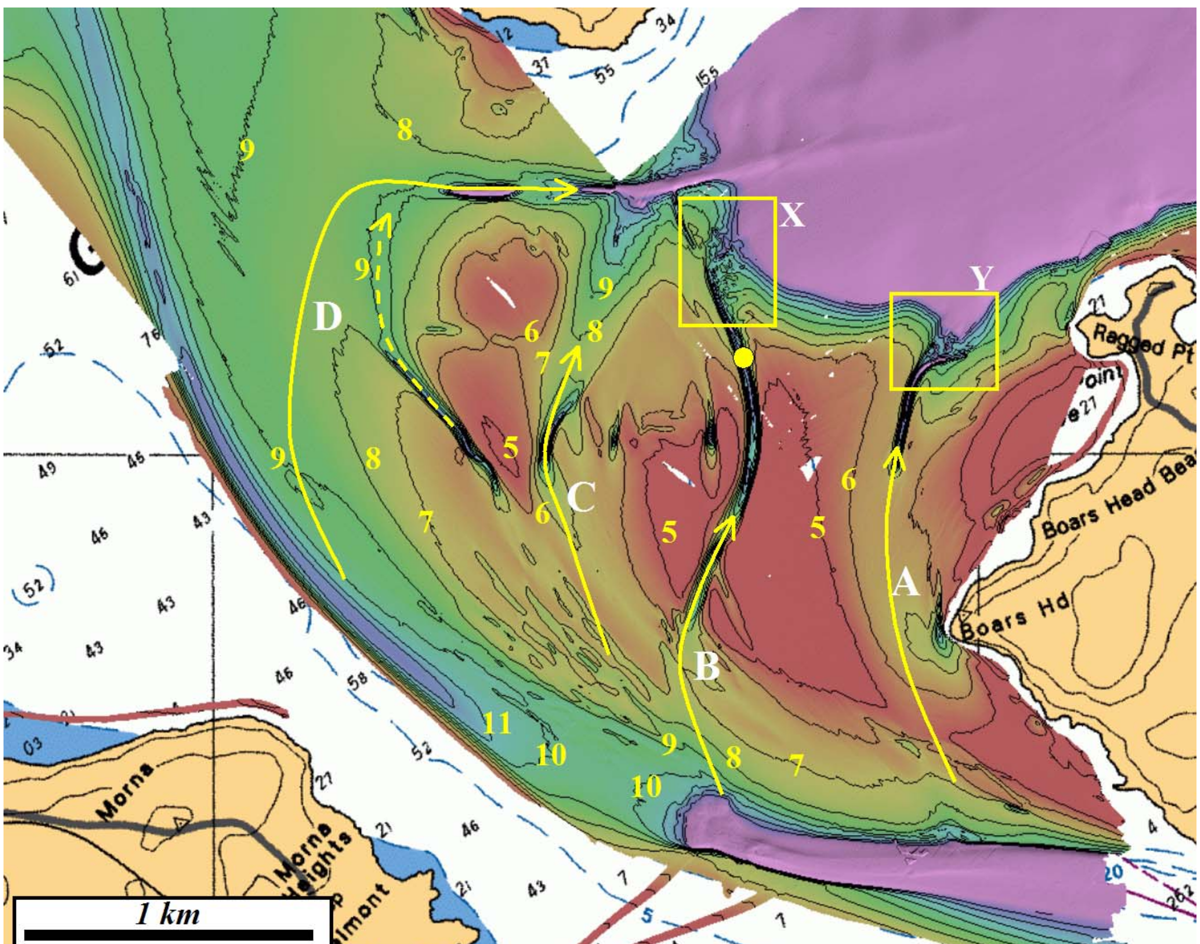

Figure 2. EM3000 multibeam survey of Boars Head Sill. 1 m contours from 5 to 14 m below chart datum presented. Yellow labels are contours in metres. 4 yellow arrows (A, B, C, D) indicate principal pathways of saline intrusions over the sill. Boxes X and Y indicate location of zoom images presented below (Figure 5). Yellow dot in channel B indicates location of moored ADCP time series (Figure 4).

3.1. Regional Sedimentation

Metcalfe et al. (1976) sampled the sediments on the sill top, recovering poorly sorted of clay rich silty sands throughout the region. Neu (1960) interpreted that the predominant mode of deposition in this region was primarily sediment brought upstream through the Reversing Falls on the flood tide. Flocculation of this suspended material was assumed to take place in the vicinity of the Grand Bay, Boars Head Sill region as a result of the interaction of the saline water mixing with the fresh.

Although extensive shallow subbottom profiling work has been done as part of this project, a near-surface or shallow subsurface gas-charged layer prevents any penetration through the sill top. Thus the depth to consolidated basement or relict sediment remains unknown.

4. EXCHANGE OF SALT WATER BETWEEN THE GORGE AND THE KENNEBECASIS

Figure 2 clearly illustrates the multiple possible pathways across the sill. In order to get there, the pycnocline has to rise up above the threshold depths of each of the channels. The 4 channels shown have a minimum depth over which the flow has to pass as well as a maximum depth of scour. These are respectively:

- A -- 6.3 m and 14.7 m
- B – 7.2 m and 14.3 m
- C – 6.2 m and 13.7 m
- D – 8.4 m and 16.7 m

Channel D is both the broadest channel and has the deepest minimum depth requirement. The standard CHS chart (# 4141) indicates this as the only channel. The other 3 are not visible on the chart. Channel A might be inferred as a minor pathway, but without the evidence of the scoured channel at the northern end would probably not be considered significant on the basis of charted soundings alone.

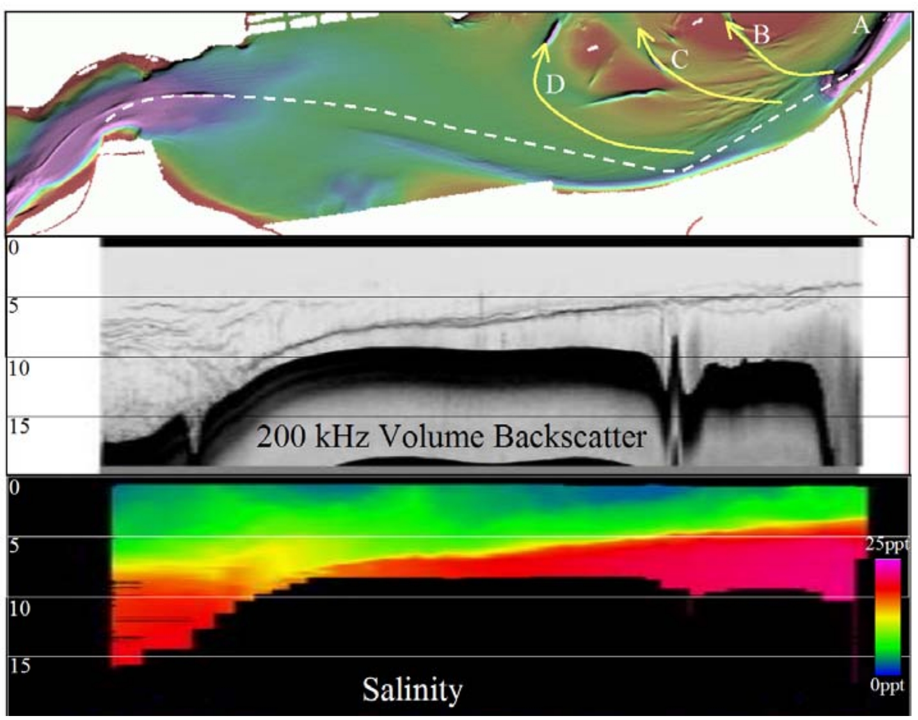

Figure 3. Illustrating the strong interfacial slope of the salt water intrusion over the sill at the time of its maximum penetration upstream, 1 hour after high water. Section derived along the white dashed line.

Trites (1960) had suggested a sill depth of 11m based on the charted soundings. Based on the newer 100% multibeamn coverage of the sill it is clear that this is not actually achievable above chart datum. However, the minimum channel depth is not necessarily a direct indicator of the likelihood of exchange as the controlling factor is the maximum height of the pycnocline, which is not a level surface at the time of maximum advance. At that point the saline intrusion represents a salt wedge with an interface that dips to the NW along the long axis of the Grand Bay Sill bypass channel (Figure 3).

In order to investigate the temporal evolution of the pycnocline on the seaward side of the sill, along the bypass channel axis (Figure 3 above), a 12.42 hour sequence of cross sections were measured using ADCP and underway CTD (MVP-30) on June 19th 2003. As can be seen from Figure 3, at the time of maximum saline intrusion penetration, the halocline is much higher downstream. Indeed at the mouth of Channel A, which is actually quite close to the mouth of the gorge, the salt water often breaches the surface. Thus, even though channel D has the deepest sill depth, it clearly is receiving salt water about 5m lower than the level seen in channel A.

5. CIRCULATION THROUGH SILL-TOP CHANNELS

Whilst the regional sill morphology controls the gross circulation, it is clear that the preferential erosive entrenchment of flow into the narrow sill-top channels is allowing enhanced exchange. The depth of the top of the sill surface is within the range of variations of the halocline depth. Cutting channels just an extra few metres down can improve exchange of the lower denser layer and maintain it for longer periods of the tidal cycle.

To examine the level of enhanced exchange in these channels, in July 2001, the UNB research vessel Mary-O was moored directly above the main channel B (yellow dot in Figure 2) and positioned using 4 anchors (Figure 4).

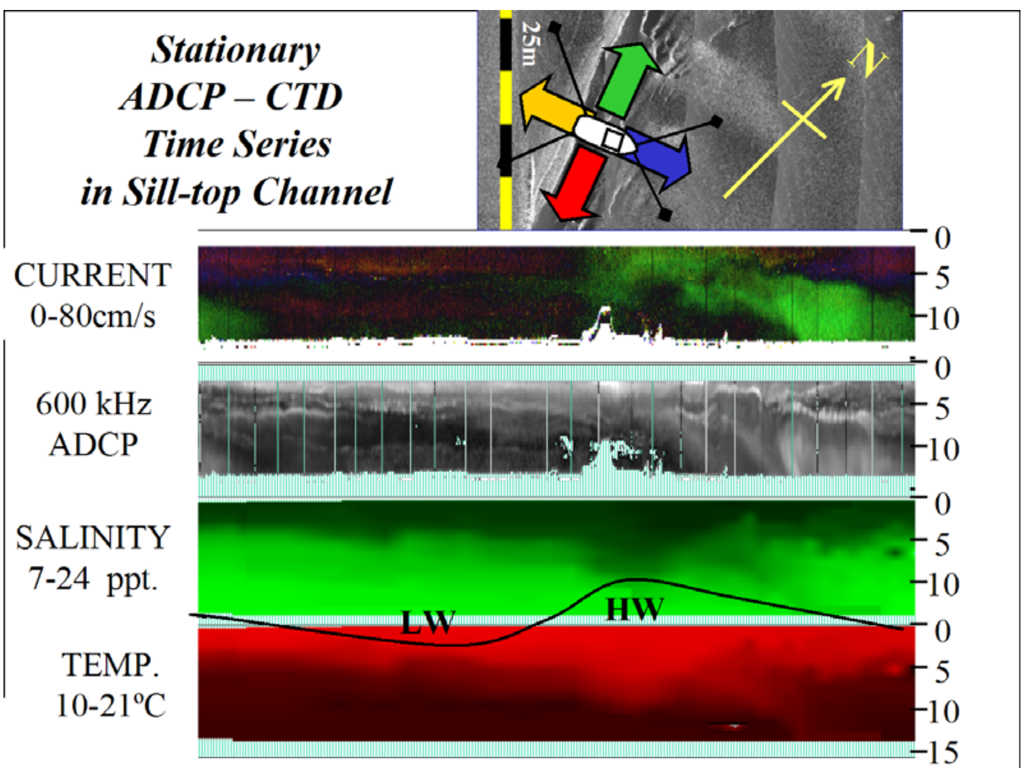

Figure 4. Showing a 12.42 hour time series of ADCP current and backscatter measurements together with CTD profiles within Channel B. The ADCP currents are presented current coded, the intensity being proportional to the magnitude of the current and the colour varying according to the azimuth (as shown by the arrows around the boat).

A 600 kHz ADCP was run at 1Hz for the full duration, together with a CTD at 15-minute intervals. The time series revealed that, just at high water, the surface water started to flow to the NNW along the channel axis, although initially there was no flow in the channel itself. Over the next 6 hours, the density of the NNW flowing water gradually increased (reflecting the greater percentage of saline waters intermixed as the salt water intrusion propagated up across the sill). As the density increased, the NNW directed flow drops into the channel itself, accelerating and reaching a peak velocity of ~80 cm/s about 4 hours after high water. It is this dense underflow with a peak salinity of 23 ppt that is probably responsible for the gradual erosion of the channels.

It is important to realise that, whilst the initial upstream intrusion is driven by the barotropic slope due to the advancing tide and the baroclinic slope due to the upper surface of the saline intrusion, once the intrusion has crested the top of the sill, the excess density in the intrusion actually drives the flow downhill, across the back of the sill in a self-sustaining manner. That flow will continue, as long as there is salt water at that level and it will flow down the sill until it reaches water of equivalent density.

6. EVIDENCE FOR FLOW SEPARATION AND HYDRAULIC JUMPS AT CHANNEL MOUTHS

Once the flow runs down the backside of the sill and meets the denser lower watermass at ~ 10-15 m in the Kennebecasis, the excess density disappears. At this point in time, two things happen. Firstly, the flow will no longer sink but flow out into the watermass along a pycnocline corresponding to the density of the mixed layer. That this occurs is clearly evident with the termination of any trace of channel morphology at depths below 15m (see Figure 5 below).

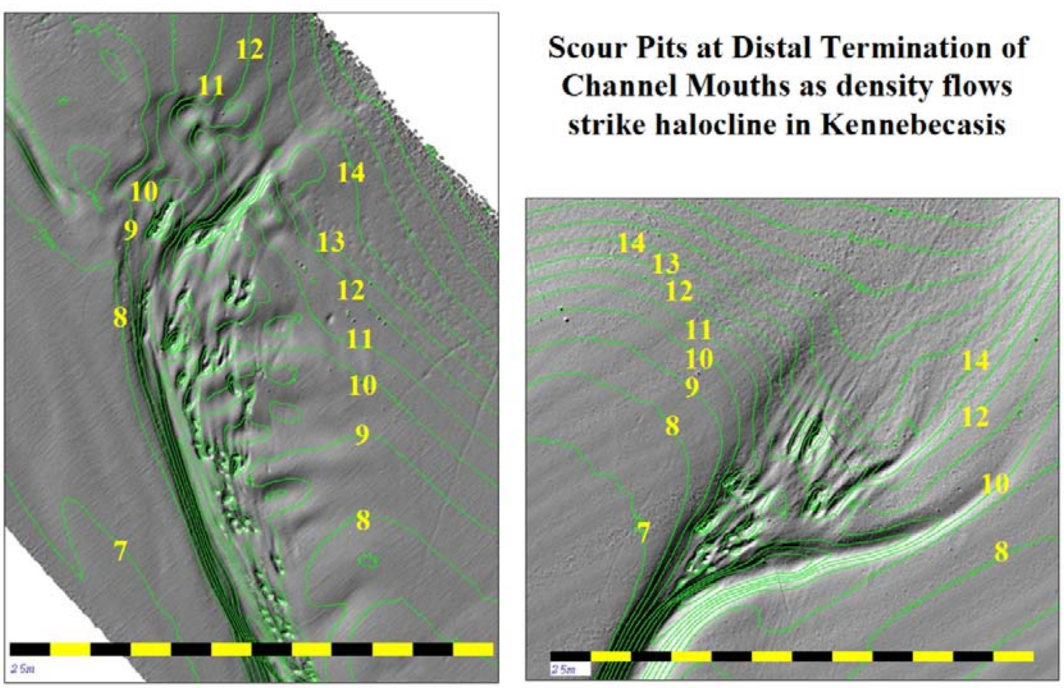

Figure 5. Showing the detailed morphology and bathymetry at the termination of the two incised channels across the sill. Areas displayed correspond to boxes, X and Y in Figure 2 above.

Secondly, as the high velocity constrained flow exits the channel mouth, the flow is now free to expand laterally causing abrupt deceleration, resulting in a hydraulic jump from super critical to subcritical flow. At this point, intense entrainment is inferred (Holland et al. 2002) and the location is often noted to be one of intense turbulence resulting in localized scour. Evidence for this hydraulic jump can be seen in the localized presence of scour pits (Figure 5) that occur at the point of contact of the dense flow with the lower dense water as it exits the three main channels cut into the back of the sill.

7. EVIDENCE OF TIMING OF FLOWS THROUGH THE VARIOUS SILL TOP PATHWAYS

In order to investigate the relative importance and timing of the four potential pathways, a second ADCP and underway CTD (MVP-30) 12.42 hour tidal cycle sequence was done on June 13th 2003, involving 20 lines across the sill, through the major sill-top conduit, along the face of the sill and into the distal Kennebecasis (Figure 6, white dotted line).

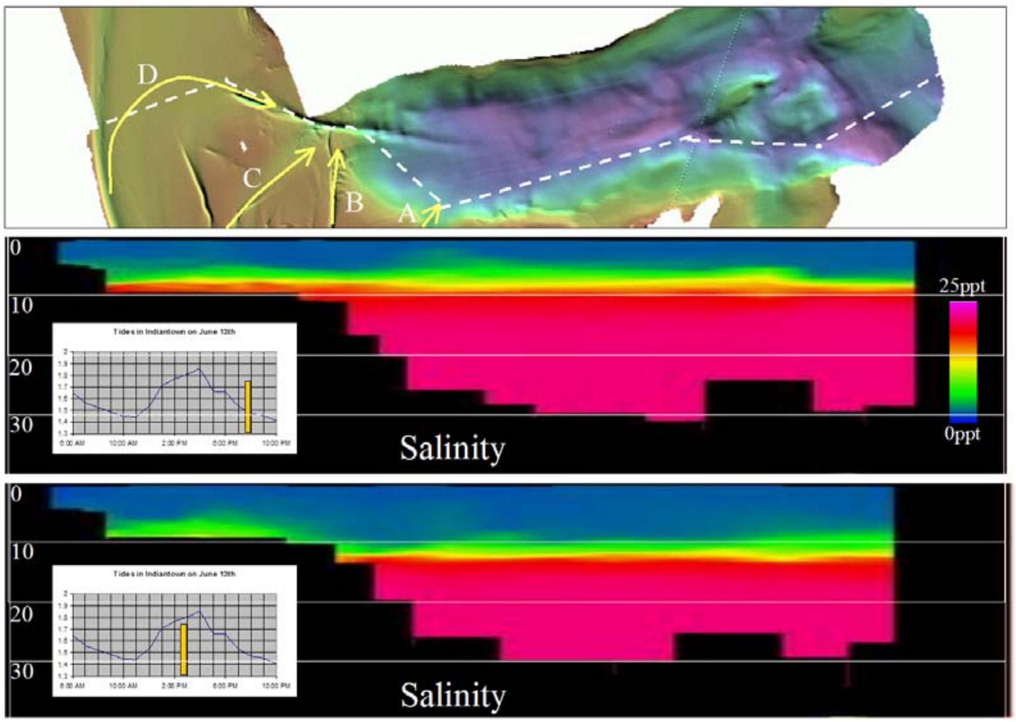

Figure 6. Showing the variations in the depth of the halocline over a tidal cycle in Kennebecasis Bay. A transect, outlined by the white dotted line, was run 20 times over a 12.42 hour tidal window.

Using this section we can investigate the time, depth and duration of intrusions across the sill into the Kennebecasis Fjord. Two main periods of north-easterly flow into the fjord were recognised. During the early to mid flood tide, the slightly brackish (~6-8ppt) water above the halocline was seen to flow into and along the fjord (Figure 7). This flow clearly does not emanate from the main sill channel (D). Thus it cannot be attributed to redirected downstream flow of the main river (which can be seen to still be continuing to the west, during the rising tide). Rather it would appear that this inflow is actually emanating from Channel A (note +ve, into-page radial flow corresponding to Channel A mouth) which implies that the near-surface, slightly-mixed water from the south end of Grand Bay is being pushed back over the Boars Head sill close to the southern boundary. This flow is slightly denser than the main upper fresh water layer in the Kennebecasis and thus is a sub-surface flow only. It probably represents the advancing edge of the new saline intrusion. Note that at this point the halocline in the fjord is at its most depressed lying at least 13m below the surface (Figure 6 bottom).

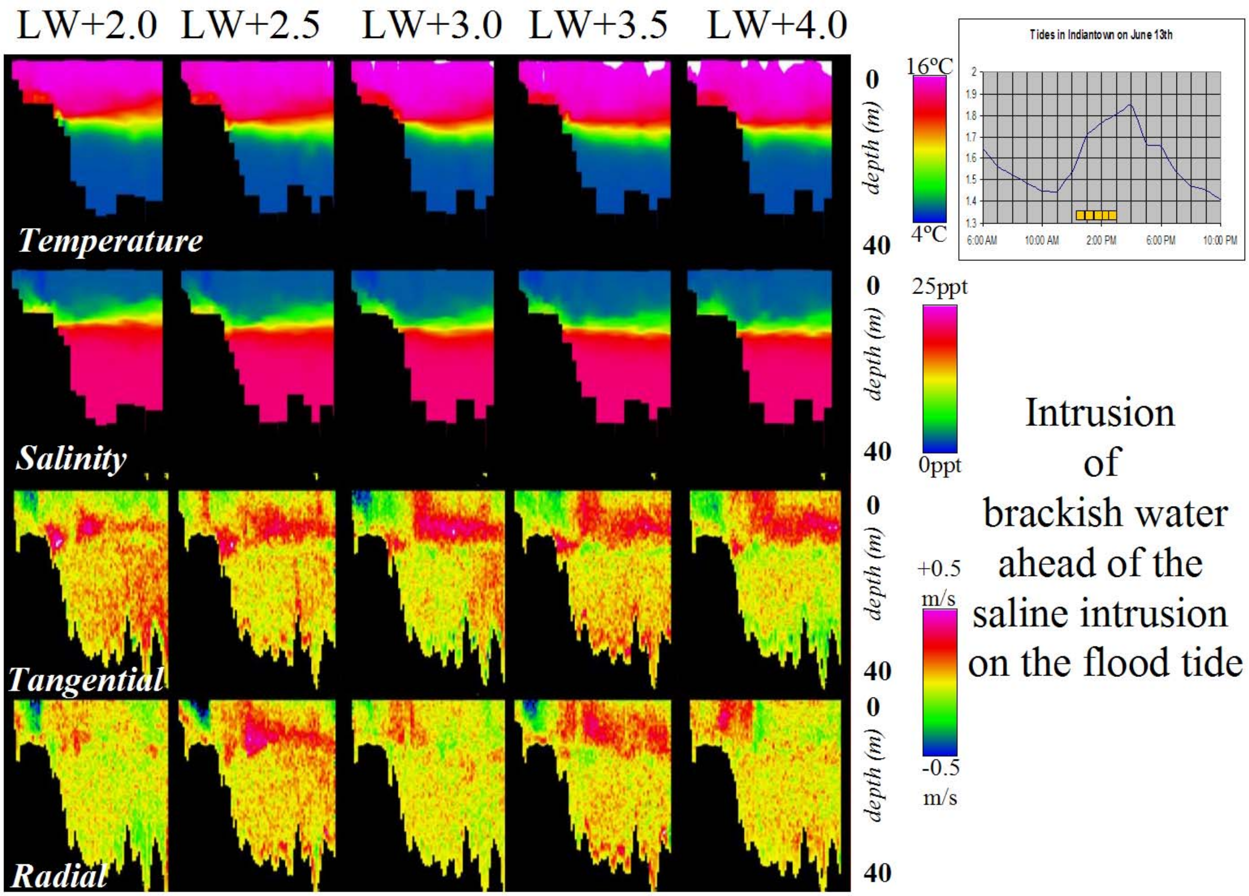

Figure 7. 5 images showing brackish intrusion into the Kennebecasis above the main halocline.

After high water, a second intrusion event occurs. This time (Figure 8) the intrusion takes place in the mixed waters (~10-16ppt) along the halocline itself. An apparent bore propagates out along the halocline, presumably reflecting the intermediate density of the intrusion. This bore propagates for several hours after the flow up the bypass channel has terminated. The nature of this intrusion, representing the densest water that managed to pass over the sill at this time, differs significantly from the exchange mechanism described by Trites (1960). In that work, a dense underflow, which displaced the pre-existing deep waters of the Kennebecasis, was postulated. In this case the intruding water is clearly less dense. This could be a combination of the degree of mixing over the sill, diluting and lightening the water, and/or the warmer nature of the intruding saline waters (~10 deg.C as opposed to the 4 deg. C of the pre-existing deep waters of the Fjord).

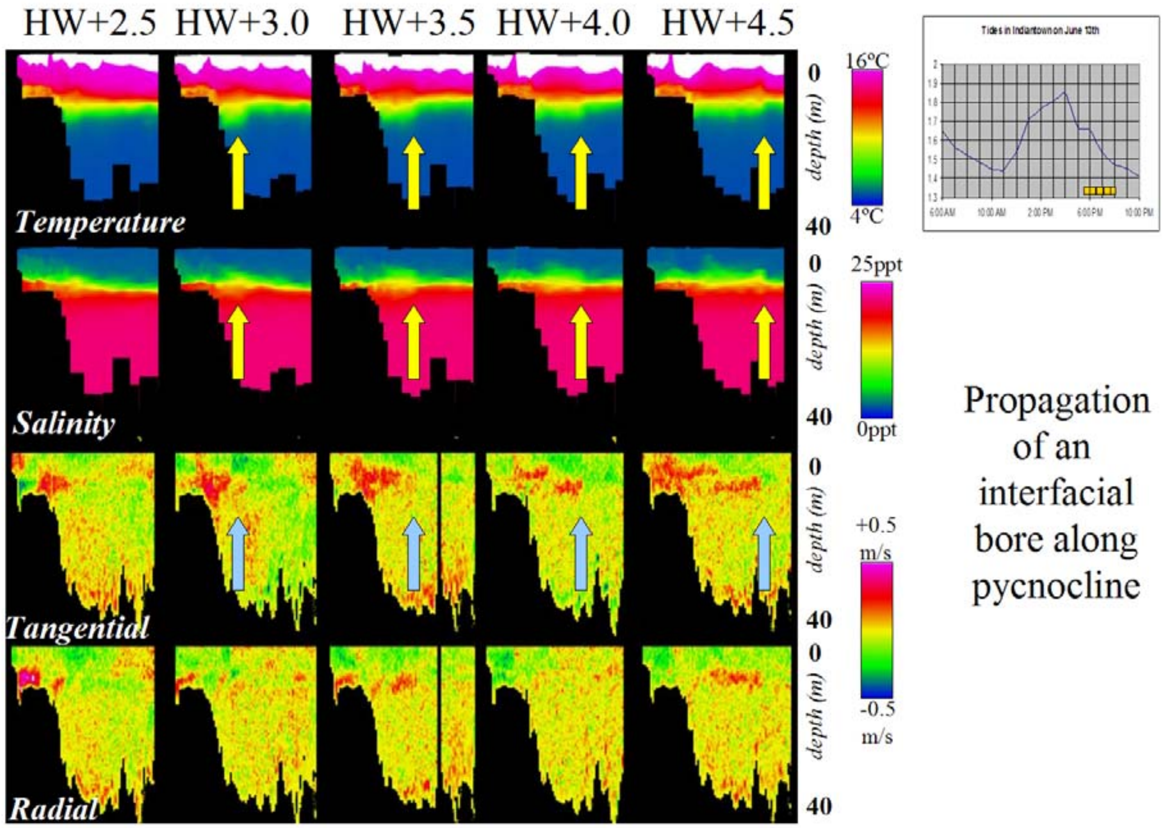

Figure 8. 5 images showing propagation of an interfacial bore along the pycnocline, propagating NE into the Kennebecasis.

8. CONCLUSIONS

Exchange and mixing of saline waters over the Grand Bay-Boars Head Sill region is seen to be strongly influenced by the constraining topography. The main exchange occurs along a bypass channel on the west side of Grand Bay, allowing discontinuous movement of water from the gorge north of the Reversing Falls into the Westfield Channel.

During the periods of maximum advance of the saline intrusion along that bypass channel, lateral diversion of some of this saline water occurs to the NE across the top of the sill, taking advantage of erosively-cut depressions. The fact that these depressions generally lie on the fjord side of the sill strongly suggests that the prime mechanism of erosion is density-driven currents tumbling down the backside of the sill.

On reaching the halocline on the fjord side of the sill, these channelized sill overflows leave the bottom and propagate out horizontally along an equivalent density contour. At this point, with the loss of lateral constriction, the flows appear to undergo a hydraulic jump as they decelerate and spread out.

The observed exchange over the Boars Head Sill differs significantly from others described in the literature. The main difference is the fact that the sill intrudes up to and above the mean level of the halocline. The flow takes place in layers, just a few metres thick at times, and is strongly influenced by sill morphology of that scale. In contrast to other sill exchange models, the flow here cannot be adequately modelled as a two dimension exchange owing to the three-way split of the watermasses and the strong three-dimensional bathymetric control.

9. ACKNOWLEDGEMENTS

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10. REFERENCES

Farmer, D.M. and Armi, L. 1986. Maximal two-layer exchange over a sill and through the combination of a sill and a contraction with barotropic flow. *J. Fluid Mech.*, 164: 53-76

Farmer, D. and Smith, J.D. 1980. Tidal interaction of a stratified flow with a sill in Knight Inlet. *Deep-Sea Res.*, 27a: 239-254.

Geyer, W.R., and Cannon, G.A. 1982. Sill processes related to deep-water renewal in a fjord. *J. Geophys. Res.*, 87: 7985–7996.

Hachey, H.B. 1935. Tidal mixing in an estuary. *J. Fish. Res. Bd. Canada*, 1(3) : 171-178.

Holland, D.H., Rosales, R.R., Stefanica, D. and Tabak, E.G. 2002 Internal hydraulic jumps and mixing in two-layer flows. *Journal of Fluid Mechanics*, 470: 63-83.

Klymak, J.K. and Gregg, M.C. 2001. Three-dimensional nature of flow near a sill. *Journal of Geophysical Research*, 106(C10): 22295-22311.

Lavelle, J.W., Cokelet, E.D. and Cannon, G.A. 1991. A model study of density intrusions into and circulation within a deep, silled estuary: Puget Sound. *J. Geophys. Res.*, 96: 16779–16800.

Metcalfe, C.D., Dadswell, M.J., Gillis, G.F. and Thomas, M.L.H. 1976. *Physical, Chemical and Biological Parameters of the Saint John River Estuary, New Brunswick, Canada*. Fisheries and Marine Service, Environment Canada, Technical Report # 686, 42pp.

Neu, H.A. 1960. *Hydrographic Survey of Saint John Harbour, N.B.* National Research Council of Canada, Mechanical Engineering Report, MH-97, 196pp.

Torrie, I.D. 1985. *Physiography and hydropgraphy at the mouth of Kennebecasis Bay, N.B*. Honours Thesis, University of New Brunswick, Saint John, NB, Canada.

Trites, R.W. 1960. An oceanographic and biological reconnaissance of Kennebecasis Bay and the Saint John River Estuary. *Journal of the Fisheries Research Board of Canda*, 17(3): 377-408.