*E-proceedings of the 38th IAHR World Congress*
*September 1-6, 2019, Panama City, Panama*
doi:10.3850/38WC092019-0895

# THREE-DIMENSIONAL MODELLING OF HYDRODYNAMICS AND THERMOSALINE CIRCULATION IN THE SAINT JOHN RIVER ESTUARY, CANADA

IVANA VOUK[(1)], ENDA MURPHY[(2)], IAN CHURCH[(3)], ABHOLGHASEM PILECHI[(4)] & ANDREW CORNETT[(5)]

[(1,2,4,5)] Ocean, Coastal and River Engineering Research Centre, National Research Council of Canada, Ottawa, Canada,
Ivana.Vouk@nrc-cnrc.gc.ca, Enda.Murphy@nrc-cnrc.gc.ca, Abolghasem.Pilechi@nrc-cnrc.gc.ca, Andrew.Cornett@nrc-cnrc.gc.ca
[(3)] Ocean Mapping Group, Department of Geodesy and Geomatics Engineering, University of New Brunswick, Fredericton, Canada,
Ian.Church@unb.ca

## ABSTRACT

From sources in Canada and the United States, the Saint John River traverses more than 670 km before entering the Bay of Fundy at Saint John, New Brunswick. Mixing and exchange of fresh and salt water between the Saint John River, the adjoining Kennebecasis Fjord and the sea is driven by strong tides in the Bay of Fundy and fluvial flows, which are seasonal and highly variable. Upstream of the Port of Saint John, the bathymetry features a series of shallow sills and deep gorges. Estuarine mixing processes are controlled by a natural sill near the mouth of the river, known as the Reversing Falls. The restriction causes a turbulent rapid to form flowing upstream with the flood tide, which then reverses and flows downstream with the ebb tide. Although tides are damped by the Reversing Falls, intermittent discharges of saline water over the sill during the flood tide can accumulate in deeper parts of the estuary and penetrate more than 30 km upstream depending on seasonal river flows. A three-dimensional, baroclinic numerical model of the Saint John Estuary was developed based on the TELEMAC-3D finite volume solver to simulate hydrodynamics and circulation. The model setup, calibration and validation processes relied on field data derived from a multi-year campaign of bathymetric surveys and oceanographic measurements, conducted by the University of New Brunswick's Ocean Mapping Group. The data included high resolution, multibeam bathymetric survey data, acoustic Doppler current profiles, and conductivity-temperature-depth measurements. The model has become a useful tool for assessing water exchange, water quality issues (e.g., fate and transport of effluent discharges), and the potential impacts of development within this dynamic estuary.

**Keywords:** Estuarine hydrodynamics; three-dimensional hydrodynamic model; tidal hydrodynamics; numerical model; baroclinic estuarine circulation.

## 1 INTRODUCTION

The Saint John River (SJR), whose traditional name is Wolastoq ('*beautiful and bountiful river*'), drains an area extending over 55,900 km$^2$ through parts of the State of Maine, U.S.A., and the Provinces of Quebec and New Brunswick in Canada (Figure 1). The river travels 673 km before flowing south into the Bay of Fundy at Saint John. The bathymetry of the SJR estuary is complex, with deep pools and gorges, and shallow sills. From Evandale, New Brunswick, the river flows through a geologic feature known as Long Reach, where depths range from 10 m to 40 m. Downstream of Long Reach, the SJR traverses two sills before discharging into Grand Bay at the confluence with the Kennebecasis River. The latter is a fjord with water depths of up to 70 m, connected to the SJR via an abrupt sill with carved channels scoured by currents (Delpeche, 2007; UNB, 2018). From Grand Bay, the SJR flows through a deep narrow section and over the Reversing Falls sill (hereafter referred to as the Falls), followed by a series of deep pools and narrow channels, to the Saint John harbour. The Falls, with depths of approximately 5 m at mean tide, is the shallowest and most downstream sill in the lower SJR (Metcalfe *et al.*, 1976). The constriction created by the Falls morphology and the large tidal range in the Bay of Fundy at the mouth of the SJR cause large rapids to form flowing upstream with the flood tide, which then reverse and flow downstream with the ebb tide. The tides at Saint John are semi-diurnal, rising and falling twice daily over a range that varies from 5.5 m to 8.5 m in the harbour. The discharge past the Reversing Falls is seasonal and highly variable, depending on the tides and the freshwater inflow.

A three-dimensional, numerical hydrodynamic model of the SJR estuary, which included temperature and salinity effects, was developed in TELEMAC-3D to simulate hydrodynamic conditions and circulation in the lower estuary. The hydrodynamic model was developed, and then calibrated and validated, using extensive bathymetric and oceanographic datasets provided by the University of New Brunswick's Ocean Mapping Group (OMG). The model was used to investigate the role of the Reversing Falls in controlling hydrodynamics and circulation in the lower estuary, and to investigate the dispersion and transport of effluent plumes (not described in this paper).

 

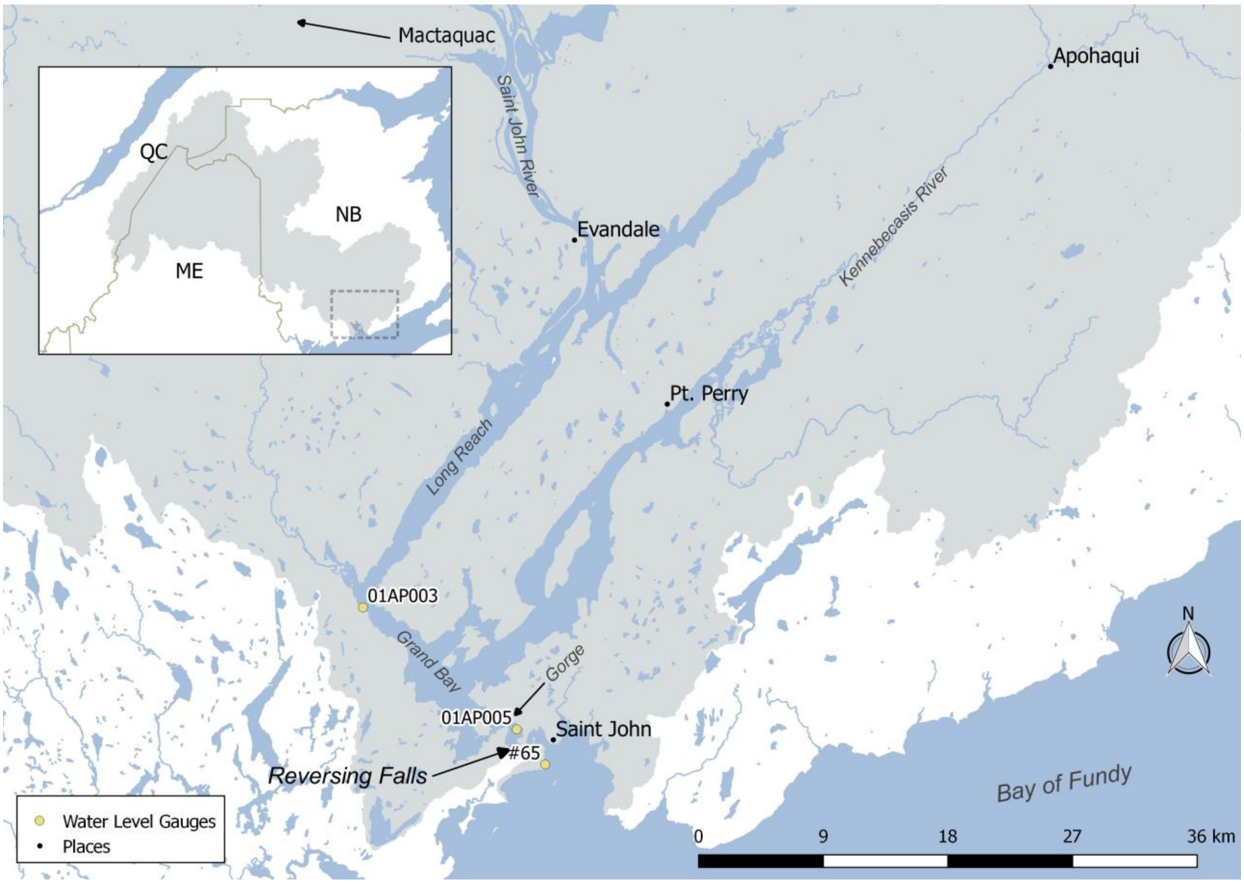


**Figure 1.** Map indicating key locations discussed in the paper.

## 2 HYDRODYNAMIC CONDITIONS

### 2.1 Bathymetry

OMG collected seabed bathymetry data in the SJR estuary and harbour between 2000 and 2009 (Figure 2). The data comprise of 15 high-frequency (i.e., 300 kHz) multibeam sonar surveys, each processed to provide georeferenced depth soundings, analyzed for noise and artifacts and transformed to a common horizontal and vertical datum. These data were combined and used to define the bathymetry throughout much of the hydrodynamic model domain. The Canadian Hydrographic Service (CHS) provided nautical charts, single-beam survey soundings in the lower SJR and high-resolution gridded data derived from multibeam surveys in the harbour, complementing the OMG data gaps. The bathymetry datasets were referenced to a common horizontal coordinate system and vertical datum to create a uniform digital elevation model of the SJR estuary bathymetry.

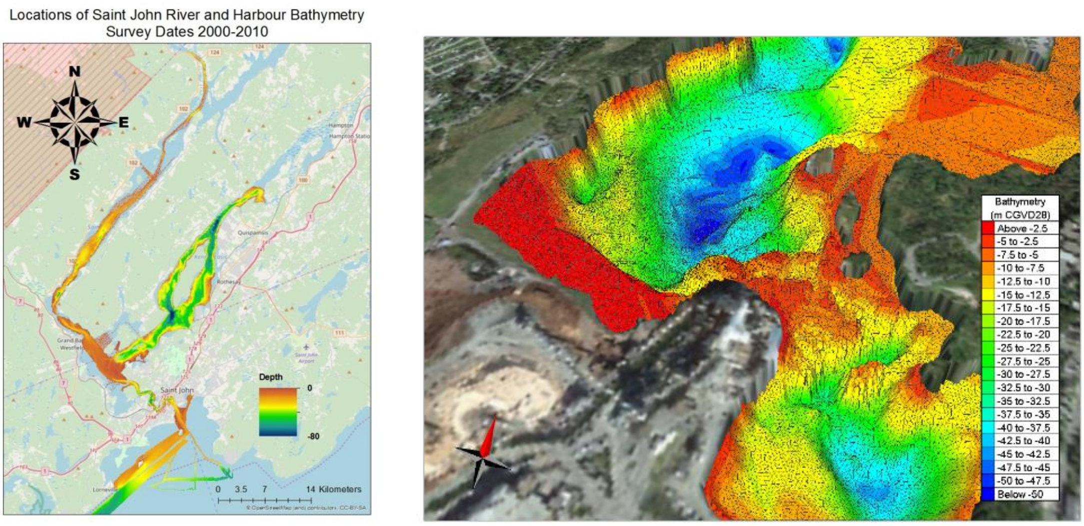


**Figure 2.** SJR estuary bathymetry (left) and close-up of the Reversing Falls sill (right).

2.2 Water levels and tides

The closest active gauges upstream of the Falls are located in the city of Saint John (i.e., station 01AP005) and at Oak Point (i.e., station 01AP003). Both stations are operated by the Water Survey of Canada (WSC) and provide hourly water level data. Hourly water level measurements for the harbour are available from a permanent CHS tide gauge situated in the Port of Saint John (i.e., station #65). Water levels measured at the three gauges indicate a large difference in tidal ranges and mean water levels above and below the Falls. Water levels (and tide-driven fluxes) outside Saint John Harbour were obtained from the National Research Council Canada's two-dimensional (depth-averaged), tidal hydrodynamic model of the Gulf of Maine and the Bay of Fundy, described by Cornett *et al.* (2010).

2.3 Flows

Freshwater flow data into the SJR estuary were provided by NB Power in the form of hourly discharge at the Mactaquac Dam tailrace. The flow variation is seasonal with discharges exceeding 10,000 $m^3/s$ during spring freshet, annual average flows of 800 $m^3/s$, and typical low flows during winter on the order of 300 $m^3/s$. The nearest active WSC gauging station to the Falls is on the Kennebacasis River at Apohaqui (i.e., station 01AP004) whose flow, significantly lower than the SJR, is typically less than 5% of flow at Mactaquac and consistent with the much smaller catchment area of the Kennebacasis River. Several studies have estimated discharge relative to water level at the 01AP005 gauge, and a summary of those findings are described in Leys (2007) (Neu, 1960; Hansen, 1970; Environment Canada, 1973; Leys, 2007).

Flushing rates within the estuary were calculated by Metcalfe *et al.* (1976) and provide a rough indication of the mean residence time of soluble contaminants released to different areas. The results indicate that flushing times at the Falls are strongly dependent on river flows. For daily mean discharges less than 150 $m^3/s$ (categorized by Metcalfe et al. (1967) as low flows), flushing times are reported on the order of 40 days. For flows around 500 $m^3/s$, this time decreases to 10 days. For high flows consistent with a strong freshet (daily averages around 4,700 $m^3/s$) flushing is rapid (less than one tidal period).

2.4 Water currents, temperature and salinity

The OMG has been collecting water current velocities from a vessel mounted Acoustic Doppler Current Profiler (ADCP) and salinity and temperature data using a Moving Vessel Profiler (MVP) in the SJR estuary since 2001 (Haigh & Hughes-Clarke, 2005; Delpeche, 2007; Toodesh, 2012; Church, 2014). Many of the surveys have been analyzed and some are briefly discussed here to provide contextual background on circulation and stratification in the estuary.

Delpeche (2007) demonstrates that the mixing and density stratification within Long Reach varies throughout the year and depends on the presence of spring or neap tides. At high tide, the denser, saline water layer moves upstream on the bottom (i.e., opposing the flow direction of the overlying freshwater layer). At low tide, both the upper and lower layers flow downstream towards the harbour, but the water column remains strongly stratified. At the start of the flood tide, the saltwater layer reverses direction and begins to migrate back upstream. The intrusion of salt water propagating up the SJR and passing into Kennebecasis River is tied to the tidal elevation (Hughes-Clarke & Haigh, 2005). Haigh & Hughes-Clarke (2005) observed that the Kennebecasis River generally exhibits stable density stratification, due to the pronounced density difference between the cooler saltwater near the bed and the warmer surface freshwater, and the trapping effect of the downstream sill.

2.5 Wind

Although wind plays a relatively minor role in directly driving circulation within the Saint John Estuary (Toodesh, 2007), initial numerical model testing suggested wind may have an important influence on stratification through its role in affecting air-water heat exchange. Available wind and air temperature datasets from the Saint John Airport were used to support investigation of the relative importance of air-sea heat exchange effects on density stratification and constituent fate and transport.

## 3 HYDRODYNAMIC MODELLING

A three-dimensional, baroclinic hydrodynamic model of the SJR estuary was developed to gain insight to the influence of the Falls on hydrodynamics and circulation, and to provide a tool for investigating water exchange and water quality.

3.1 Hydrodynamic modelling software – TELEMAC-3D

The hydrodynamic model was developed using TELEMAC-3D, part of the TELEMAC finite element and finite volume-based hydrodynamic modelling system (Hervouet, 2007). TELEMAC-3D solves the non-hydrostatic Navier-Stokes equations that describe free surface flow in three dimensions, on unstructured (flexible) computational meshes, typically consisting of triangular prisms. Wetting and drying capabilities are provided to effectively model intertidal areas and floodplains. TELEMAC-3D includes the capability to simulate baroclinic advection-dispersion, which allows parameters such as water temperature and salinity (and associated effects on water density) to be simulated. It includes a module for tracer (conservative and decaying) transport and diffusion, making it ideal for plume dispersion studies.

3.2 Hydrodynamic model setup

The computational domain of the hydrodynamic model was set up to reflect the available field data and to capture interactions between freshwater flows in the SJR estuary and the saline water from the Bay of Fundy, which penetrates upstream in response to tidal forcing. Two upstream freshwater flow boundaries were assigned, near Evandale on the SJR and Perry Point on the Kennebecasis River (Figure 3). A single tidal boundary was assigned in the Bay of Fundy, approximately 15 km seaward of Saint John Harbour. The model domain is approximately 75 km long from Evandale to the open sea boundary in the Bay of Fundy. The model domain extends significantly beyond (upstream and downstream of) the important Reversing Falls feature to properly simulate interactions between fresh and saline water in the lower estuary, and to minimize interactions between the SJR freshwater plume and the downstream model boundary.

The model's computational mesh consists of triangular prisms with characteristic edge lengths ranging in size from approximately 5 m to 2500 m, organized into ten sigma (bathymetrically conforming) layers. The horizontal mesh resolution was increased in the vicinity of the Reversing Falls region to better resolve the complex bathymetric features affecting local hydrodynamics in the area. The vertical resolution was increased near the surface and the estuary bed to capture vertical heterogeneity in temperature and salinity profiles near the Falls, which periodically alternated between thin freshwater layers at the surface and a thin salt wedge near the bed.

Freshwater inflows were prescribed at the SJR upstream boundary based on measured flow rates at Mactaquac Dam scaled by a factor of 1.3, approximately proportionate to the area of the watershed between the dam and the model boundary that is not reflected in the measured data. Freshwater inflows were prescribed at the Kennebecasis River boundary based on gauge 01AP004. The downstream open boundary of the model in the Bay of Fundy was forced by tidal elevations and depth-averaged velocities obtained from the tidal model described in Cornett *et al.* (2010). A logarithmic velocity profile in the vertical was assumed when applying the depth averaged velocity output as boundary condition input to the SJR estuary hydrodynamic model. Spatially and temporally constant water temperatures and salinities were applied along the upstream and downstream open water boundaries of the model.

A constant model time step of 10 seconds was selected to satisfy Courant stability criteria. Model output was saved at 15-minute increments to temporally resolve the changing hydrodynamic conditions, water temperatures and salinities in response to tides and river flow.

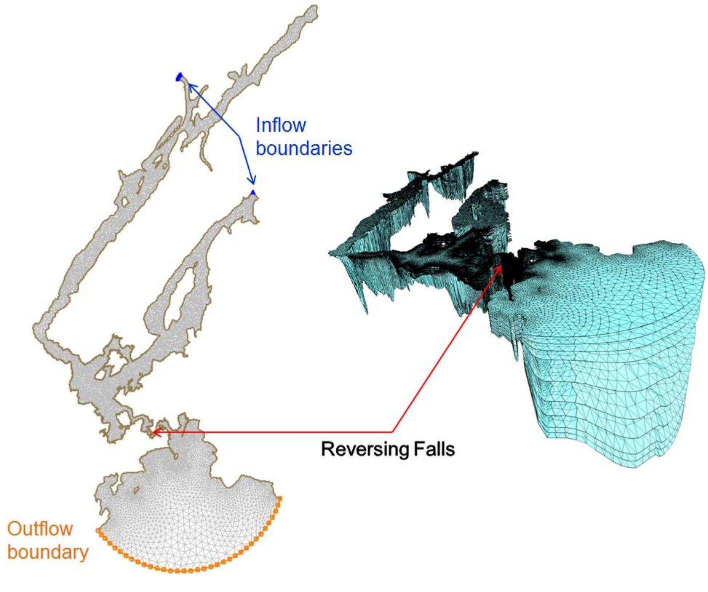


**Figure 3.** Example of the model's boundaries, and horizontal and vertical mesh.

3.3 Hydrodynamic modelling scenarios

Three scenarios were simulated and used as the basis for model calibration and validation, and to establish a broad range of river flow and tidal hydrodynamic conditions at the Falls. These were selected to encompass:

- periods of available ADCP and MVP data both upstream and downstream of the Falls;
- a range of seasonal conditions (and the associated range in stratification levels in the upper estuary);
- a broad range of river flow conditions at Mactaquac; and
- broad variations in tidal range.

The duration of each simulation was 41 days, spanning two full spring-neap tidal cycles (i.e., 30 days) and up to 11 days of model spin-up. Water temperatures and salinities at the upstream (freshwater) and downstream (Bay of Fundy) model boundaries were prescribed and are based on seasonally representative (i.e., summer – July/August, fall – October/November, and spring freshet – April/May) field data.

3.4 Hydrodynamic model calibration and validation

The hydrodynamic model was calibrated (using the summer simulation) by adjusting model input variables, comparing the predicted water levels, velocities and temperature / salinity profiles to measured values, and then assessing the quality of fit between the predictions and observations. The main input variables adjusted as part of the model calibration process were bed roughness, turbulence parameters, vertical discretization (i.e., number of layers, resolution, and refinement), and air-water heat exchange parameters. Observed (measured) and simulated (modelled) water levels are compared in Figure 4 for three water level gauge locations and the final set of calibrated model input parameters. The model effectively captures the significant reduction in tidal range moving upstream from Saint John Harbour past the Falls and into the estuary, as tides are damped by the shallow sill. Lower frequency variations in river water levels at the 01AP005 gauge, driven by changes in fluvial discharges, are also captured. Further upstream at gauge 01AP003, the tidal range is over-predicted by the model. Further calibration effort could potentially lead to improved prediction of upstream water levels; however, the performance of the model in this region is likely impacted by poor bathymetric data coverage in some shallow areas of the upper watershed, and a lack of long-term river flow data downstream of the Mactaquac Dam closer to the model boundary. Nevertheless, the model performance in predicting water level fluctuations in the vicinity of the Falls is satisfactory.

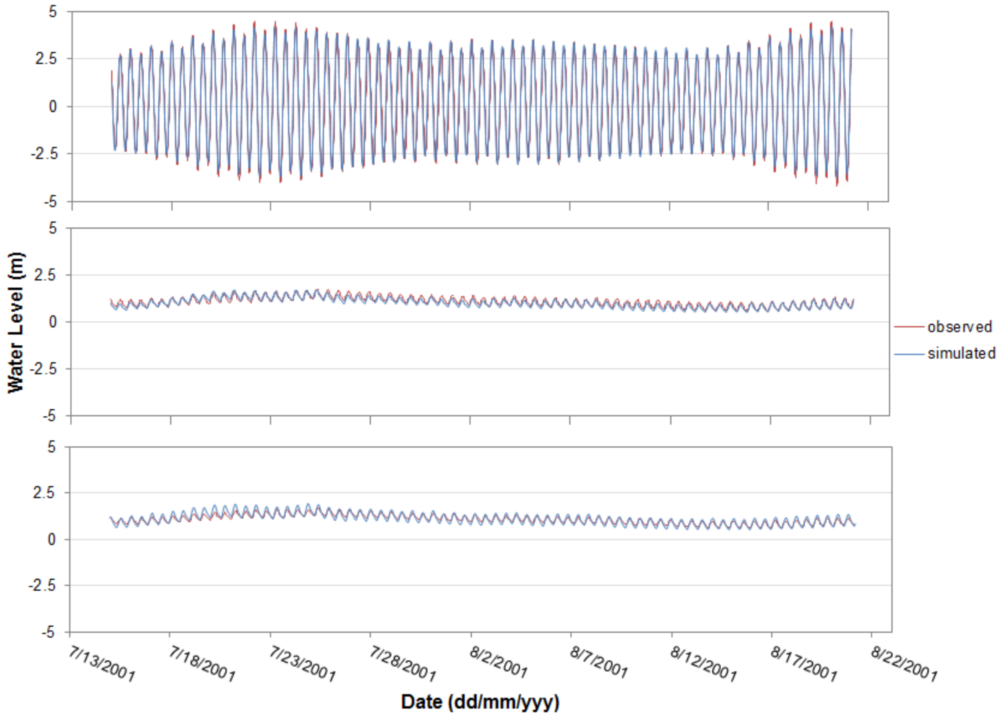


**Figure 4.** Observed and simulated surface water levels at gauge locations for the summer scenario.

Observed and simulated temperature and salinity profiles at Gorge, approximately 3.5 km upstream of the Falls, are shown in Figure 5, for hourly intervals over a full tidal cycle. Also, shown is a continuous time series (i.e., over a full tidal cycle which equals to approximately 12.5 hours defined by a 360° phase) of the measured profiles, along with water levels and velocities throughout the water column. The measured profiles were collected in 2001 during the summer (coinciding with the modelled summer scenario period) and developed by Haigh & Hughes-Clarke (2005). The range and temporal variability of the velocity, temperature and salinity profiles are captured by the model. However, the modelled profiles tend to be more homogeneous in the vertical than the measured profiles at Gorge, particularly with respect to temperature and salinity. Increasing the number of model layers and/or increasing model spin-up time could potentially improve the model's ability to capture strong gradients and predict temperature and salinity profiles in deeper areas (such as Gorge) but would also increase computational demands. Calibration testing with different vertical discretization configurations (e.g., combined sigma and fixed layer systems) did not result in significant improvements in model performance.

Once the final model parameter inputs were established through calibration based on the summer scenario, simulations were performed for the fall and spring freshet periods using the calibrated model inputs.

 

The goodness-of-fit between measured and modelled water levels was re-assessed (validation). Observed and simulated water levels for the fall (for this period only, partial information was available) and spring freshet scenarios are shown in Figure 5 for the three gauge locations and the final model input parameters. The measured and modelled tidal range and phase are in reasonable agreement at all three gauge locations. General water level trends associated with lower frequency (river flow-driven) fluctuations are also captured but total water levels are under-predicted during moderate to low river flow conditions. This may be associated with the fixed scaling of Mactaquac flows at the upstream boundary, and could potentially be addressed in the future by further hydrologic analysis, and/or short-term gauging of flows at Evandale to establish an improved correlation with flows at Mactaquac.

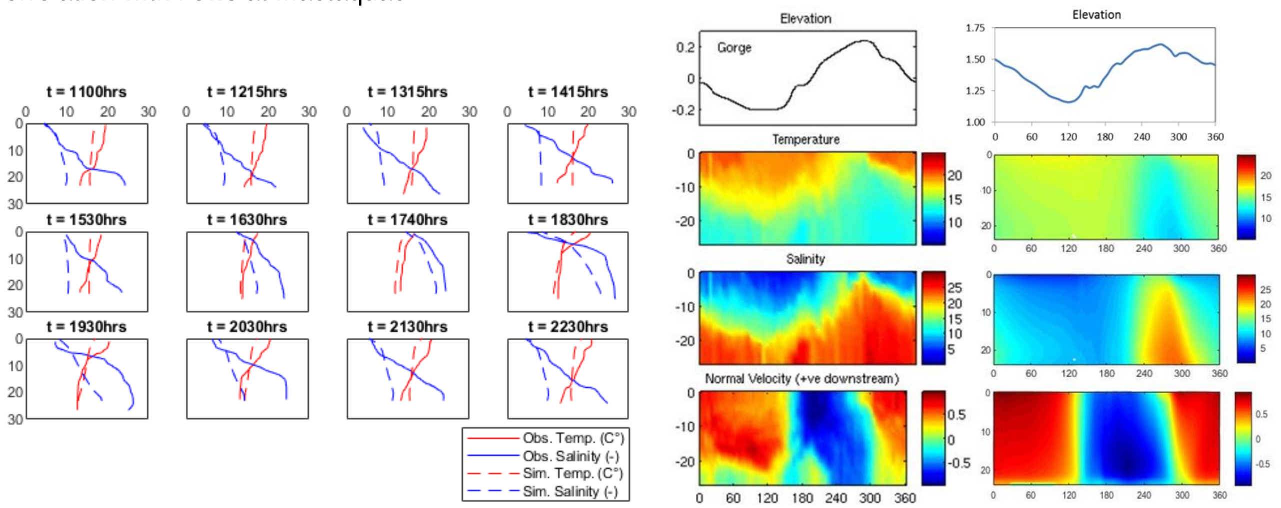


**Figure 5.** Hourly intervals (left) and continuous time-series (right) of observed (Haigh & Hughes-Clarke, 2005) and simulated vertical profiles.

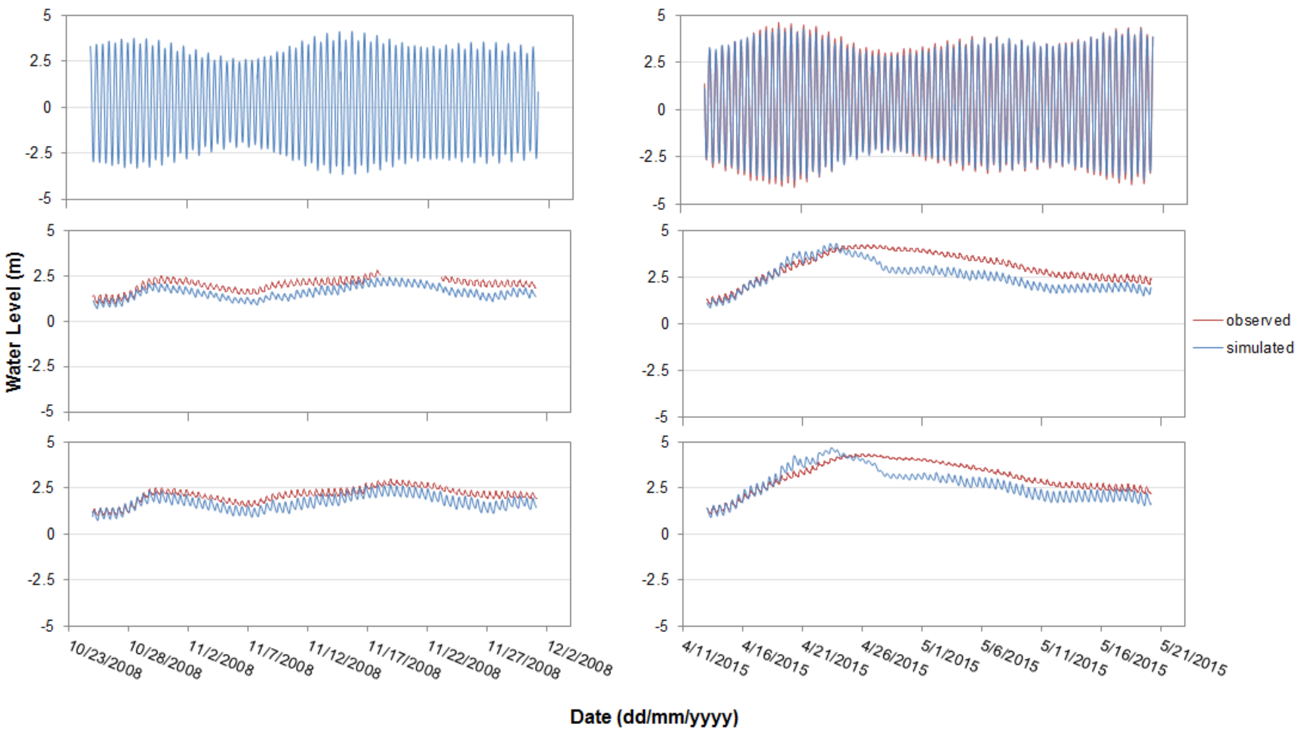


**Figure 6.** Observed and simulated surface water levels at gauge locations for the fall (left) and spring freshet (right) model simulation.

3.5 Calibrated model parameters

The final calibrated model parameters are as follows:

- Bed roughness – the Strickler law (Mattic, 2018) was used with friction coefficients in the range 15 to 40 $m^{1/3}/s$ depending on the water depth;
- Horizontal turbulence parameters – a constant viscosity model was selected with eddy viscosity and dispersion coefficients of 0.01 $m^2/s$;

- Vertical turbulence parameters - mixing length model (Prandtl, 1925; as cited in Hervouet, 2007) and the mixing length profile of Tsanis (1989), as cited in Hervouet (2007);
- Air-water heat exchange was included based on the model of Sweers (1976), which determines air-water heat fluxes based on the air-water temperature differential and wind speed. Temporally varying but spatially uniform wind speeds and air temperatures were specified as input based on measurements at Saint John Airport downloaded from Environment & Climate Change Canada online archives.

## 4 HYDRODYNAMIC MODEL RESULTS AND DISCUSSION

Time series of modelled water levels for all three scenarios (summer, fall and spring freshet) are shown in Figure 7 for the harbour, immediately downstream of the Falls (below RF) and immediately upstream of the Falls (above RF). The control exerted by the Falls sill on water levels in the lower estuary is evident, with the tidal range decreasing by an order of magnitude across the sill (from downstream to upstream), and a mean water level difference of approximately 0.5 m. Mean water levels in the estuary upstream of the Falls are dominated by fluvial discharges, which are strongly seasonal (e.g., higher mean water levels coincide with higher fluvial discharges during the freshet). These results are consistent with previous field and numerical modelling studies in the region (Neu, 1960; Metcalfe, 1976; Haigh & Hughes-Clarke, 2005; Delpeche, 2007; Church, 2014; Church *et al.*, 2017). A comparison of analyzed harmonic constituents at a privately operated gauge directly downstream of the Falls and the 01AP005 gauge, located 1.1 km upstream of the Falls, demonstrates the immense damping power of the Falls. The same comparison was made using equivalent locations in the model. The gauges indicate that the principal semi-diurnal constituent, M2, is reduced in amplitude by 1.8 m, while the model predicts a 2.0 m reduction. An examination of the seven leading constituent amplitudes (i.e. sum of M2, N2, M4, S2, M6, K1 and O1) shows a 5.5 m reduction in measured tide range, versus a modelled reduction of 5.7 m.

For a period of about 9 days during the spring freshet scenario when fluvial discharge is highest (shaded blue area in Figure 7), water levels upstream of the sill exceed downstream water levels throughout the full duration of each tidal cycle, implying a continuous flow downstream towards the harbour. Flow reversal does not occur at the Falls under these circumstances, an interesting phenomenon consistent with anecdotal evidence and other studies in the region (Metcalf, 1976; Delpeche, 2007).

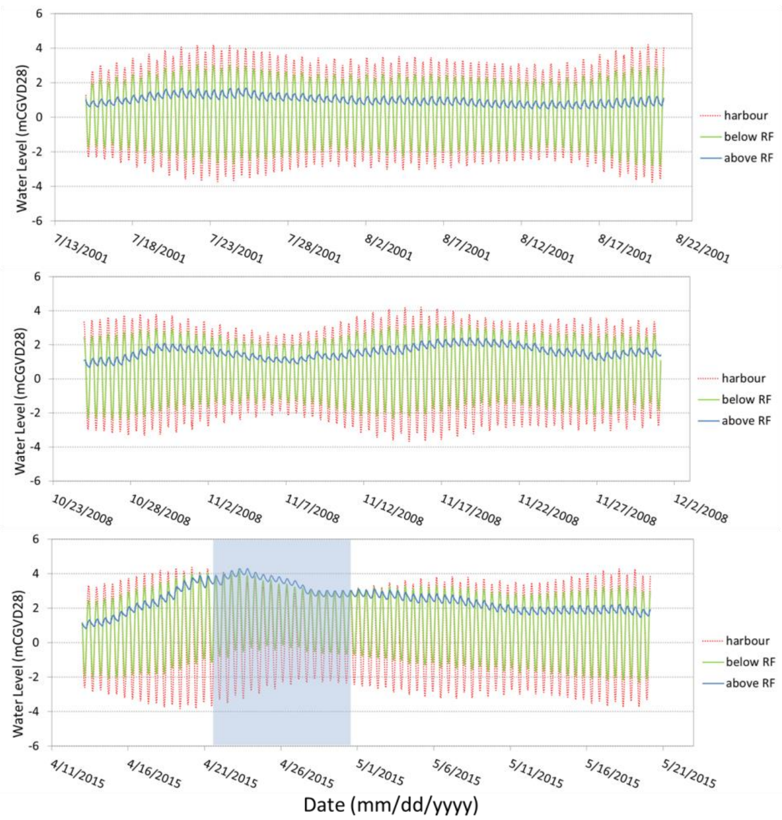


**Figure 7.** Modelled water levels at three different locations for three scenarios: summer (top), fall (middle) and spring freshet (bottom).

Instantaneous snapshots of depth averaged current speeds near the Falls during low (i.e., summer) and high (i.e., winter) river flow conditions are shown in Figure 8. During low flow conditions, peak current speeds occur during the ebb tide when river flows augment tidal flows out of the estuary. Highly turbulent regions and recirculating eddies form around the island located north-northeast (NNE) and west (W) of the Falls. Depth averaged current speeds decrease in the deeper waters on either side of the sill. Recirculating eddies occur in the embayments on either side of the peninsula W of the Falls, driven by strong velocity shear associated with the jet-like flows over the Falls. These lateral eddy patterns and strong gradients in free surface elevation are qualitatively consistent with available satellite imagery and observations during a site visit by the authors. During the flood tide, river flows counteract tide-driven flows and peak current speeds at the Falls are lower than during the ebb. The Falls create a highly dynamic environment, with high ambient flow speeds and intense turbulence. By comparison, a relatively quiescent environment exists directly S of the Falls, with ambient flows characterized by a rotational gyre/eddy, which flows clockwise during the ebb tide and counter-clockwise during the flood tide. During high river flows, the general patterns of flow and recirculation are similar to those described above for low river flow conditions. However, the current speeds during ebb tidal conditions are increased relative to low river flow conditions (due to augmentation of tide-driven flows by river flows). Conversely, current speeds during the flood tide are decreased because the tidal flows and high river discharges oppose each other. During ebb tides, two standing waves are discernable and more pronounced during high river flows. The Falls create highly turbulent environment, while downstream the ebb tidal current speeds are higher than during summer low river flow conditions.

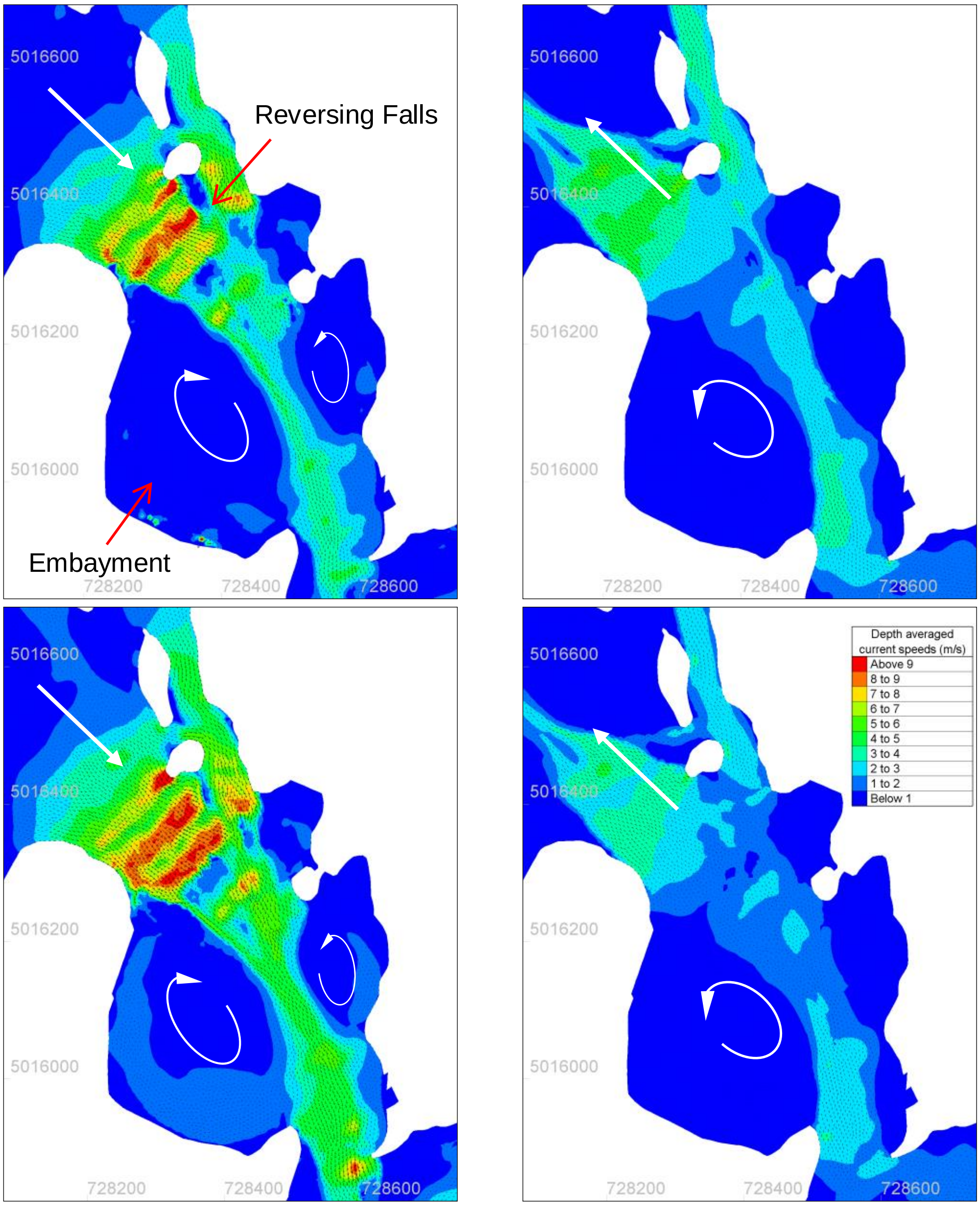


**Figure 8.** Contours and velocity vectors of depth-averaged current speed at the Reversing Falls during low (above) and high (below) river flow and ebb (left) / flood (right) tidal conditions.

Rose plots showing the directional distribution of depth average current speeds of the Falls for the three modelled scenarios are shown in Figure 9. The predicted currents are distinctly bi-directional, oriented along the axis of the main channel and perpendicular to the Falls sill, towards the WNW during flood tidal conditions and towards the ESE during ebb. The frequency and magnitude of flood tidal currents are reduced for the spring freshet scenario compared to the other two, due to ebb dominance associated with strong river flows. In the embayment directly downstream of the Falls predicted currents (plots not shown) are distinctly bi-directional, oriented parallel to the W shoreline and towards the SSW during flood tidal conditions and towards the N/NNE during ebb. These flow directions reflect the flow patterns associated with the rotational gyre/eddy in the bay to the SE of the Falls, which flows counterclockwise during flood tide and clockwise during the ebb tide. N/NNE flow directions are more prevalent during the spring freshet scenario, due to the ebb dominance associated with strong river flows.

Velocity exceedance curves for all three modelled scenarios at the two sites (noted in Figure 8) are shown in Figure 10. The exceedance curves beside the Falls indicate that depth-averaged current speeds exceed 0.2 m/s for more than 99% of the time and 1 m/s for more than 93% of the time, confirming the extremely dynamic flow conditions at the site. Depth-averaged velocity magnitudes are significantly less at the downstream site; however, they still exceed 0.4 m/s for the majority of the time.

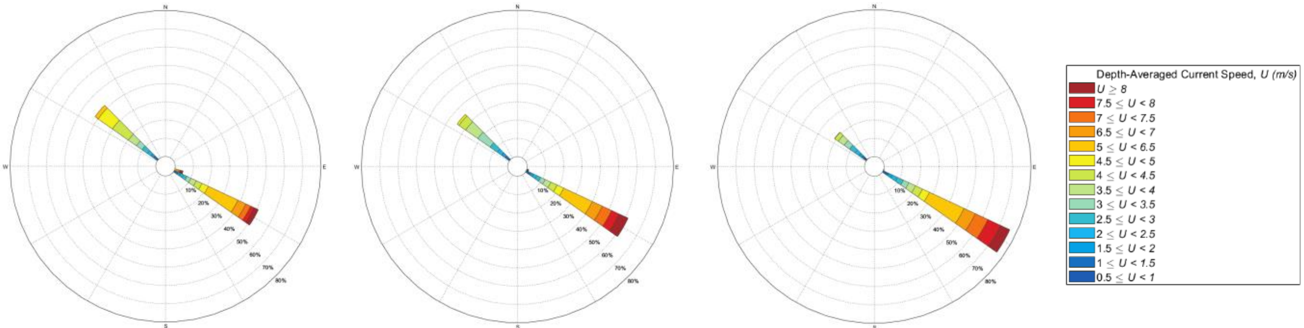


**Figure 9.** Modelled depth-averaged current speed distributions at the Reversing Falls for summer (left), fall (centre) and spring freshet (right) scenarios.

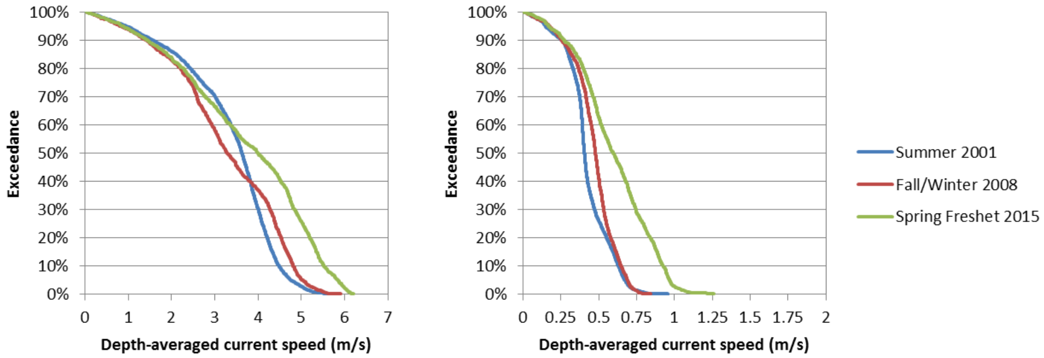


**Figure 10.** Modelled exceedance of depth-averaged current speeds at the Reversing Falls (left) and in the bay downstream of the Reversing Falls (right) for all 3 scenarios.

## 5 CONCLUSION

The hydrodynamic modelling results indicate that the Reversing Falls sill exerts considerable influence on hydrodynamic conditions in the lower Saint John Estuary, damping tides as they propagate upstream and causing a significant drop in mean water level from upstream to downstream. Current speeds and flow reversal at the Reversing Falls site are governed by the balance between fluvial and tide-driven flows, with the former being highly seasonal. Current speeds are always highest during peak ebb tidal flows (i.e., ebb dominance), exceeding 8 m/s at some locations over the Reversing Falls. During low river flows (e.g., summer and winter), flood tidal flows are more pronounced at the Reversing Falls site, whereas during the spring freshet, strong river flows inhibit and prevent the reversal of flow during flood tides. The intensely turbulent, jet-like flow over the Reversing Falls drives recirculating eddies in the bays on either side of the peninsula immediately SW of the sill.

The Saint John Estuary hydrodynamic model provides valuable insight to hydrodynamic conditions at the Reversing Falls and circulation in the lower Saint John estuary for a broad range of river flows and tidal conditions, and is a useful tool for investigating fate and transport of waterborne contaminants. Further calibration and validation of the model would likely help to improve confidence in the model output and reduce uncertainty, particularly at sites in the upper estuary.

 

**ACKNOWLEDGMENTS**

The research was funded by J.D. Irving, Limited and the National Research Council of Canada. The authors would like to thank Mike Chiasson of NB Power and Michelle Desjardins of the Water Survey of Canada for their timely help in sharing hydrometric data.

Supplemental bathymetry was produced is based on Canadian Hydrographic Service charts and data, pursuant to CHS MOU No. 2017-0906-1260-I.

**REFERENCES**

Church, I. (2014). Modelling the Estuarine Circulation of the Port of Saint John: Applications in Hydrographic Surveying. *Doctoral Dissertation*, University of New Brunswick.

Cornett, A., Durand N., Serrer M. (2010) 3D modelling and assessment of tidal current resources in the Bay of Fundy, Canada. *Proc. 3rd Int. Conf. on Ocean Energy (ICOE),* Bilbao, Spain

Delpeche, N. (2007) Observations of advection and turbulent interfacial mixing in the Saint John River Estuary, New Brunswick Canada. *Master's Dissertation*, University of New Brunswick.

Haigh, S., and Hughes-Clarke, J. E. (2005). A numerical study of exchange and mixing over a sill at the mouth of the Saint John River Estuary. *2nd CSCE Specialty Conference on Coastal, Estuary and Offshore Engineering* (p. 10). Toronto, ON.

Hansen, P. L. (1970). Hydraulic Model Study of the Reversing Falls at Saint John, New Brunswick. University of New Brunswick, Fredericton, New Brunswick.

Hughes-Clarke, J. E., & Haigh, S. (2005). Observations and Interpretation of Mixing and Exchange Over a Sill At the Mouth of the Saint John River Estuary. *2nd CSCE Specialty Conference on Coastal, Estuary and Offshore Engineering* (p. 10). Toronto, ON.

Hervouet, J. M. (2007) Hydrodynamics of Free Surface Flows: Modelling with the Finite Element Method. *John Wiley & Sons, Ltd.* Online ISBN:9780470319628.

Leys, V. (2007). 3D Flow and Sediment Transport Modelling at the Reversing Falls - Saint John Harbour, New Brunswick. *MTS/IEEE Oceans Conference* (p 16). Vancouver, BC.

Mattic, O. (2018) Telemac3d User Manual, Version v7p3. March 16, 2018. http://www.opentelemac.org/

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.

Neu, H. (1960) Hydrographic Survey of Saint John Harbour, N. B. Ottawa, ON.

Sweers, H. E. (1976) A nomogram to estimate the heat-exchange coefficient at the air-water interface as a function of wind speed and temperature; a critical survey of some literature. *J. Hydrol.*, 30: 375-401.

Toodesh, R. (2012). The Oceanographic Circulation of the Port of Saint John over Seasonal and Tidal Time Scales. *Master's Dissertation*, University of New Brunswick.

UNB. (2018). Lower Saint John River. *University of New Brunswick Engineering*. Accessed: 2018.11.14, URL: http://www.omg.unb.ca/lower-saint-john-river/.

 