



MODELLING STRATIFIED FLOWS IN THE SAGUENAY FJORD WITH TELEMAC-3D

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ABSTRACT

The Saguenay Fjord, located on the north shore of the St. Lawrence Estuary in the Province of Quebec, Canada, is notable for its complex and strongly stratified flows, with freshwater at the surface flowing over and mixing with denser seawater at lower depths. A new three-dimensional numerical model based on the TELEMAC-3D solver has been developed to simulate the stratified flows in the Saguenay Fjord and provide useful predictions of the surface currents in the upper part of the fjord for use in a parallel study of ice cover dynamics. The development, calibration and validation of the new model is presented and discussed, as are results from several simulations. The simulation results help clarify the influences of tide range, tide phase and the freshwater discharge entering the fjord on the surface currents in the upper fjord. This study demonstrates that the TELEMAC-3D solver can be applied with a modest level of effort to obtain reasonable and useful estimates of hydrodynamics in a fjord or estuary with complex stratified flows.

Keywords: Saguenay Fjord, hydrodynamics, numerical model, stratified flow, Telemac

1. INTRODUCTION

The Saguenay Fjord extends for 110 km between the communities of Chicoutimi, where the fjord transitions to the Saguenay River, and Tadoussac, where the fjord meets the St Lawrence Estuary, see Figure 1. The fjord varies in width from approximately 1.5 to 4 km, while the depth varies from ~15m near Tadoussac to over 275 m near Cap Trinité. The Saguenay Fjord is notable for its complex and strongly stratified flows, with freshwater at the surface flowing over and mixing with denser seawater at lower depths. The sketch presented in Figure 2 depicts the more buoyant freshwater moving downstream near the surface over the denser seawater at lower depths. Over 90% of the water volume in the fjord is estimated to be salt water. During winter a stable ice cover forms over the upper part of the fjord, and commercial ships accessing port facilities in Chicoutimi and Port Alfred are escorted by ice breaking vessels operated by the Canadian Coast Guard.

A three-dimensional numerical model of the hydrodynamics in the Saguenay Fjord has been developed to support the planning of future port facilities and improved navigation safety. In particular, surface currents predicted by the new hydrodynamic model have been used to force an ice dynamics model that in turn gives predictions of ice concentration, ice thickness and ice pressure throughout the region for a range of hypothetical scenarios. The development of the 3D hydrodynamic model is described herein, while the set-up and application of the ice dynamics model is discussed in Cornett *et al.* (2017).

The new hydrodynamic model is based on the TELEMAC-3D solver, which employs finite-element methods to solve the Navier-Stokes equations, in non-hydrostatic form, over a computational domain subject to initial conditions and time-varying boundary conditions. In two-dimensions (plan) the computational domain is represented by an unstructured mesh of triangular elements. Discretization in the third dimension (depth) is achieved by defining a constant number of sigma layers, whose thickness varies with space and time depending on the local water depth. In its final iteration the entire 110 km long fjord was discretized into 21 sigma layers, with 22,800 triangular elements defined in each layer.



Figure 1. Map of the Saguenay Fjord region (source: Google).

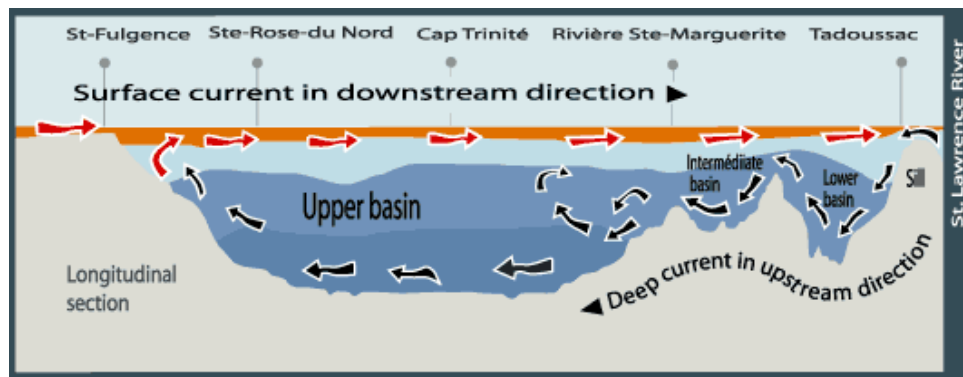


Figure 2. Sketch of general circulation pattern in the Saguenay Fjord (source: <http://www.virtualmuseum.ca>).

2. HYDRODYNAMIC CONDITIONS

Available information on tides, freshwater inflows to the fjord, water currents and salinity was reviewed, analyzed and referenced in setting up and calibrating the 3D hydrodynamic model. Some of the most important field measurement information is summarized in what follows. The present research was also informed by previous investigations into the hydrodynamic, oceanographic and geologic conditions of the Saguenay Fjord, including those reported in Urgales *et al.* (2002), Bourgault *et al.* (2011), and De Vernal *et al.* (2011).

Freshwater Inflow

A flow-duration curve for the total upstream freshwater flow into the Saguenay Fjord was generated based on analysis of measured discharge data from five sources, including the outflow from the dam at Shipshaw and four other important tributaries. The freshwater flow data was provided by Division Énergie Électrique of Rio Tinto Alcan and the Water Survey of Canada. Figure 3a shows the temporal variation of the Saguenay River discharge at

Shipshaw from 1972 to 2001, while Figure 3b shows the flow-duration curve obtained from analysis of the flow data. Based on this analysis, the average inflow is 1,310 m³/s while the inflow exceeded 1% of the time is 6,493 m³/s. The inflow during the month of March when the ice-cover breaks up was also investigated; the mean freshwater inflow during March is 1,244 m³/s while the maximum recorded inflow during March is 1,907 m³/s.

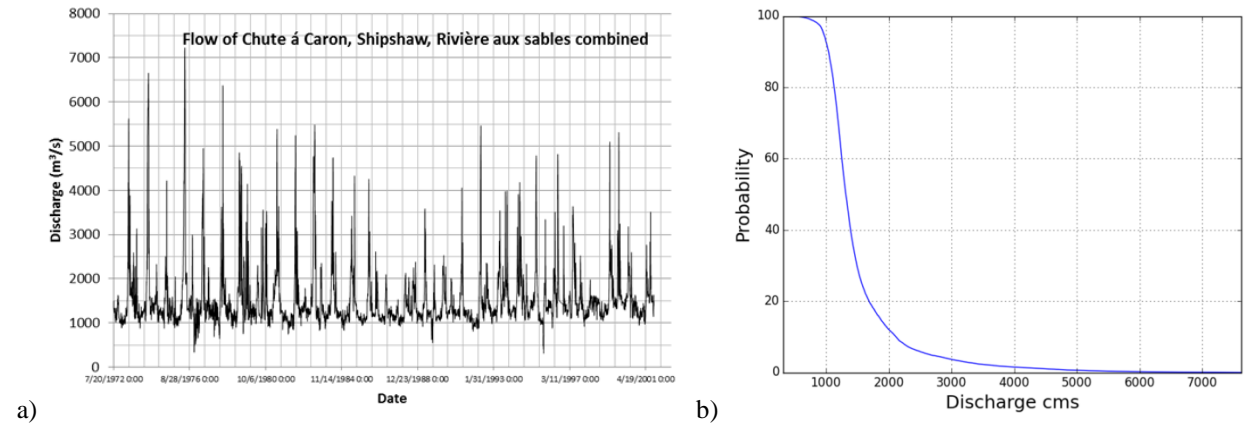


Figure 3. Freshwater inflow: a) Saguenay River discharge at Shipshaw, 1972-2001; b) flow-duration curve.

Tides

Information on the tides at Port Alfred and Tadoussac was obtained from Fisheries and Oceans Canada and reviewed, see Figure 4. The tides in the region are semi-diurnal, rising and falling twice daily. The tides at Port Alfred, located in the upper fjord, are generally between 0.5 to 1.0 m larger than the tides at Tadoussac, located at the lower end of the fjord where the fjord joins the St. Lawrence Estuary. The Spring tide range at Port Alfred can exceed 6 m while the Neap tide range can be less than 2.5 m.

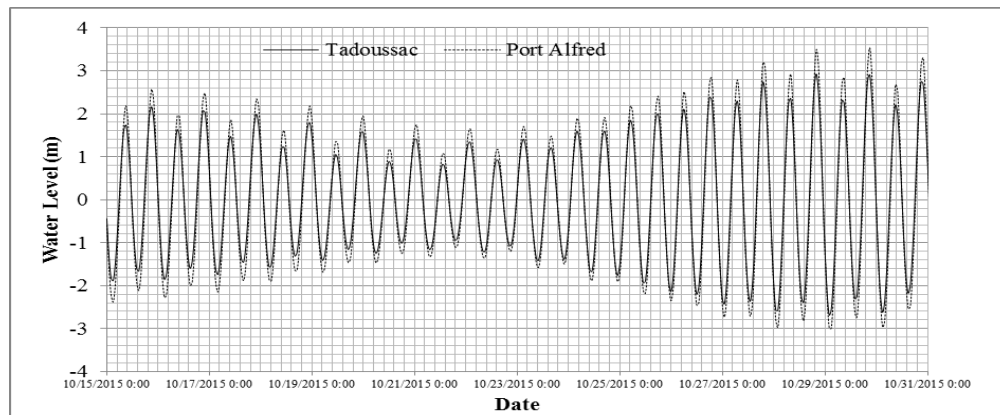


Figure 4. Observed tides at Tadoussac and Port Alfred, 15-30 October 2015.

Water Current

The currents near the Grande Anse wharf were measured (by others) on two occasions using an Acoustic Doppler Current Profiler (ADCP) unit. A mobile survey was conducted on 23 November 2015 wherein the ADCP unit was mounted to a boat and used to measure water currents along six shore-perpendicular transects. Data was collected for a ~3 minute duration at roughly five stations along each transect.

A stationary upward-looking ADCP unit was deployed in ~17 m water depth near the Grande Anse wharf from 27–29 October, 2015. The raw ADCP data from the stationary deployment was analyzed to estimate the speed and direction of the near-surface currents at this site over the deployment, accounting for the vertical fluctuation of the

free surface. The raw ADCP data and the estimated speed of the surface currents are shown in Figure 5. It is noted that the estimated surface velocity may not be entirely accurate due to difficulties measuring velocities near the free surface, where reflections can produce erroneous readings, and uncertainties related to the variable density of the water in the fjord.

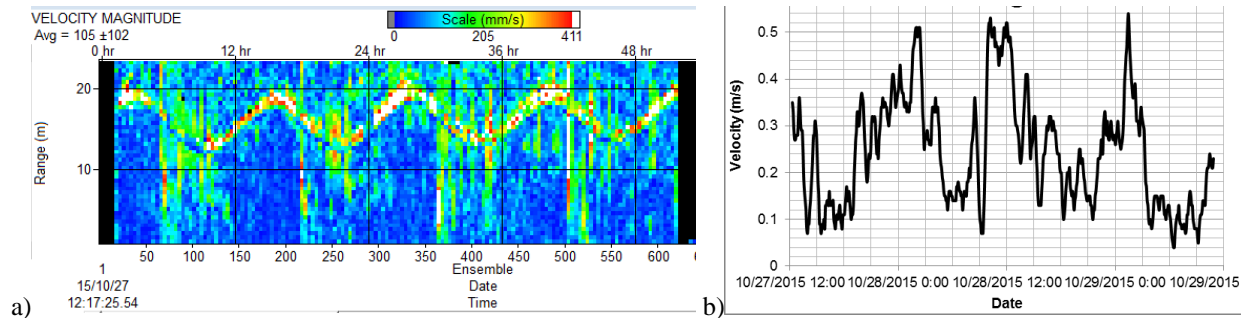


Figure 5. Observed flow velocity near the Grande Anse wharf:
a) raw ADCP data from stationary deployment; b) estimated surface current speed.

Salinity

Twenty-five salinity profiles (describing the variation of salinity with depth) measured in the upper fjord (by others) at various times and locations were reviewed and analyzed. The salinity profiles coincide with times when the freshwater inflow to the fjord was low ($\sim 1,100 \text{ m}^3/\text{s}$), moderate ($\sim 1,600 \text{ m}^3/\text{s}$) and high ($> 5,000 \text{ m}^3/\text{s}$). Three typical salinity profiles indicative of each freshwater inflow condition are presented in Figure 6. All the profiles show that the water column in the fjord is strongly stratified, with lower-density freshwater or near freshwater (salinity $< 10 \text{ PPT}$) at the surface, and higher-density seawater (salinity $> 25 \text{ PPT}$) at lower depths. The thickness of the freshwater layer and the gradient of the transition from freshwater to seawater varies with time and location. In general, the thickness of the freshwater layer varies from a minimum of approximately 3 m when the freshwater discharge is low, up to 15 m when the freshwater discharge is exceptionally high.

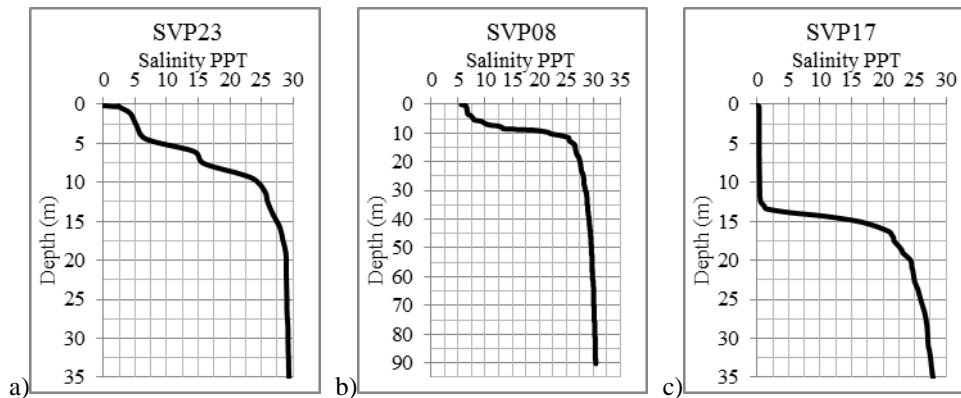


Figure 6. Typical salinity profiles recorded in the upper Saguenay Fjord:
a) low freshwater inflow; b) medium freshwater inflow; c) high freshwater inflow.

Bathymetry

Information on the bathymetry throughout the region was assembled from several sources, including navigation charts published by the Canadian Hydrographic Service (CHS) as well as high-resolution bathymetric surveys covering several smaller sub-regions. The information from these sources was referenced to a common datum and merged to form a single digital elevation model. Figure 7 shows the resulting bathymetry for a portion of the upper fjord. The upper fjord is generally deep, with water depths less than 30 m prevailing only very near the shoreline, and at the head of the fjord near Shipshaw.

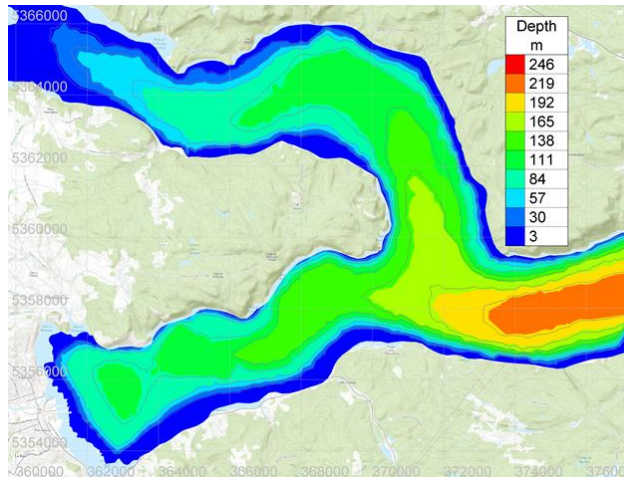


Figure 7. Bathymetry for a portion of the upper Saguenay Fjord.

3. NUMERICAL MODEL SETUP

Telemac Modelling System

A three-dimensional numerical model based on the TELEMAC-3D solver from the TELEMAC System (v7.0) was developed to simulate the hydrodynamics in the Saguenay Fjord. The model employs finite-element methods to solve the Navier-Stokes equations, in non-hydrostatic form, over a computational domain subject to initial conditions and time-varying boundary conditions. In two-dimensions (plan) the computational domain is represented by an unstructured mesh of triangular elements. Discretization in the third dimension (depth) is achieved by defining a constant number of layers, whose thickness can vary with space and time depending on the local water depth. The unstructured grid allows the size of the elements to vary in space: a fine mesh can be used to improve accuracy in areas of interest and in areas with high velocities and/or strong spatial gradients, while a coarse mesh can be used in less important areas in order to reduce computation effort and cost. Further details on the TELEMAC system are provided in Hervouet (2007). The TELEMAC System was originally created by the Laboratoire national d'hydraulique et environnement d'Électricité de France (EDF) but is now managed by a consortium of core organizations under the OpenTELEMAC-MASCARET umbrella (see www.opentelemac.org).

Computational Domain and Grid

The new model extends from a point ~700 m downstream from the Chute-à-Caron dam at Shipshaw down to the St-Lawrence Estuary. The model domain includes the entire Saguenay Fjord and small portion of the St-Lawrence River, see Figure 8. The configuration of the triangular mesh in four sub-regions (A – D) is also shown in this figure. Some shallow tidal flats in the upper part of the fjord were excluded in order to simplify and speed-up the numerical computations. The exclusion of the tidal flats is believed to have little influence on the water levels and currents in the region of interest.

To minimize numerical errors and computational cost, the total number of grid cells and the distribution of the cell sizes were chosen based on a sensitivity analysis. The final mesh has 22,838 triangular elements and 12,456 nodes in each layer. The horizontal resolution varies from 15 m near the upstream boundary, where velocities are greatest, to ~1,000 m in the St. Lawrence River. The horizontal resolution near two reference sites of interest (B and C in Figure 8) was refined to ~40 m.

Initially, the water column throughout the domain was discretized into 11 layers. Results from these initial simulations suggested that additional layers would be required in order to simulate the strong density stratification that exists in the fjord. In the final set-up, the water column throughout the domain is discretized into 21 layers. The layers are unevenly distributed throughout the water depth: a finer layer thickness was specified in the upper part of the water column near the free surface, a medium layer thickness was used near the bottom, while the largest layer

thickness was specified over the middle portion of the water column, away from the upper and lower boundaries. It is noted that the thickness of each layer varies with space and time based on the local water depth, which depends on the local bathymetry and the local free surface elevation.

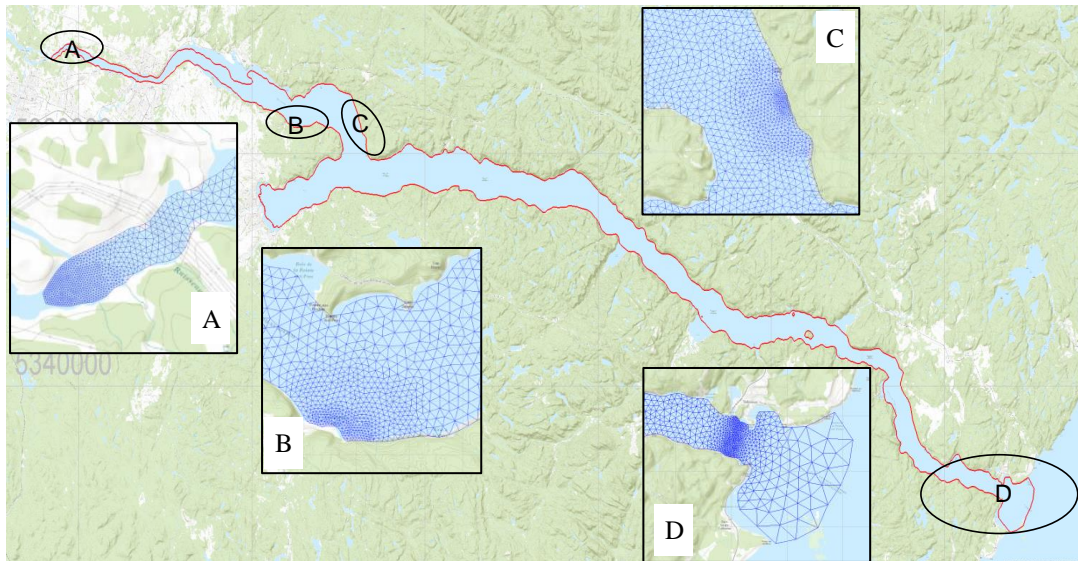


Figure 8. Computational domain (red outline) and triangular mesh with variable horizontal resolution.

Boundary and Initial Conditions

The model was set-up with two dynamic boundaries. Time-varying water levels were prescribed at the downstream boundary in the St-Lawrence Estuary (D in Figure 8), while a steady inflow (discharge) of freshwater was specified at the upstream boundary near Shipshaw (A in Figure 8). The water level boundary condition was developed from analysis of tide data for Tadoussac and other nearby tide stations in the St. Lawrence Estuary. The steady upstream discharges were based on analysis of the freshwater inflows discussed above (see Figure 3).

The hydrodynamic model was initially run for a one-month warm-up period to establish realistic equilibrium conditions for the density stratification and salinity gradient throughout the domain. The one-month warm-up simulation was conducted using a steady up-stream freshwater inflow of $2,000 \text{ m}^3/\text{s}$ combined with the tides during May 2014. The quasi-equilibrium condition obtained at the end of the one-month warm-up simulation is depicted in Figure 9. This figure shows the spatial distribution of surface salinity computed over the entire domain, together with the salinity profiles computed for six stations along the fjord. In the model, the surface salinity varies gradually from 0 PPT (pure freshwater) at location A (near the upstream boundary) to 30 PPT (pure seawater) at location G (near the downstream boundary), as expected. The surface salinity at location B (upstream from Grande Anse) is less than ~ 3 PPT, while the surface salinity at location C (downstream from Grande Anse) is ~ 12 PPT. The modelled salinity profile at location A shows only freshwater, as expected, while the modelled salinity profile at location G in the St. Lawrence shows pure seawater, again as expected. The modelled salinity profiles at locations B and C show a strongly stratified water column comprised of a thin layer of near freshwater at the surface over a much thicker layer of near seawater at depth, and is generally consistent with the form of the measured salinity profiles for this region (three examples in Figure 6). The salinity/density stratification predicted by the model is considerably less pronounced in the lower parts of the fjord, below location D.

The equilibrium condition obtained at the end of the one-month warm-up simulation was used as the initial condition for subsequent model runs conducted primarily to estimate surface currents in the upper fjord for different scenarios.

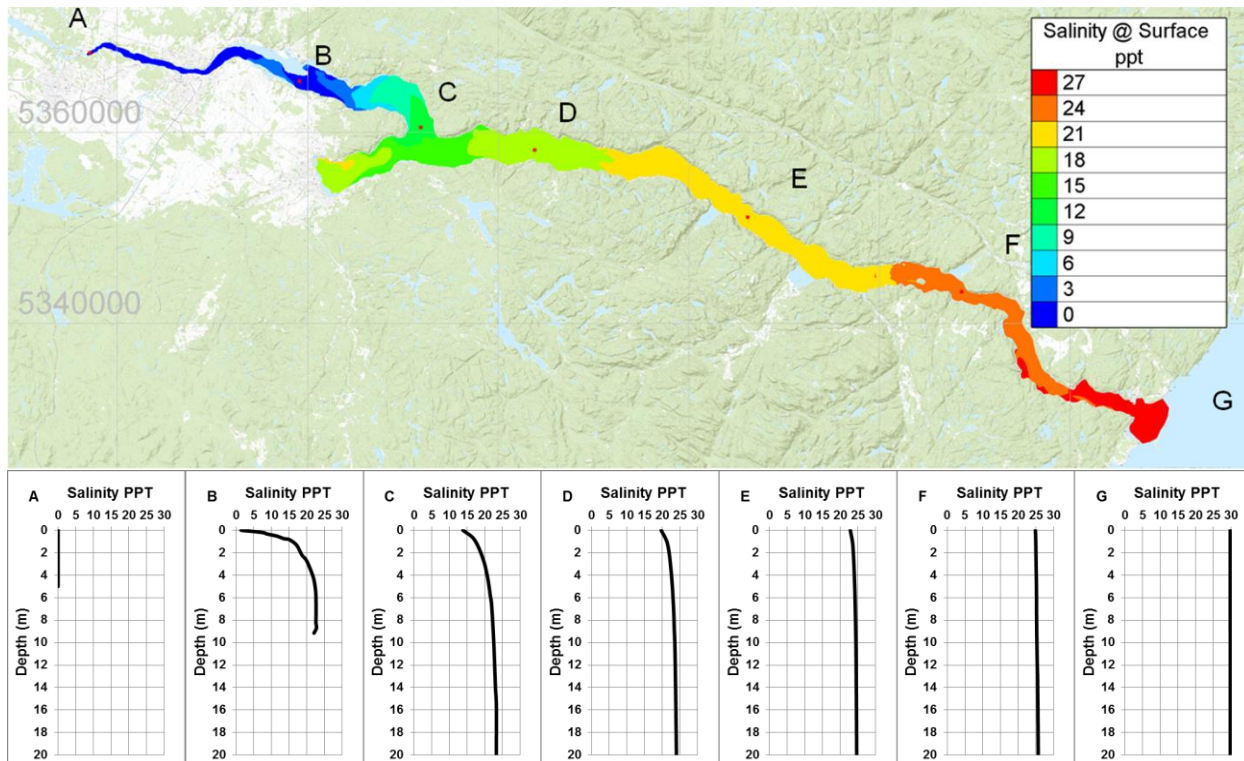


Figure 9. Distribution of modelled surface salinity at the end of the warm-up simulation and salinity-depth profiles for selected locations A-G.

Calibration and Validation

The hydrodynamic model was initially calibrated to ensure that it provided reliable predictions of the water level fluctuations at Port Alfred. The model was calibrated through an iterative process of varying the bottom roughness until the water-surface elevations predicted by the model were in close agreement with tide level predictions for Port Alfred issued by Fisheries and Oceans Canada. In the end, a single Manning’s roughness coefficient value of 0.04 was used throughout the computational domain. Using the optimized roughness coefficient, both the magnitude and the timing of the high and low tides at Port-Alfred were reasonably well predicted by the model.

Next, the surface currents predicted by the model were compared with the surface current estimated from data collected during the stationary ADCP deployment. The horizontal eddy viscosity specified in the model was adjusted to achieve reasonable agreement between the modelled surface currents and those estimated from measurements. In the end, a horizontal eddy viscosity of 20 m²/s was selected for use in the model.

Although the agreement between modelled and ‘measured’ water currents was not perfect, it was confirmed that the model provides a reasonable prediction of the speed of the surface current and the timing of its fluctuations at the ADCP deployment location. The model indicates that the current speed near the Grande Anse wharf is highest during times of ebbing tide, when the tidal current reinforces the freshwater outflow at the surface, and lowest during times of flooding tide, when the tidal current opposes the freshwater outflow at the surface.

The numerical simulation of the density stratification in the fjord was found to be sensitive to several factors, including the vertical turbulence model, the number of layers, and vertical distribution of the layers throughout the water column. Better results were obtained when the number of layers was doubled from 11 to 21, and the layers were concentrated in the upper part of the water column where the vertical gradient in salinity was greatest, instead of being evenly distributed with depth. Several alternative vertical turbulence formulations were investigated and assessed, but in the end, the “Nezu and Nakagawa” mixing length model (Nezu and Nakagawa, 1993) was selected as the most appropriate model from those available within TELEMAC-3D.

Extensive comparison between measured and modelled salinity profiles indicates that the model generally over-predicts the salinity near the surface and under-predicts the salinity at lower depths, relative to the measured data. The freshwater layer predicted by the model is generally thinner than indicated by the salinity profile data. These observations suggest that the degree of vertical mixing may be somewhat over-estimated in the model. It is noted that the hydrodynamic model was developed to provide a reasonable prediction of surface currents for various scenarios, and was not intended to provide a complete and full description of the salinity/density stratification and mixing over the water column and throughout the fjord.

The numerical model was validated by comparing model output with different data sets and for different periods than those used during calibration. The results of the validation were judged to be satisfactory and adequate for the model's intended purpose.

4. RESULTS AND DISCUSSION

Once the final model configuration and set-up was established, the model was used to simulate the water levels and three-dimensional flows in the fjord for four different scenarios. The scenarios were selected to include both typical and extreme conditions during the month of March, when the ice cover breaks up and moves out of the fjord, as well as conditions during the peak of the spring freshet when freshwater inflows are highest. Conditions on 27 October 2015, when the stationary ADCP was deployed near the Grande Anse wharf, were also modelled. The specifications for the four scenarios are summarized in Table 1. In all cases, the model was run for a 15-day period that included both a full Spring tide and a full Neap tide. The end state of the one-month warm-up simulation (see Figure 9) was adopted as the initial condition of salinity for each scenario.

Scenario 1 represents conditions at the peak of the average annual freshet, when freshwater inflows to the fjord are $\sim 4,297 \text{ m}^3/\text{s}$. The distribution of surface currents over the upper fjord predicted by the model for Scenario 1 is shown in Figure 10, while Figure 11 shows the modelled currents at mid-depth.

Table 1 : Specifications for selected scenarios

Scenario	Tide signal	Freshwater inflow (m^3/s)	Remark
1	15-30 October 2015	4297	Average annual maximum freshwater inflow
2	15-30 October 2015	1907	Maximum freshwater inflow during March
3	15-30 October 2015	1244	Average freshwater inflow during March
4	15-30 October 2015	1120	Freshwater inflow on Oct 27, 2015

The simulation results suggest that the surface currents and circulation in the upper fjord are dependent on the tide range, the phase of the tide (ebb or flood) and the discharge of freshwater entering the upper fjord. The strongest surface currents tend to occur during Spring (large) tides when the water level is falling (ebb tide) and when the freshwater inflow discharge is high. The surface current tends to weaken at times when the freshwater inflow is lower, when the tide is rising (flooding), and when the tide range is smaller. In many locations the surface current continues to flow downstream (towards the lower fjord) even during times of rising (flood) tide.

The currents and circulation below the surface tend to be quite different. Near mid-depth, the flows are influenced more strongly by the tides and less by the fresh-water inflow, such that the flow direction generally reverses every ~ 6.4 hrs. The horizontal circulation at depths near the interface between the freshwater and the salt wedge tends to feature many eddies and gyres of varying sizes; possibly a manifestation of mixing between the freshwater and saline flows.

It should be noted that in reality the surface currents may also be influenced by the local wind conditions and the state of the ice cover (if any); however, these factors were not explored in the present study. It should also be noted that smaller eddies or gyres may form close to shore in small bays that were not resolved by the present hydrodynamic model and therefore are not included in the simulation results presented here.

Probability curves for modelled surface current speed at two reference sites (B, C) are presented in Figure 12. The reference site locations are shown in Figure 8. Scenarios 3 and 4 produced very similar results, as expected, considering that the initial conditions and tide signal forcing were identical and the upstream freshwater inflows

were very similar in these two cases. Surface current speeds for Scenario 2 were slightly larger than for Scenarios 3 and 4; a result that can be attributed to the greater freshwater inflow (1,907 m³/s in Scenario 2 compared to ~1,200 m³/s in Scenarios 3 and 4). The surface current speeds throughout the region are consistently greater for Scenario 1; in which a freshwater inflow of 4,297 m³/s was modelled.

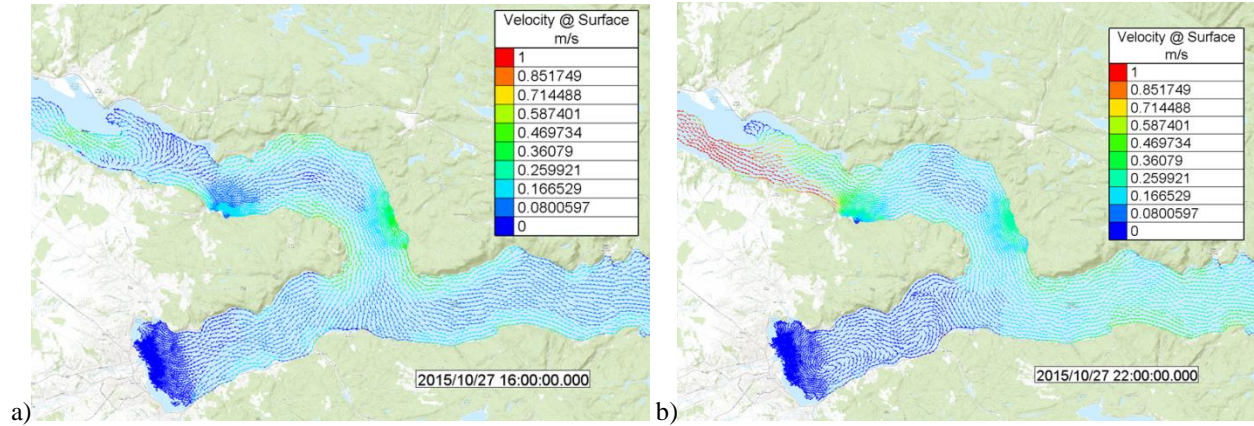


Figure 10. Modelled surface currents in the upper fjord, Scenario 1: a) Spring flood tide; b) Spring ebb tide.

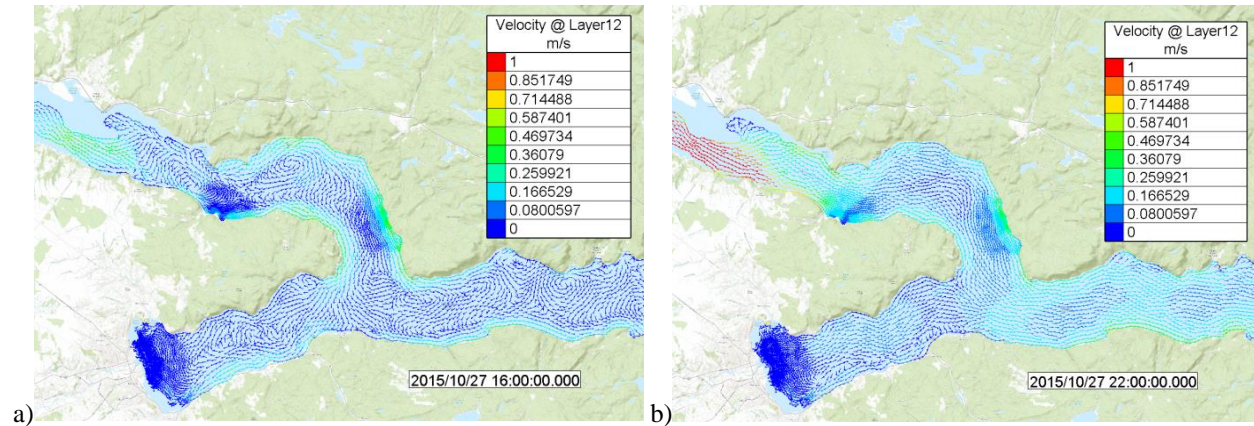


Figure 11. Modelled mid-depth currents in the upper fjord, Scenario 1: a) Spring flood tide; b) Spring ebb tide.

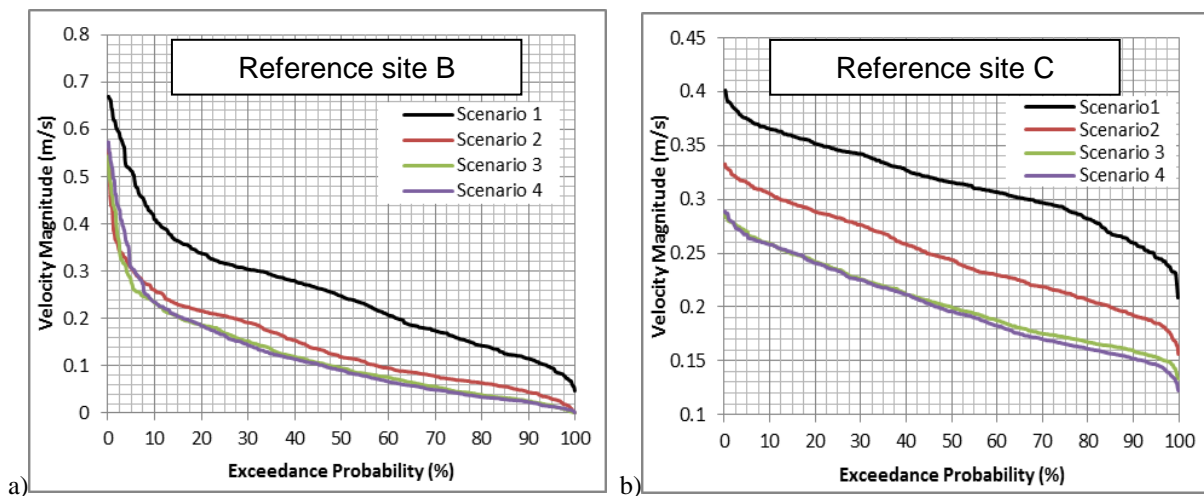


Figure 12. Comparison of exceedance probability curves for surface current speed at two reference sites, Scenarios 1 – 4.

5. CONCLUSION

The Saguenay Fjord, located on the north shore of the St. Lawrence Estuary in the Province of Quebec, Canada, is a highly complex and dynamic body of water where freshwater and seawater combine, mixed by the tides. The complex and highly stratified flows in the fjord are particularly challenging to model numerically.

A three-dimensional numerical model based on the TELEMAC-3D solver has been developed to simulate the stratified flows in the Saguenay Fjord and provide useful predictions of the surface currents in the upper part of the fjord for use in a parallel study of ice cover dynamics. In the final version of the model, the 110 km long fjord is discretized into 21 layers, with 22,838 triangular elements in each layer. The model is forced by prescribing a fluctuating water level at the St. Lawrence Estuary, combined with a steady freshwater inflow entering near Shipshaw. A quasi steady state initial condition for the salinity and density stratification throughout the fjord was developed by conducting a warm-up simulation with one month duration. The model has been calibrated and validated by comparing simulation outputs with field observations of fluctuating water levels, near-surface currents, and salinity profiles. A reasonable level of agreement between the various measured and modelled quantities was achieved, considering the complexity of the hydrodynamic processes involved and the relatively short amount of time that could be dedicated to the effort. Useful predictions were generated for four hypothetical 14-day long scenarios, each corresponding to a different freshwater inflow. The simulation results help clarify the influences of tide range, tide phase and the freshwater discharge entering the fjord on the surface currents in the upper fjord. Due to the complexity of the flows and mixing in the fjord, and the numerous assumptions and approximations inherent in the simulating these flows in a numerical model, the numerical simulations of near-surface currents that have been obtained should be associated with a moderate degree of uncertainty.

This study has demonstrated that the TELEMAC-3D solver can be applied with a modest level of effort to obtain reasonable and useful estimates of hydrodynamics in a fjord or estuary where freshwater and seawater combine. It is noted that the presence of an ice cover and the potential effects of an ice cover on the flows and surface currents in the fjord were not included in these numerical simulations, nor were the potential effects of winds blowing over the water surface. The simulation results are therefore truly valid only for open-water conditions in the absence of strong winds.

6. REFERENCES

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