HYDRODYNAMIC MODELING ANALYSIS OF THE CIRCULATION OF THE BAY OF FUNDY

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Abstract: The purposes of the Bay of Fundy Simulations are or background information for a field trip to Acadia University in Wolfville, NS dealing with different aspects of the Bay of Fundy. To apply the Introgllvht Water Quality and Hydrodynamic model [1] to a large enough water body for which the Coriolis acceleration could be significant. To examine how the Introgllvht model sets up and performs for another case. (Alpha testing of the model software). The study investigates the following aspects of theBay of Fundy. Its general surface and bottom circulation patterns. The surface distribution of the Saint John and Saint Croix River outflows to show how they might distribute eggs and larvae spawned within their shoreline embayments. The flushing time of water from different locations within the bay to estimate how fast exchange takes place within it and as an indication of possible water quality problems. The study covers: A general description of the processes driving circulation within the Bay, and the data required for setting up a hydrodynamic and transport model of the bay. The tidal, freshwater inflow and bathymetric data available from the internet for setting up the model. Development of the model grid.The model setup Input Data for the simulations Graphical descriptions of the circulation, spreading of the Saint John and Saint Croix Rivers.Surface and bottom water flushing times. The possible role of Coriolis Acceleration. Tides at different locations. Tidal velocities at the mouth for comparison to available data.

Key words: Bay of Fundy, Hydrology, Hydrodynamic Modeling, Oceanography, Tidal Circulation.

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1 Why A Model and The Model Being Used

Why perform numerical hydrodynamic and transport mathematical modeling anyway? Some of the reasons are to be thought about as being a possibility relatively cheaply with the availability of high speed PC computers, and they are fun to do. It is less expensive to do computer simulations of a water body than to collect and interpret an equivalent amount of field data. Simulations can be performed to study features in the bay that do not presently exist such as dredging and channeling, effects of industrial discharges into the bay, effects of changing land use on bay water quality due to surface water runoff. Preliminary simulations can indicate features of the bay that will aid in designing field surveys for specific studies. Simulations can be performed for conditions other than those that have been observed. Examples are the study of the effects of different river inflow rates, different tidal conditions at the mouth and different wind conditions on the bay.

Different kinds of results can be produced by a model that cannot be observed from field data. Examples in this study are the spreading of the Saint John and Saint Croix River discharges using a virtual dye simulation, and estimating flushing times throughout the bay using the same technique. The need for field data should not be discounted even with the availability of modeling. Field data is important to describe the general oceanography of the bay and for verifying model results from simulations run under the conditions of the surveys. Field data is important to study features of the bay that are difficult if not impossible to model, such as fisheries resources and related biota. Modeling, however, can provide information about the bay that can aid in such studies.

2 The Model Being Used

The model being used is a three dimensional numerical hydrodynamic and transport model based on the fundamental relationships of fluid motion. The latter are basically the fluid momentum relationships in each of the two horizontal directions, and the continuity relationships that required fluid mass be conserved while it is flowing. The hydrodynamic or momentum relationships essentially give the fluid velocity field at each location in the model grid.The velocity field is used to transport constituents such as heat (for temperature distributions), salinity, tracer dyes and different water quality constituents. The model and accompanying software is found in the American Society of Civil Engineers publication prepared by Edinger [1], and the organization and approach to this study follows as closely as possible the Guidelines presented by Stewart [2].

3 Description of Processes And Available Input Data

The physical processes driving the circulation of the Bay of Fundy is circulation is driven by the tides at the mouth the freshwater inflows of the Saint John and Saint Croix River. Surface wind shear Density driven circulation due to salinity and temperature profiles at the mouth. Also, the inflow temperature of the rivers and surface heat exchange. Temperature effects will be neglected in the preliminary study. The above represents the major inputs required to perform the numerical hydrodynamic and transport modeling of the bay. The major data required are the tides at the mouth and the fresh water inflows. Location of nearby tidal stations and current speed data are shown in The current speed data is used for comparison to the model results and is not an input to the model. Available tidal, fresh water inflow and current speed data are presented in the Attachment at the end of this write up. Also given are the values of the major parameters chosen for the Introgllvht simulations.

4 Model Bathymetry and Grid Setup

Bathymetric data is required to set up the three dimensional computational grid of the model. Detailed digital bathymetric data is not generally available over the internet. It is fairly expensive to obtain in the digital format that is useful for setting up the model grid. A very general picture of the bathymetry in the Gulf of Maine extending into the Bay of Fundy is shown in Figure 1. This, and some spot depth measurements taken from an Atlas were used to approximate the bathymetry. The first step in setting up the model grid was to approximately map the land borders of the bay. The actual locations of land and water are refined when the bathymetric data file is set up. The second step in setting up the model grid was to determine the x and y coordinate locations of the ends of each of the borderlines shown in. A general reference x and y coordinate axis was placed on a larger version of and the coordinate locations of the ends of the lines were measured. For reference the distance across the mouth of the Bay of Fundy grid is about 76.8 km.

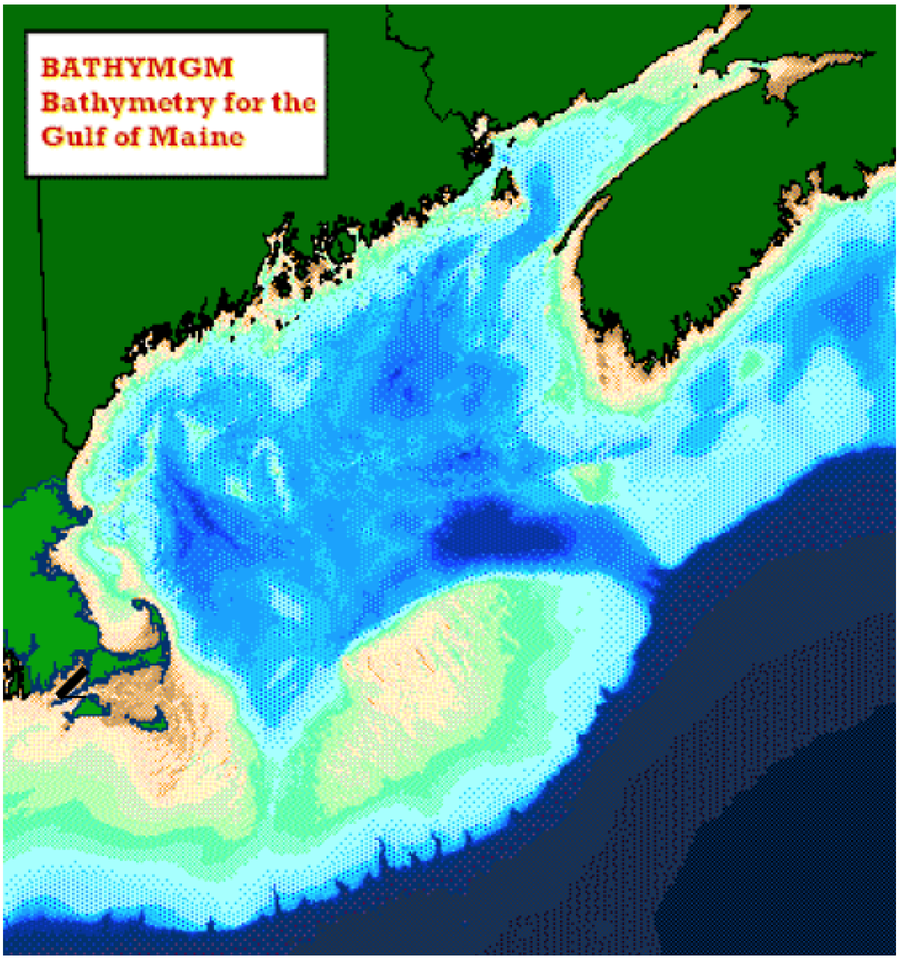

Figure 1: **Color image of bathymetry in Bay of Fundy (Source: Author)**

The third step was to place the x and y coordinates in an Excel spreadsheet so that the borderlines could be mapped onto a grid. Further computations were to divide the x and y coordinate distances by various choices of the model dx and dy to determine how much of the allowed 40 x 40 cell grid of the model could be used to get the most detail. The resulting model grid is shown in Figure 5 when using surface cells of 7.5 km x 7.5 km.

Depths were then located within the center of the model cells within the land boundaries. The depths were chosen to preserve roughly the bathymetry shown in Figure 1. The resulting bathymetric depth file for the model simulations is shown in Table 1. A vertical layer thickness of dz is equal to 2

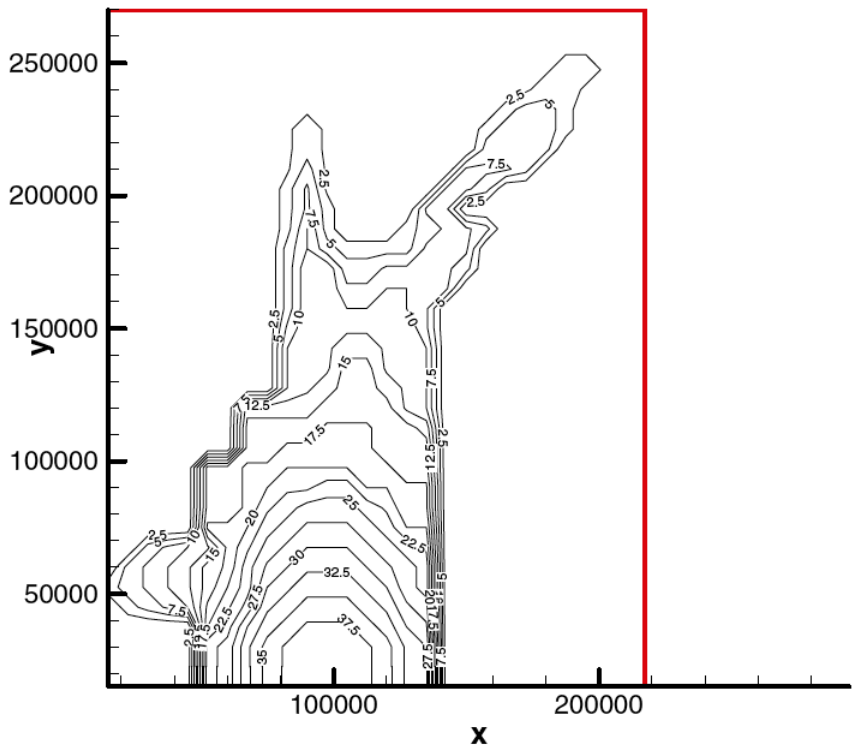

Figure 2: **Mapped model bathymetry from 7.5 km x 7.5 km cell grid. Low tide depths in meters. Model vertical layer thickness is 2 m. (Source: Author)**

m was chosen for the modeling. The resulting bottom bathymetry resulting from the 7.5 km x 7.5 km surface cell resolution and the vertical layer thickness of 2 meters is shown in Figure 2. The grid size and the depths are sufficiently detailed the point of land in the upper eastern arm shown on the previous maps is reproduced in the model bathymetry.

5 Model Input Data

IThe Introgllvht model is designed such that preliminary studies can be performed with little input data. The input data for the model is presented in the project folder entitled "Bay of Fundy Introgllvht Files" which are summarized in section 9 of this report. Various aspects of the input data are examined here primarily to discuss the assumptions made when using the Introgllvht model. The water quality model being used *nwqm* equal to 2, is a dissolved oxygen depression (DOD) model that includes sources for biochemical oxygen demand (BOD), Ammonium, and Organic Nitrogen. However in this case the model is used for another purpose other than modeling DOD.

The reaction and decay rates required for DOD parameters have all been set to zero. The BOD and Ammonium thus become conservative substances and can be used as virtual dye tracers for the Saint John and Saint Croix River inflows. The first inflow shown is the Saint John River median July inflow of 300 m/s and it is located to enter the modeling grid at I equal to 9, J equal to 3, J equal to 8 on the surface. The NH_3 in the discharge is set for a virtual dye concentration of 1,000 μg/l.

There is one tidal boundary across the mouth of the Bay of Fundy extending from I equal to 7 to I equal to 18 at J equal to 2 on the modeling grid. The Introgllvht model uses only a sinusoidal tide. For the Bay of Fundy the mean tide height is set at 2.5 meters, and the tidal amplitude is set at 2.5 meters. The tidal period is set at 12.45 h. The tide at the mouth is taken as an M2 tide with a range of 5 m.

The salinity profile at the mouth of the bay is set to a constant value of 30 ppt. The computations are initialized for a salinity of 5 ppt throughout the bay to allow the salinity induced circulation to spin up during the computations. A constituent is initialized throughout the bay at 100 μg/l of a virtual dye that is used in the computation of flushing and residence times. The external parameters are a Chézy bottom friction coefficient of 35 $m^{1/2}/s$, no wind, and latitude of 44.66^o N. For output only surface and bottom distributions of constituents are examined in the output results tables. However, all the constituents and velocity components are available in the plotting files for graphical output for the surface and the bottom. Time series are extracted for water surface elevations at the mouth of the bay, near the end of the northern arm and part way up the eastern arm. The model simulates at a time step of 120 s over a simulation time of 1,200 hours (50 days).

6 Model Results and Surface Circulation

The tidally averaged surface circulation is at the mouth of the bay, it shows the tidally averaged flow inward over the eastern half of the tidal boundary, and outward over the western half. This coincides with the circulation within the bay being northward along the eastern shore, and southward down the western shore. The tidally averaged current is from east to west at the northern end of the bay. In the western arm, the circulation is again generally inward along the eastern shore and outward along the western shore. There tends to be a radial circulation in the mouth of the eastern arm where the flow is confined by the point of land.

The surface salinity entering from the tidal boundary, tends to be pushed in further into the bay on the east than on the west. This coincides with the general tidally averaged circulation of inflow along the eastern shore and outflow along the western shore. The inflow of the Saint John River is quite noticeable and is strong enough to be able to deflect the southerly flowing tidally averaged current. These also combine to form a clockwise gyre south of the entrance of the Saint John River inflow. The gyre south of the Saint John River inflow is connected to a longer one that extends almost to the tidal boundary and passes up along the western shoreline across the mouth of the Saint Croix River embayment. Within the Saint Croix River embayment there is another tidally averaged counterclockwise gyre driven by the northerly flow off its mouth.

6.1 Spreading of Saint John River Inflow

The Saint John River inflow was continually injected with a virtual dye such that the discharge concentration would be maintained at 1000 μg/l. The virtual dye release allows examining the dilution of the Saint John River inflow and its densimetric spreading over the surface of the bay. The result of the Saint John River inflow tracer study is shown in Figure 3. The plume isopleths are mapped from tidally averaged dye concentrations. Offshore the Saint John River inflow plume concentration is down to about 5 μg/l indicating that at this location it is diluted about 200:1 (1,000/5). The outward extent of the plume is illustrated by the 2 ug/l contour at which the dilution is 500:1. As the plume spreads outward, due to the fresher water spreading on the denser more saline water, it reaches northward along the shoreline, and somewhat southward of the point of discharge.

6.2 Spreading of the Saint Croix River Inflow

A similar virtual dye release was made into the Saint Croix River inflow. The resulting plume is shown in Figure 4. It shows that the Saint Croix River inflow is diluted to 0.3 μg/l within the confines of its receiving embayment giving a dilution of about 3,000:1 before the mouth of the embayment is reached. Part of the difference from the Saint John River inflow is that the Saint Croix River inflow is one tenth of the former. Proportioning by flows, if the St.Croix River inflow were as large as the Saint JohnRiver inflow, it would

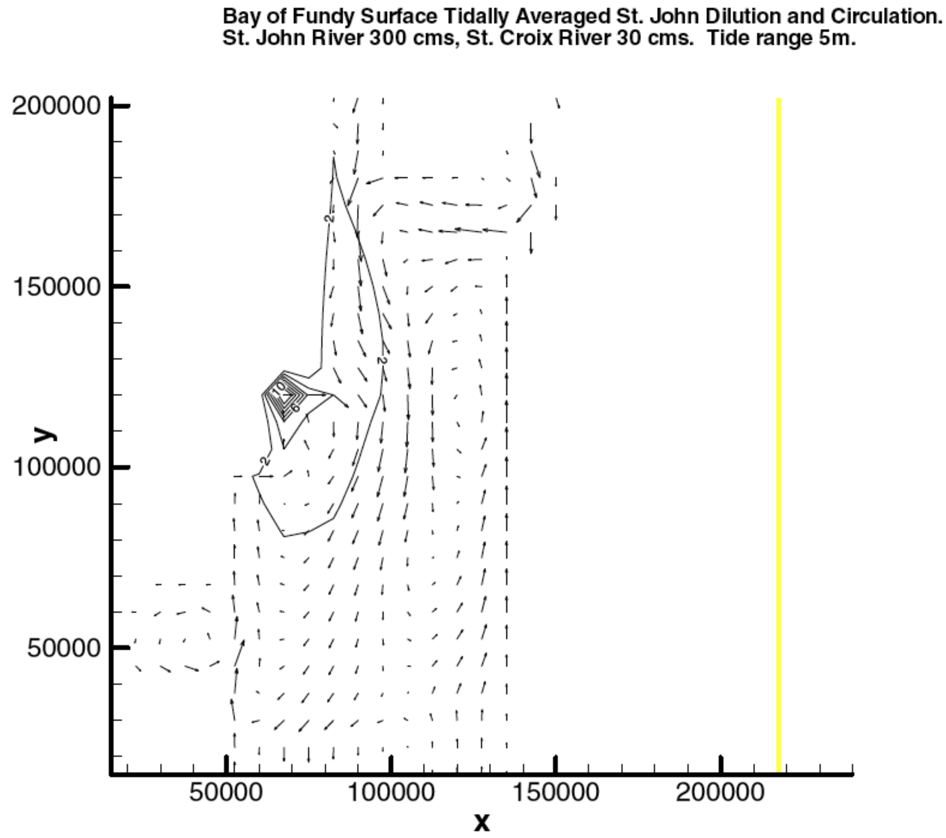

Figure 3: **Dilution and spreading of the Saint John River outflow (Source: Author)**

still probably be diluted to about 300:1 at the mouth of the embayment. This could be checked to greater detail by simulating a larger Saint Croix River inflow.

6.3 Surface Flushing Times of the Bay

The model allows estimating the flushing time at all locations over the computational grid. The flushing time at any location is approximately the time it takes for a parcel of water at that location to leave the bay. The isopleths of surface flushing time are near the mouth of the bay, the flushing time is approximately 3 to 4 days. It increases going up the eastern shoreline reaching about 9 days in the mouth of the eastern arm.

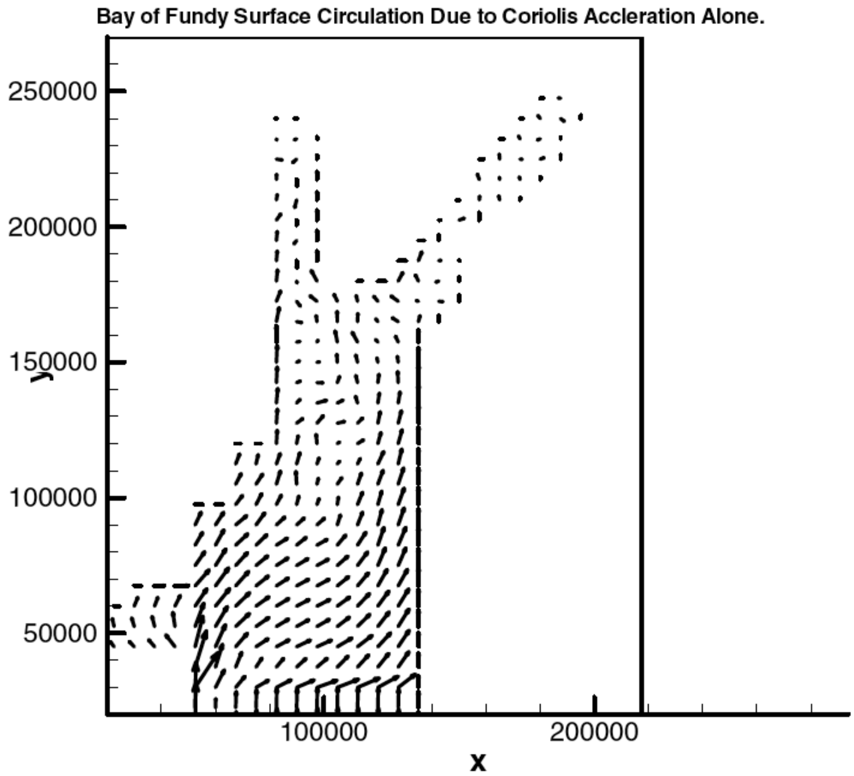

Figure 4: **Dilution and spreading of the Saint Croix River inflow (Source: Author)**

The flushing time is greater at the same latitude along the western shoreline than along the eastern shoreline particularly in the vicinity of the gyres off the entrance of the Saint John River and the long gyre extending south of it. Apparently the gyres play an important role in retaining the water play an important role in retaining the water within the bay along the western shoreline.

6.4 Bottom Velocities and Flushing of the Bay

The isopleths of flushing times along the bottom of the bay are shown along with the bottom velocity vectors. It shows that the tidally averaged bottom inflow is almost uniform along the tidal boundary and extends inward along both the eastern and western shore. The bottom flow is outward from the Saint John River inflow, but is inward to the Saint Croix River embayment.

These results indicate that most of the dilution water entering bay is probably a bottom inflow. The flushing time isopleths have a shape and times similar to the surface values.

7 Influence of Coriolis Acceleration

The Coriolis acceleration results from the rotation of the earth. A particle of fluid moving in a generally northerly or southerly direction will be deflected in relation to the rotation of the earth. This deflection is clockwise in the northern hemisphere. The effect is named after the French physicist Gaspard de Coriolis, who first analyzed the phenomenon mathematically. Coriolis forces are of considerable importance in determining prevailing winds and ocean currents. The Coriolis acceleration increases with latitude. In order to simulate the effects of the Coriolis acceleration, it is necessary to have a generally northerly current. One way to produce a generally northerly current is to impose a surface wind. For this example, a northerly wind speed of 2 m/s is used. There are no freshwater inflows, no tide and no salinity in this simulation. Also, to demonstrate a full Coriolis complete clock-wise circulation like the Gulf Stream, it would be necessary to have a very wide water body where the circulation is not influence by the shorelines.

The results of the simulation are shown in Figure 5 it can be seen that the northerly current that would be induced by the wind is deflected to the right in a clock-wise manner as would be expected due to Coriolis. However, the flow moving to the right piles up against the eastern shore line and begins to move northward leading to a more complex circulation. The velocities resulting from the Coriolis acceleration and a 2 m/s are very small and would be dominated by the stronger tidal velocities. However, the Coriolis acceleration may play a role in moving water toward the eastern shore and adding to the northern circulation along that shoreline

8 Tides and Velocities

The time series of tides and velocity produced by the model is the primary result that should be compared to observed data. Observed tidal elevations are given for a number of locations up the Bay of Fundy in the Attachment. Time series of tides at different locations within the Bay of Fundy show that the mean tide level and tidal range increase when moving up the bay. The computed mean tidal level increases by about 1.5 m between the mouth and

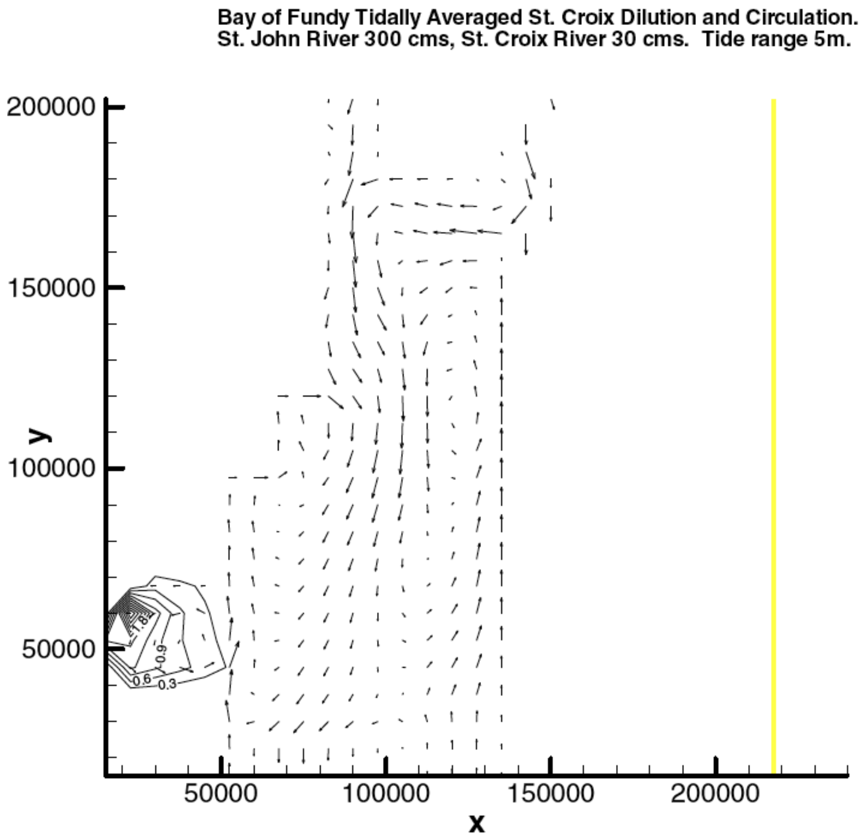

Figure 5: **Circulation with northerly surface wind of 2 m/s and Coriolis acceleration alone. No freshwater inflows, tides or salinity (Source: Author)**

Grindstone Island in the western arm of the bay. The observed data (see attachment) shows an increase in the mean tide level of 2.1 m. Between these two locations, the computed tide range increases by about 2 m while the observations show an increase of about 3 m.

9 Conclusion

The inability to predict exactly the increase in mean tide level and range could be due to local bathymetric features at the Grindstone Island location not included in the model. However, the comparisons are quite good considering the limited detail provided in the model grid. The time series of tidal velocity at the mouth of the bay is shown in Figure 6 it indicates that at this location the current speed reaches a maximum of 2.0 m/s at maximum flood

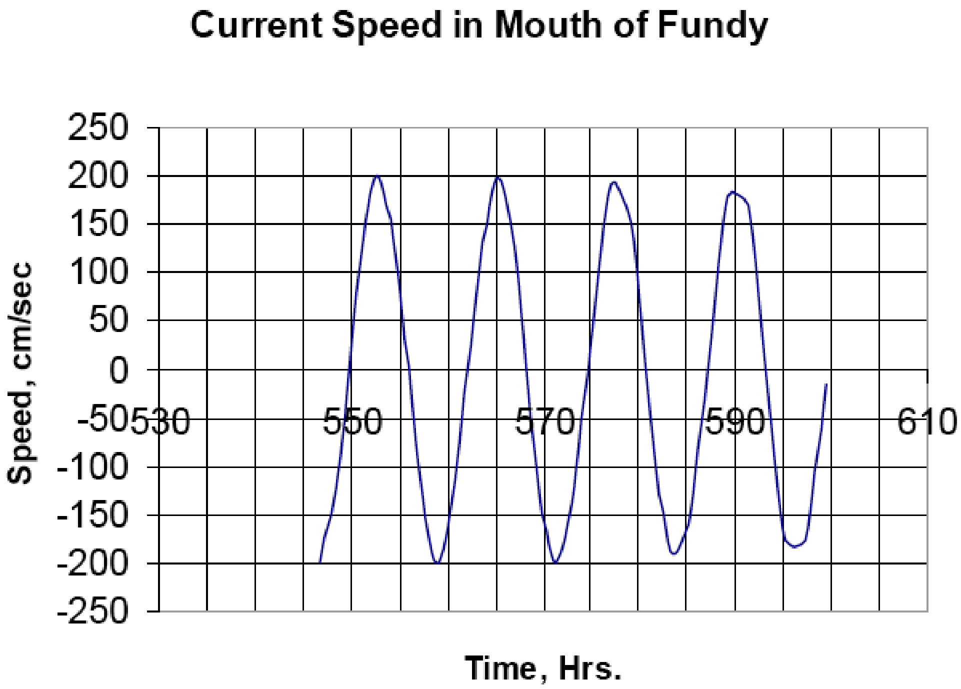

Figure 6: **Current Speed, cm/sec in mouth of Bay of Fundy. NOAA data gives average Current Speed in Grand Manan Channel (Bay of Fundy Entrance) of about 1.28 m/s (2.5 knots) on maximum flood and ebb tide. The above current speeds are based on a tidal range of 5 meters at the mouth of the Bay of Fundy (Source: Author)**

and ebb tide. Data in the attachments give maximum ebb and flood current of about 1.3 m/s (2.5 knots). This difference between observed and computed current speed in the mouth of the bay could be due to overestimating the surface area of the bay in the model grid. This could be due to not having sufficiently accurate maps. Having an incorrect tidal range at the mouth of the bay. This could be due to the tide at the location of the data used is not the same as in the mouth of the Bay of Fundy. Either of these could be examined in greater detail using on site tidal gages with simultaneous wind observations by extending the data base.

9.1 Acknowledgements

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References

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