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Long Term Water Temperature Modeling of the Bay of Quinte, Ontario

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Abstract

During the International Joint Commission (IJC) Lake Ontario and St. Lawrence River Study, research was conducted to predict long term water temperatures in the Bay of Quinte. The purpose of this research was to study of the impacts of the water level management alternatives for Lake Ontario on the availability and quality of fish habitat. To evaluate the management options, water temperatures in the Bay of Quinte, were required over a 101-year period (1900 to 2001). A special hydraulic-temperature coupled model was developed using a one-dimensional hydrodynamic engine to derive the temperature model. The hydrodynamic model was developed earlier for the St. Lawrence River and was adopted for this study employing a double-sweep solution to the tree structured hydraulic system. The solution of the St. Venant's unsteady flow equation was obtained by a finite element predictor-corrector method. The temperature model was based on temperature balance and conservation employing an explicit scheme. In order to simulate and predict water temperatures through out the Bay system, three types of data were acquired, reduced and employed in the model developed. First, bathymetry data were obtained and extracted to describe a cross-section and other geometric and resistance data for the one-dimensional hydrodynamic modeling. Second, discharge and hydraulic data were obtained and estimated from the flow records collected by the Water Survey of Canada, while the water level data for Lake Ontario were obtained from Canadian Hydrographic Service. Finally, air temperature data were obtained from information collected at Belleville. When air temperature data for the earlier period were not available, Toronto data were ported with a regression correction between Belleville and Toronto. The model was calibrated and verified prior to simulation for ice-free periods between April and November. Model calibration and validation were accomplished using water temperature data collected over a three-year period at six sites in the Bay of Quinte. The model showed the same trends as those observed reaching the critical temperatures for spring and fall spawning within the tolerance of the fish habitat model.

Introduction

The International Joint Commission (IJC) recently completed a study of the regulation of Lake Ontario and the St. Lawrence River. The study took five years to complete and cost \$20 million dollars (U.S.). The goal of the study was to develop a new plan to regulate the water levels and flows in Lake Ontario and the St. Lawrence River. The historic regulation plan created in the 1950's considered only the interests of riparian home owners, commercial navigation, and hydroelectric power generation. The new plans evaluated in this study, consider the original interests but additionally the impacts of water level regulation on coastal erosion, recreational boating interests, and the environment.

To evaluate the impacts of water levels on the environment, an Environmental Technical Working Group (TWG) was established. The TWG was tasked with developing science and measures to define the ecological response of the Lake Ontario and St. Lawrence River system to different water level and flow conditions. The Environmental TWG developed performance indicators relating the performance of individual fish, bird, and mammal species to particular regulation plans. One region that was studied by the Environmental TWG was the Bay of Quinte in Ontario. The Department of Fisheries and Oceans (DFO) Canada applied habitat-based fish population models to the Bay of Quinte to predict the growth and reproduction of four species of fish based on daily water levels and water temperature in the Bay of Quinte (Susan Doka, Department of Fisheries and Oceans Canada, personal communication, September 5, 2006). Measured water temperatures for the Bay of Quinte were not available so a water temperature model was developed to fulfill the requirement. This paper documents the water temperature model that was developed and describes how it was utilized to generate historical water temperature at selected locations in the Bay of Quinte. Additional information regarding the Lake Ontario – St. Lawrence River Study can be obtained from the IJC (International Joint Commission 2005).

Study Area

The Bay of Quinte is a 50-kilometre arm of Lake Ontario situated between Hastings and Prince Edward Counties. The study area comprises of water body defined by the Bay of Quinte from the Trent Bay in the west to the outlet of Adolphous reach in the east. The outlet of the Adolphous reach is considered to be at the same water level and thermal regime as Lake Ontario. The study area in context with Lake Ontario is shown in Figure 1.

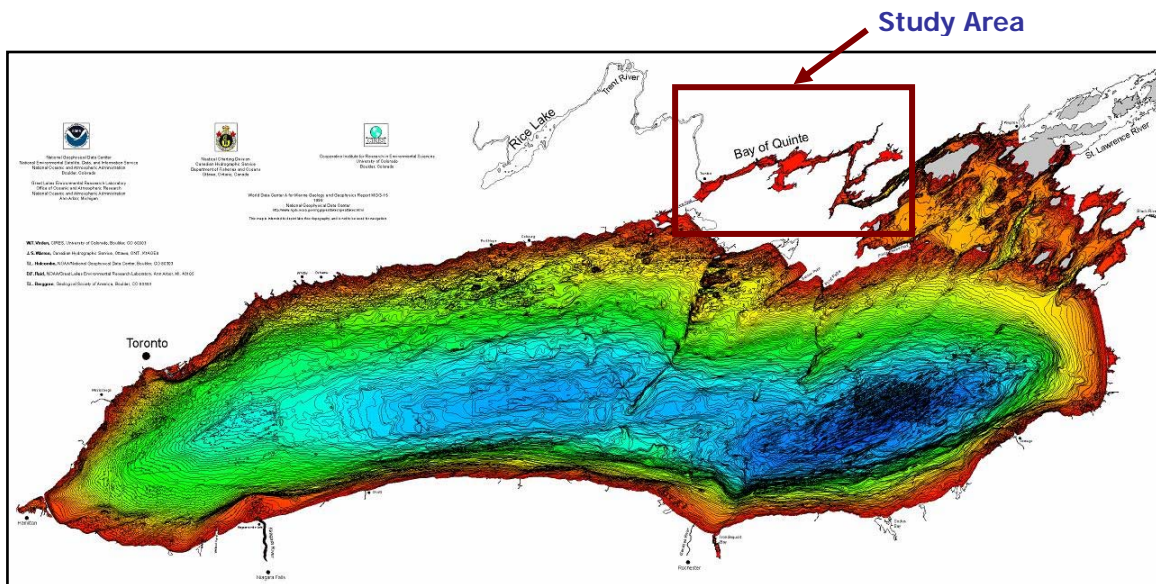


Figure 1

Within the Bay of Quinte there are several Bays connected with long reaches. The important bays are: Trent Bay, Big Bay, Muscote Bay, Hay Bay and Picton Bay. There are two critical reaches namely the Long Reach and Adolphous Reach.

Hydrology and Hydraulics

The hydrology of the area is dictated by the flow in four major streams draining into the Bay of Quinte. From west to east these are: Trent River, Moira River, Salmon River and Napanee River. The majority of the discharge in the Bay of Quinte system comes from the Trent and Moira rivers. The water levels in the Bay are reflective of the water levels in Lake Ontario. The maximum fall occurs during spring freshet when the water levels in the upper parts are 5 to 7 cm higher than the lake levels (do we have a reference?).

Data Collection and Reduction

In order to simulate and predict water temperatures throughout the Bay system, several types of data were acquired, reduced and employed in the model.

Bathymetry data for the Bay of Quinte was obtained from the Canadian Hydrographic Service. The point bathymetric data was used to generate a triangular irregular network (TIN) using the Surface Water Modelling System (SMS) software (Brigham Young University 2001). Bathymetry data were extracted from the TIN as cross-sections for the one-dimensional hydrodynamic model. Figure 2 presents the nature of physical information that was available and Figure 3 shows the discretization of cross-sections for the model.

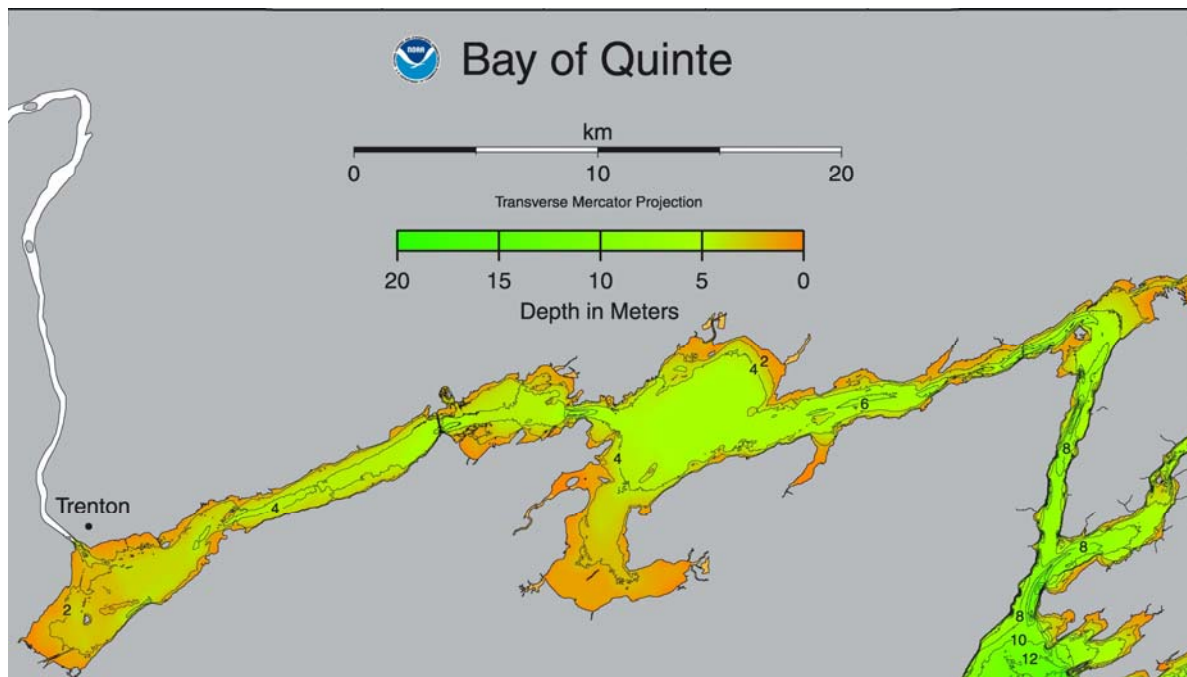


Figure 2

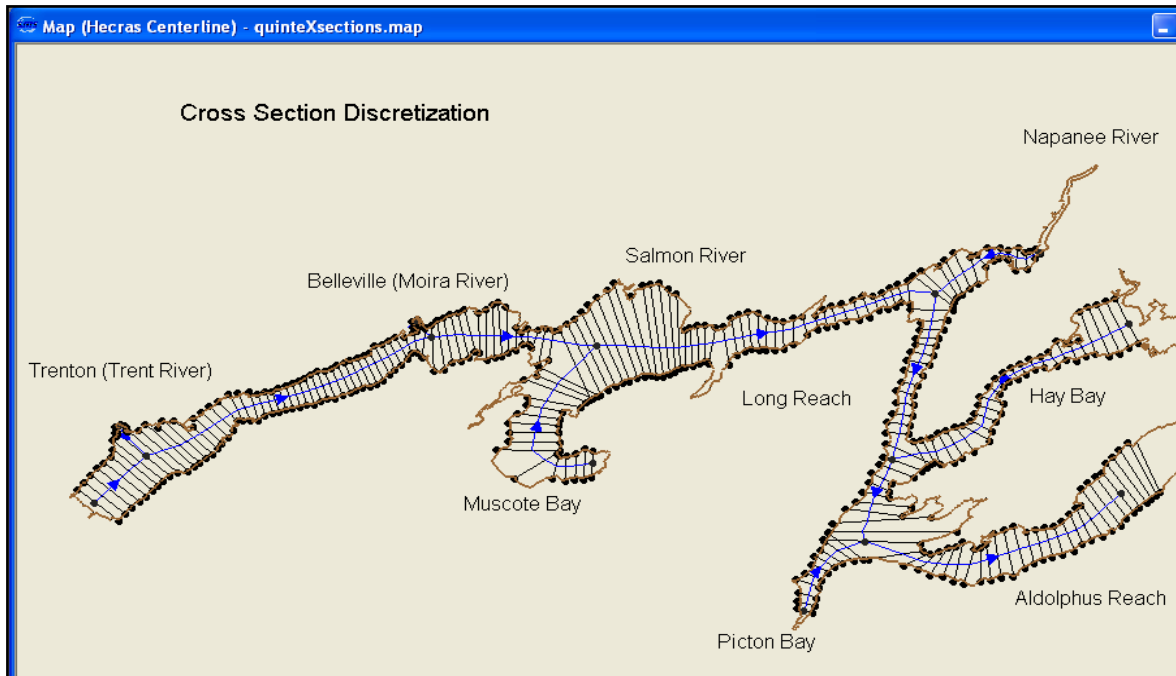


Figure 3

While the east-west distance measured as a crow flies is 50 km, the actual distance along the waterway is about 75 km. A total of 226 cross-sections were extracted to properly discretize the reach and the bays. The maximum and minimum distances between two cross-sections were 2068 and 294 m respectively. The average distance was 486 m, which is more than adequate for this type of modelling.

Hydraulic data was obtained and estimated from the flow records collected and published by the Water Survey of Canada on the Hydrologic Database (HYDAT) compact disk while the water level data for Lake Ontario were obtained from Canadian Hydrographic Service gauge at Kingston. The data consisted of daily flow for the Trent, Moira and Napanee rivers. The flow in Salmon River was estimated by an area ratio developed through regional flow analysis (Moin & Shaw, 1985). For periods when flow data was not available, indirect flow estimation using regression analysis for the net basin supplies was employed. There are no other stations in the study area collecting water level or flow data.

Air temperature data were obtained from information collected at Belleville. When data for the earlier period were not available, Toronto data was ported with regression correction between Belleville and Toronto. In all, 104 years of data were developed (1900 to 2003). Air temperature served two purposes; a four-day average surrogated for the water temperatures in the inflow streams. Further, air temperature provided the exchange between the air and water body for thermal transfer.

Water temperature data were available for six stations in the Bay of Quinte for a three year period. Only six stations had full data from ice free periods of mid-April to mid-November in 2002 and 2003. This data was utilized to calibrate and verify the

hydrodynamic model developed in this study. These stations were operated by Dr. Susan Doka of the Department of Fisheries and Oceans Canada. The stations are depicted in Figure 7 as 46, 66, 109, 125, 145 and 155. The information on the temperature series was generated at these six stations along with the additional 11 stations where data were requested.

Modeling

A special hydraulic-temperature coupled model was developed using one-dimensional hydrodynamic engine to derive the temperature model. The hydrodynamic model was developed by Moin (1979) for the St. Lawrence River and was adopted for this study employing a double-sweep solution to the dendritic (tree) structure for the hydraulic system. The solution of the St. Venant's unsteady flow equation was by a finite element predictor-corrector method. The following equations of continuity and momentum were employed (reference).

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} - q = 0 \quad (1)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial(QV)}{\partial x} + gA \frac{\partial y}{\partial x} - gA(S_o - S_f) = 0 \quad (2)$$

The variables are defined as follows:

- Q = Discharge, m³/s
- A = Cross-sectional area, m²
- V = Area averaged velocity, m/s
- y = depth or stage of flow, m
- q = Lateral flow per unit length, m³/s/m
- S_o = Channel slope
- S_f = Friction slope

Two different time steps were used in solving the equations, three hour and one day. As the two different solutions did not show any difference, all further computer runs were made using daily time step.

The temperature model was based on temperature balance and conservation based on the following generalized relationships (Fisher et al. 1979).

$$\frac{\partial T}{\partial t} + u_x \frac{\partial T}{\partial x} + u_y \frac{\partial T}{\partial y} + u_z \frac{\partial T}{\partial z} = \frac{\partial}{\partial x} \left(D_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(D_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(D_z \frac{\partial T}{\partial z} \right) + \frac{q_{net} A}{\rho_w C_s V} \quad (3)$$

Simplified to:

$$\frac{\partial T}{\partial t} + u_x \frac{\partial T}{\partial x} = \frac{q_{net} A}{\rho_w C_s V} \quad (4)$$

Where:

T = Temperature, °C

x, y, z = independent distances in three Cartesian directions

u_x, u_y, u_z = Velocities resolved in x, y and z directions

q_{net} = Net heat flux

T_e = Equilibrium temperature, °C

C_s = Specific heat

ρ_w = Density of water, kg/m³

A = Surface area between cross-sections, m²

V = Volume of water in the reach, m³

The upstream boundary was the Trent River outflow described using discharge data while the downstream boundary was Lake Ontario at the end of Adolphous Reach specified using water levels.

Model Calibration and Verification

To calibrate the model the factor K in equation 4 was adjusted to obtain a reasonable fit. The calibration utilized the year 2002 data and was repeated until a good fit between the simulated and observed water temperature was achieved. The key parameters employed for goodness of fit were the dates when the temperatures start to rise, the day-to-day fluctuations and the date in the fall when the temperature starts to drop off. In some cases the fit was not as good as was required. This was due to the fact that a number of causal factors were not thoroughly accounted. Such data were not available (e.g. radiation, cloud cover, wind near water surface, canopy effects, etc). Two examples from the calibration runs are shown in Figures 4 and 5. For the purposes of model verification, year 2003 data was employed. The model was executed to simulate year 2003 water temperatures with model factor K determined during the calibration. The performance of the model was again measured against the same goodness of fit measures and was determined to be adequate.

In general, the model reproduced the water temperature regime in the Bay of Quinte well. Based on the performance of the model during the calibration and verification runs, it is evident that the surrogate four-day average air temperature to estimate tributary water temperatures provided reasonable results.

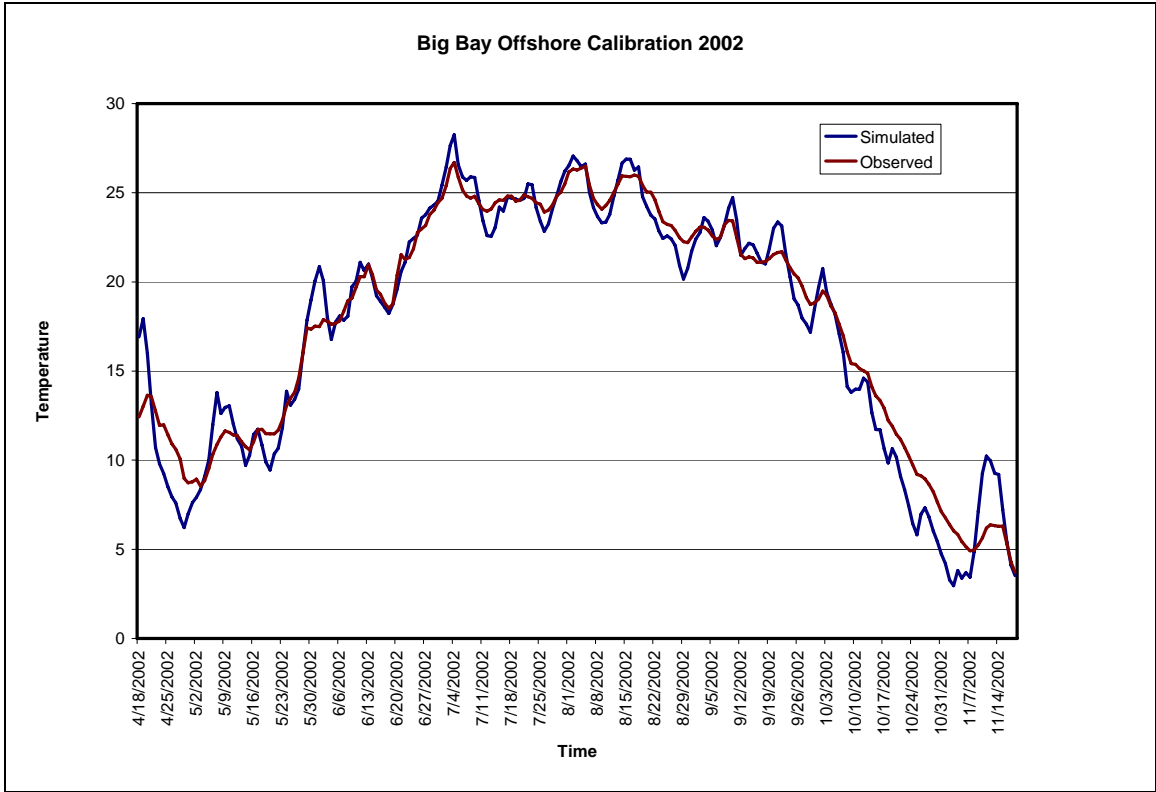


Figure 4

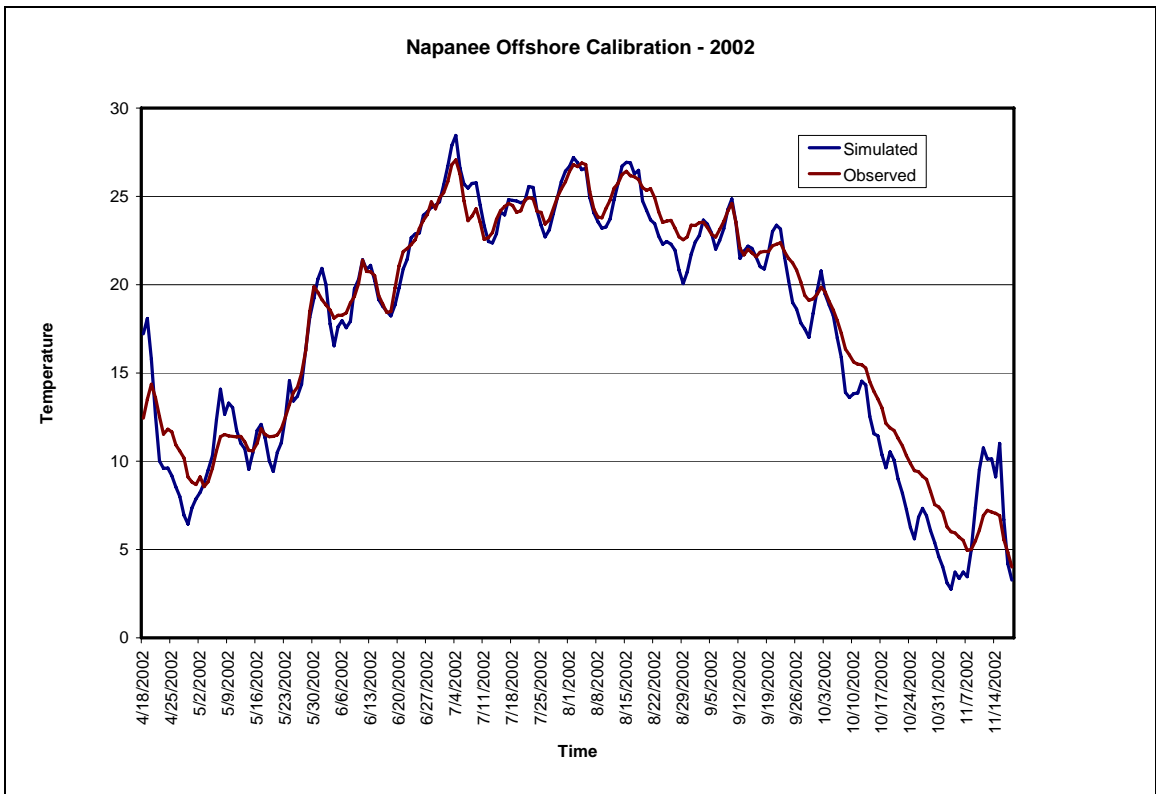


Figure 5

IJC Study Application

After the model was calibrated and validated, it was applied for the IJC study. The simulation was carried out for 1900 to 2001 year period. The model was run continuously for this time period. The water temperature data was then utilized to evaluate the health of fish species in the Bay of Quinte for 100 year time periods under various water level regulation plans. To deal with ice, when the water temperature reached one degree Celsius, the Bay is assumed to be frozen until such time as the water temperature rises above one degree Celsius in the spring. Water temperature during winter was not of interest to the Environmental TWG fish scientists.

A special program was written to parse the output into two types of files. The first set of parsing involved writing the output in Microsoft Access database format; variables were stored in a manner such that the Environmental TWG would have direct access to the results for their habitat modeling purposes. The second set of data parsing involved writing a special program that populated a Microsoft Excel spreadsheet on a yearly basis for a number of variables. It also outputted graphs for water temperature, discharge and velocity and tables for other variables. The model output locations are shown in Figure 6.

The 101-year simulation provides a reasonable estimate of the water temperature in the Bay of Quinte. Anecdotal information received during study discussions with the public indicated that the water temperature in the Bay of Quinte reached an excess of 30 degrees Celsius in 1936 which was faithfully reproduced by the model during the simulation.

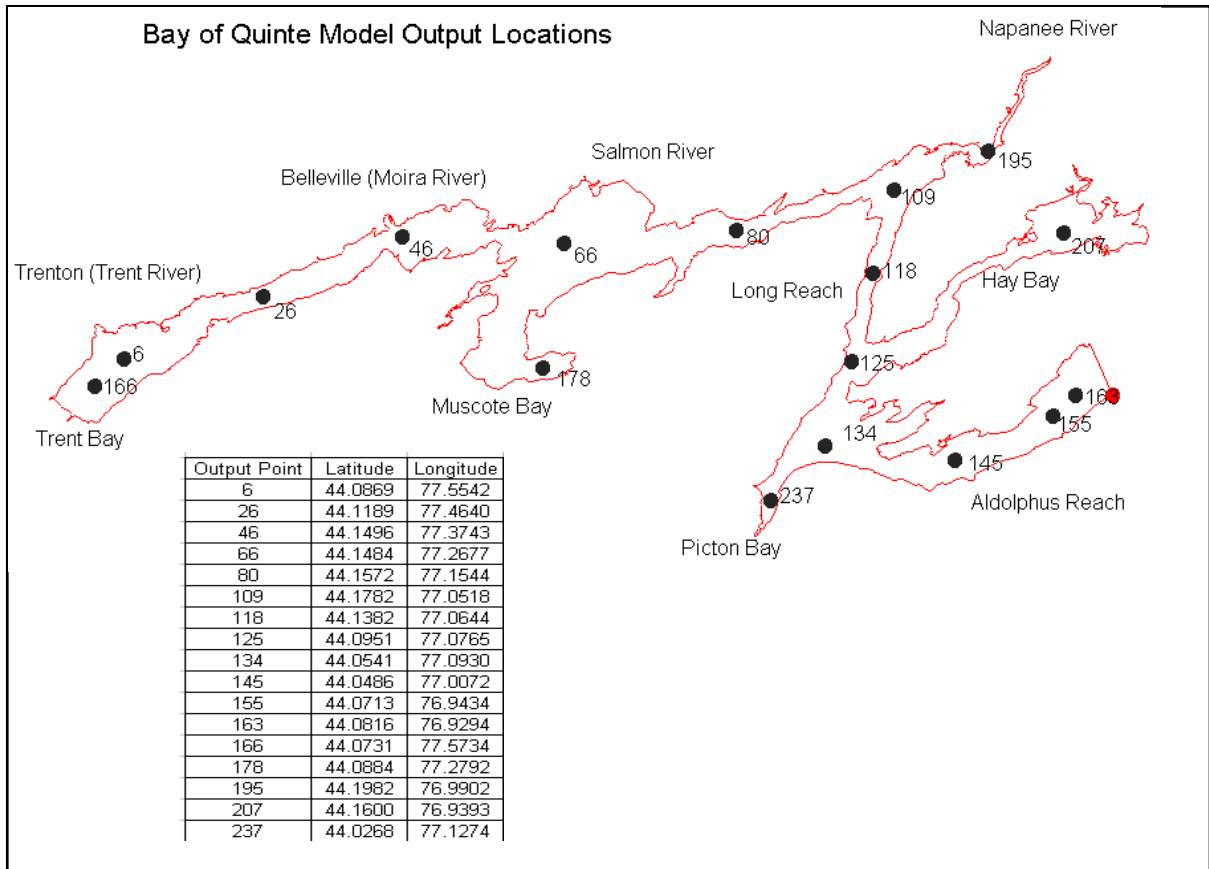


Figure 6

Conclusions

To meet the needs of the Environmental Technical Working Group during the Lake Ontario and St. Lawrence River Study, a water temperature model of the Bay of Quinte was developed. The model calculates daily water temperature at 226 cross sections within the Bay based on air temperature, tributary flow and Lake Ontario water temperatures. The model was applied to generate 101 years of daily water temperature for use in fish habitat models for the Bay. The model was able to reproduce the water temperature regime in the Bay of Quinte well.

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