# SOURCE WATER PROTECTION: PROTECTING OUR DRINKING WATERS

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## ABSTRACT

*Many municipalities throughout the world rely on surface water for their drinking water supply. These surface waters include lakes, rivers and streams where intake pipes withdraw water for drinking. These intakes may be located in areas where risk of contamination (accidental or malicious) may be high. Special consideration to homeland security in the wake of the recent events and terrorist activities has countries such as USA and Canada develop plans to protect source waters for intakes. Protecting this intake water means protecting the surrounding water defined as intake protection zone (IPZ). The area of water and land within an IPZ is usually determined based on a variety of factors such as the amount of time it would take for any contaminant to flow towards the water intake. This amount of time is called the time of travel (TOT) and usually depends on the response time needed for any mitigation measures. Typically the TOT adopted for the delineation of IPZ is the time plant operators need to respond to the contamination. In Canada this is chosen as two (2) hours. Depending on the hydrodynamic conditions, the IPZ for a two hour TOT can vary significantly from one waterbody to the other.*

*This paper demonstrates a study performed for the Lake Simcoe Region (LSR) and Nottawasaga Valley Conservation Authorities (NVCA) to delineate the IPZ for five municipal drinking water systems that withdraw water from Georgian Bay in Lake Huron, Canada. Development of IPZ required a development of detailed hydrodynamic and transport models for regions near these intakes. The regions of primary interest for this study were at three distinct locations: Collingwood, Severn Sound and Christian Island. Within these regions, limited data were available to ensure successful hydrodynamic model setup and calibration. Thus, a nesting approach was adopted where a far-field study region was first selected which covered the entire Georgian Bay. The hydrodynamic model was set up and calibrated for this far-field region. Once calibrated, the model outputs were used to set up three separate near-field (regional) models. Using a regional model allows adopting higher resolution modeling grids which are essential to capture the intake zone of influence and the hydrodynamic aberrations attributable solely to the intake operations.*

*The modelling system employed in this study is called GEMSS®, an acronym for Generalized Environmental Modelling System for Surfacewaters. GEMSS® is an integrated system of 3-D hydrodynamic and transport modules embedded in a Geographic Information System (GIS). A new module called Source water protection zone module (GEMSS®-SPM) was also developed that can compute the TOT for spill contaminants to an intake. The module runs in conjunction with GEMSS®-HDM (Hydrodynamic Module) retrieving the circulation data and transporting the spill constituents while marching forward in time. Both Lagrangian and Eulerian transport algorithms were developed to transport spill constituents. GEMSS®-SPM, at the end of a model simulation, provides a spatially varying probability contour depicting the probability of individual regions contaminating the intake within the defined TOT.*

## INTRODUCTION

IPZ is the area around a surface water intake where potential contaminants could pose a significant risk or threat to the source water. In most cases, the protection zone includes the water and the land that surrounds the intake and takes into account the influence of land use and water activities. In this study, the extent of the zone within a waterbody is developed. These zones are established based on the amount of time that it could take for any spilled contaminant to reach the intake. There are three distinct zones within IPZ that are defined as follows:

1. *IPZ-1*: This is the zone closest to the intake where the contaminant reaches the intake with little or no dilution. IPZ-1 is usually defined as a region within the 1-kilometre radius around the intake. However, consideration is given to the withdrawal zone based on the intake velocities and time of travel.

2. *IPZ-2*: IPZ-2 is the next zone beyond IPZ-1 where time of travel is considered along with the spatially varying hydrodynamic circulation. A two-hour time of travel is considered appropriate to allow a water plant operator time to shut down the intake and deal with a potential spill or threat to the source water supply. All factors affecting the hydrodynamics such as local currents, river and stream flows, and any municipal storm sewers or drains that empty into the lake are also considered.
3. *IPZ-3*: IPZ-3 is the zone that considers extreme events such as storms, strong winds and high waves. This zone extends beyond the IPZ-2 and is conservative considering events that have a lower probability of occurrence but with higher impacts on the environment.

The development of both IPZ-2 and IPZ-3 requires comprehensive understanding of the local flow patterns, meteorological conditions and historical extreme events. This is normally accomplished by setting up a 3-D hydrodynamic model for the study region; obtaining spatial and temporally varying currents, and subsequently developing a transport model to model the travel of various contaminants from the point of spill to the intake.

In this paper, all three IPZs have been developed for five intakes located at three distinct locations: Collingwood, Christian Island and Severn Sound. Both Collingwood and Christian Island regions have one intake each while Severn Sound has three intakes: Beausoleil, Rope and Victoria Harbor. In addition to the development of the three IPZs, a generic risk analysis approach is also shown that is useful in cases where facility response plan isn't available, and limited information is available in terms of risk of contamination.

## MODELLING APPROACH

The modelling system employed in this study is called GEMSS®, an acronym for Generalized Environmental Modelling System for Surfacewaters. GEMSS® is an integrated system of 3-D hydrodynamic and transport modules embedded in a Geographic Information System (GIS) and environmental data system, grid generator and editor, control file generator, 2-D and 3-D post processing viewers and additional tools such as meteorological and time varying data generators to aid the modelling process. The modules used for this study were the hydrodynamic and transport module (GEMSS-HDM) and the source water protection zone module (GEMSS-SPM).

### GEMSS® – Hydrodynamic Module (HDM)

GEMSS-HDM is a state-of-the-art three-dimensional numerical model that computes time-varying velocities, water surface elevations, salinity and temperature in rivers, lakes, reservoirs, estuaries, and coastal water bodies. Prior to 2000, GEMSS-HDM was referred as GLLVHT (Generalized, Longitudinal-Lateral-Vertical Hydrodynamic and Transport) which has been peer reviewed for several applications (Buchak and Edinger, 1984).

The theoretical basis of GEMSS-HDM was first presented in Edinger and Buchak (1980) and subsequently in Edinger and Buchak (1985). Essential improvements to the transport scheme, construction of the constituent modules, and the incorporation of supporting software tools well as the GIS interoperability, the visualization tools, the graphical user interface (GUI), and the postprocessors have been developed by Kolluru et al. (1999; 2003a; 2003b) and Prakash and Kolluru (2006). GEMSS® and its component modules have met agency approval in the U.S. and Canada many times since 1981. GEMSS®-based studies have been accepted by the U. S. Environmental Protection Agency (EPA), several U.S. state agencies including California, Massachusetts, Pennsylvania, Louisiana, Texas and Delaware. Washington State's Department of Ecology has adopted GEMSS® as their standard tool for estuarine and water quality modelling. Recently GEMSS® has been published as a recommended 3-D hydrodynamic and water quality model in studies funded by EPA (HGL and Aqua Terra, 1999) and by the Water Environment Research Foundation (Water Environment Federation, 2001).
The computations are done on a horizontal and vertical grid that represents the waterbody bounded by its water surface, shoreline, and bottom. The water surface elevations are computed simultaneously with the velocity components. The water quality constituent concentrations are computed from the velocity components and elevations. Included in the computations are boundary condition formulations for friction, wind shear, turbulence, inflow, outflow, surface heat exchange, and water quality kinetics. The model can be used to analyze system dynamics and predict the impacts of actual events or possible design or management alternatives.

### GEMSS®-Source water Protection zone Module (SPM)

Source water protection zone module (GEMSS-SPM) is a state of the art three-dimensional transport module that can compute the time of travel for spill constituents to an intake. The module runs in conjunction with GEMSS-

HDM retrieving the circulation data and transporting the spill constituents while marching forward in time. The interaction between GEMSS-SPM and GEMSS-HDM can be simultaneous (both running at the same time) or sequential (GEMSS-HDM currents written to a file which is read by GEMSS-SPM as input) depending on the user's preference. Sequential mode is usually preferable when the region of interest is relatively large and the computational time is of concern. Transport computations do not suffer from severe time step limitations that are imposed by on hydrodynamic modelling and thus can be run at larger time steps reducing computational time. Both Lagrangian and Eulerian transport algorithms were included. If Eulerian algorithm is used, then GEMSS-SPM introduces unique dye at each individual model cell and tracks its movement till the end of an iteration. Iteration ends when either the dye concentration at the target zone (intake cell) is above the threshold concentration or the total elapsed time is greater than the time of travel criterion. In Lagrangian algorithm, GEMSS-SPM introduces several clusters of particles (user defined) for each individual model cell within the region of interest and tracks their movement till the end of the iteration. Iteration ends when either the number of particles is above the threshold number in the target zone or the time elapsed is more than the time of travel criterion. Threshold concentration is usually defined as dilution less than which can pose a potential threat to the intake water. For instance if the release dye concentration is 100 mg/l (or number of particles released is 1000) then a threshold dilution value of 1000 will mean a target concentration of 0.1 mg/l or 1 particle. The entire simulation consists of several iterations (total simulation period/time of travel criterion) during which GEMSS-SPM keeps track of the number of times the dye or particles from individual model cells have met the contamination criterion (reaching or exceeding the target number of particles/concentration within the time of travel criterion) and uses it to compute a probability envelope.

Within the GEMSS-SPM framework, the user is presented with flexibility in the way computations are carried out and impact criteria are defined. Both Eulerian and Lagrangian methods share substantial sets of parameters. The user first selects the region of interest which is usually chosen to be slightly bigger than the expected withdrawal zone for the intake. Next the user selects the target zone (intake location) by specifying the model cells in which the intake exists. During the Eulerian computations, only the intake cells are needed to be specified. However, during the Lagrangian computations, the intake location and the target zone dimensions are defined. The vertical extent of the zone in Lagrangian method (and vertical layers in Eulerian method) is usually chosen based on the intake location and level of conservatism desired. The vertical zone can be chosen to extend from top to bottom to be conservative as it will accommodate for additional vertical movement (buoyancy/settling) that constituents may experience that are not modelled by the conservative dye (or particles). Subsequent to these parameters, if Eulerian method is used, the user can select the type of target concentration computation method. If the target zone consists of several cells (horizontal as well as vertical layers), the user can select instantaneous or regional average. If instantaneous is selected than the maximum concentration in the target zone is used and if regional average is chosen then the model computes the volumetric average concentration. In the end the user has to select the initial concentration of dye (or initial number of particles to be released), the target concentration (or number of particles) and the time of travel criterion based on the response time. The end result is a cumulative probability contour depicting the zones with different probability of contaminating the intake cell (or target zone) within a pre-defined time of travel (time of travel criterion). This probability plume can be used to delineate a source water protection zone, or help to define its characteristics.

## MODELING METHODOLOGY

The regions of primary interest for this study were at three distinct locations with a relatively small spatial extent (Figure 1). Since limited data were available in these regions to ensure a successful hydrodynamic model setup and calibration, a nesting approach was adopted where a far-field study region was first selected. This far-field model that covered the entire Georgian Bay was set up and calibration using available data. Measured surface elevations and water surface temperatures at multiple locations were used as calibration targets for this far-field model. Once calibrated, the model outputs were used to set up separate near-field (regional) models for Collingwood, Severn Sound and Christian Island. Using a regional model allows adopting higher resolution modelling grids which are essential to capture the intake zone of influence and the hydrodynamic aberrations attributable solely to the intake operations. These near-field models were also calibrated using measured temperatures and currents (ADCP and drogues) as calibration targets.

The far-field model grid varied in resolution throughout the Georgian Bay. Lower grid resolution (6 km) was used in the northern half of the Georgian Bay, medium (3 km) in the outer Nottawasaga Bay and higher (1.5 km) near the Collingwood Intake, Christian Island and Severn Sound. The model grid is shown in Figure 2. The near-field grids that covered the three regions of interest are shown in Figure 3. The grid resolution for near-field grids ranged between 30 m to 60 m near the intakes. Highest resolution was adopted at the intake locations. The

Severn Sound near-field grid that contained three intakes had spatially varying grid resolution such that the intakes were located in the regions of higher resolution. Figure 3 shows the three near-field model grids.

All models were forced with time varying fresh water flows from the Nottawasaga River, Severn River and other rivers entering the bay. Several meteorological stations were available throughout the Bay including two buoys that provided data for surface heat exchange computations along with the wind stresses. Spatial interpolation (inverse distance weighing) was applied to calculate the applicable meteorological constituent (air temperature, solar radiation, wind speed etc) to each computational model grid. The connections of Georgian Bay to Lake Huron were in terms of open boundary water surface elevations at Tobermory and Little current (Figure 1).

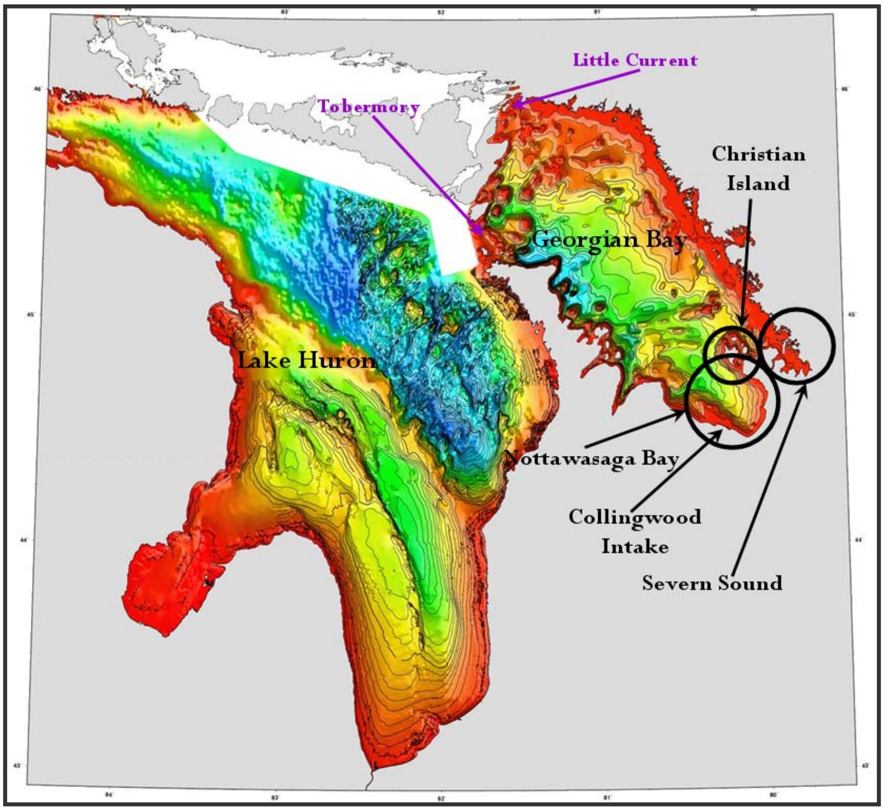


**Figure 1 Region of interest: Lake Huron and Georgian Bay**

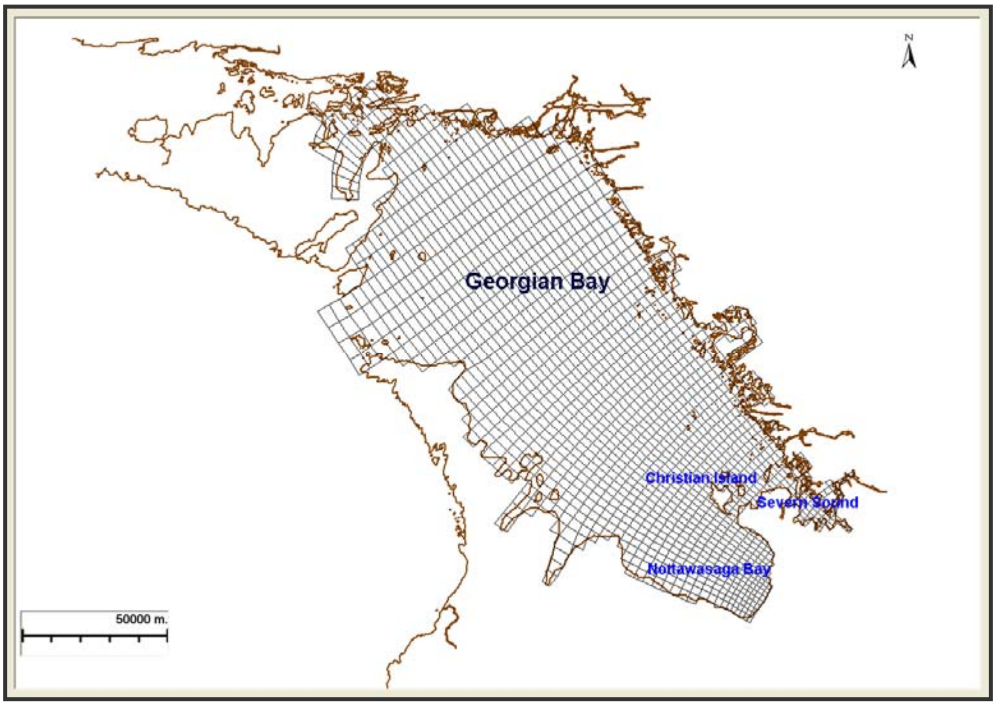

**Figure 2 Far-field model grid for Georgian Bay**

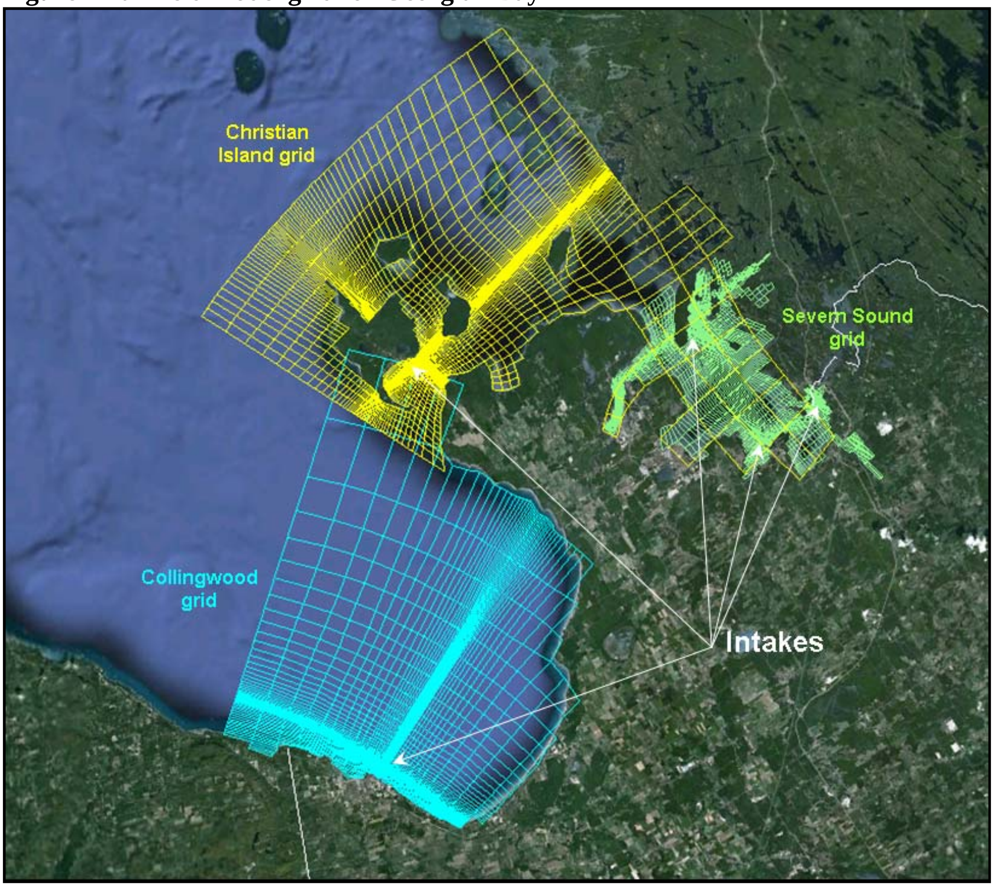

**Figure 3 Near-field regional grids used for GEMSS-SPM analysis**

**MODEL CALIBRATION**

The far-field Georgian Bay model was calibrated using available data that included elevation data at two locations (Collingwood and Parry Sound) and the temperature data at three locations (C45137 and C45143 buoy and Collingwood intake). The model simulation was done for a 4 month period starting 05/01/2006 to

09/01/2006. The circulation in Georgian Bay was found to be mostly wind driven with influence of local bathymetry.

The near-field models for Collingwood, Severn Sound and Christian Island were developed using water surface elevation and temperature results from the far-field grid. These results were applied at the open boundaries of these regional model grids. The results from these near-field grids were compared to measured currents (ADCP and drogues) along with the measured temperatures.

**Far-Field Model**

The far-field model was calibrated to water surface elevation data at two separate locations at Collingwood and Parry Sound. The comparison of model computed water surface elevations against the measured elevations are shown in Figure 4. The model reproduces the measured surface elevations well with the exception of some instances when the model fails to reproduce sudden elevation peaks. This is expected as some of the localized flow conditions can not be modelled with a resolution adopted for the far field grid. The measurements are also sensitive to sudden wind events which are also not reflected in the model setup.

Temperature data at three locations were available for the calibration of the far-field model. These locations consisted of two buoys and the Collingwood intake. Figure 5 shows the temperature time series as predicted by the model at these three locations along with the measured temperatures. The model successfully reproduces the temperature pattern at these three locations.

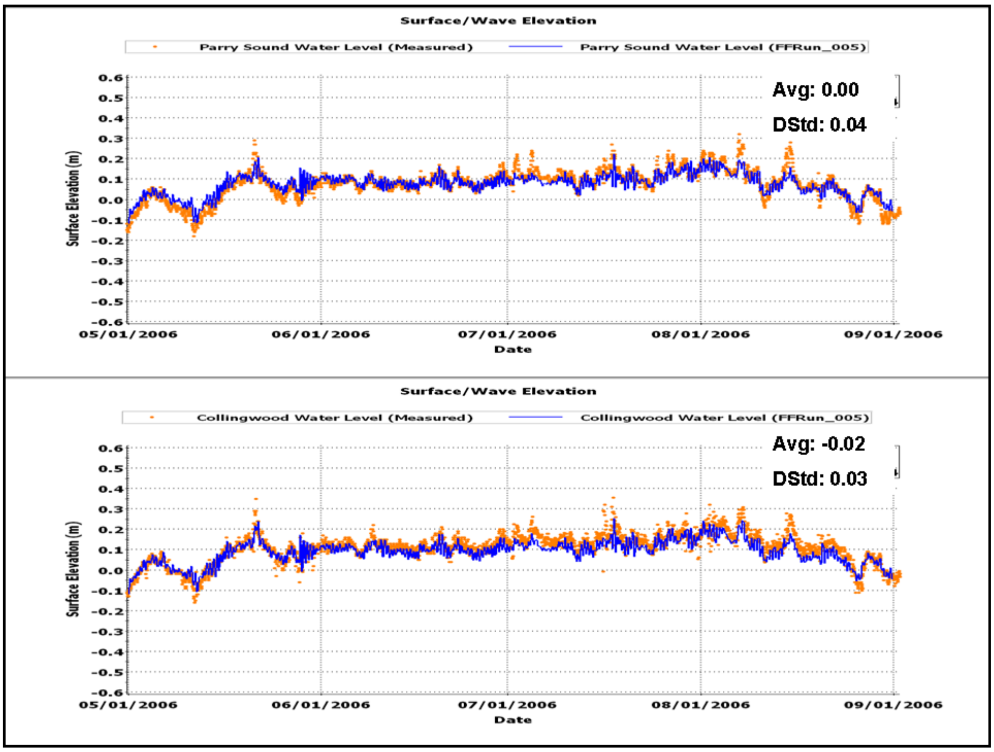


**Figure 4 Far-field Georgian Bay model: water surface elevation comparison**

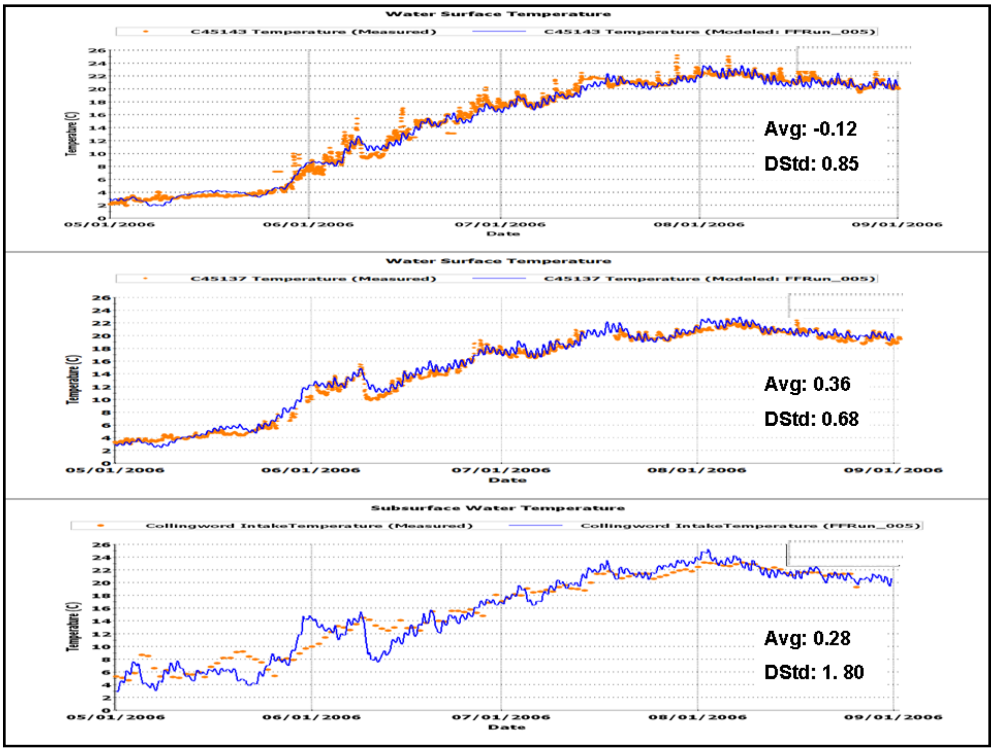


**Figure 5  Far-field Georgian Bay model: water surface temperature comparison**

## Near-Field Models

The three near-field models set up using outputs from the far-field model were calibrated based on currents measurements (ADCP and drogues) and temperature measurements. For brevity only a few comparisons are shown. Figure 6 shows the modeled currents versus currents calculated from released drogues near Collingwood intake. Figure 7 shows the comparison against measured currents using ADCP and Figure 8 shows the comparison against measured temperatures in Severn Sound. The near-field models perform well in reproducing observed currents and temperatures.

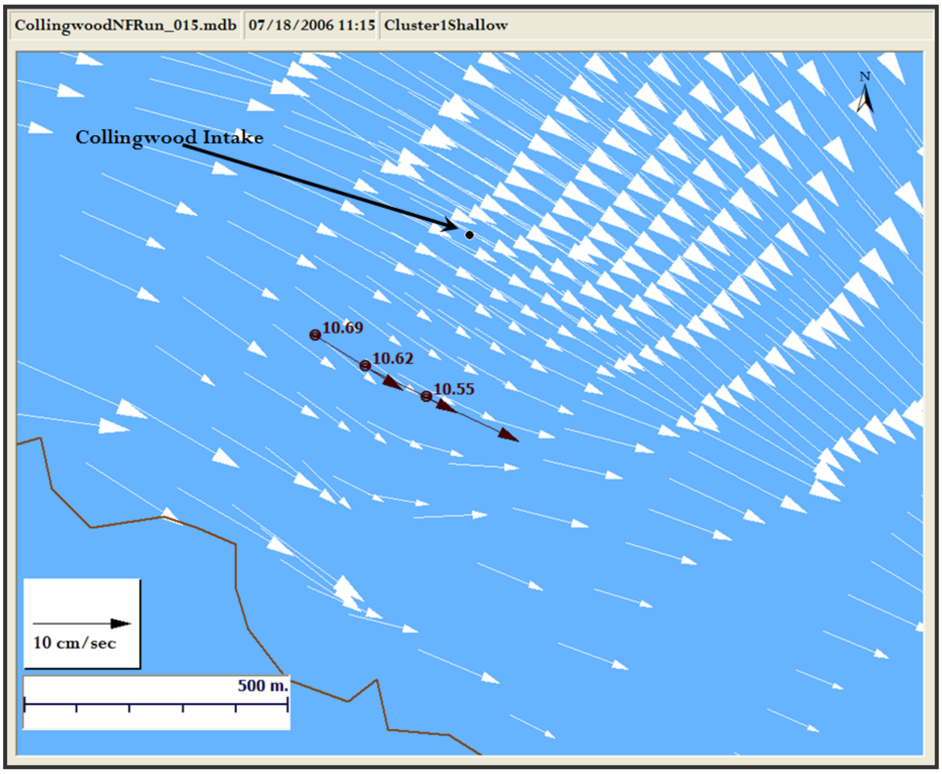

**Figure 6 Model predicted currents compared with measured currents using the drogue results at a depthf of 2 m below water surface**

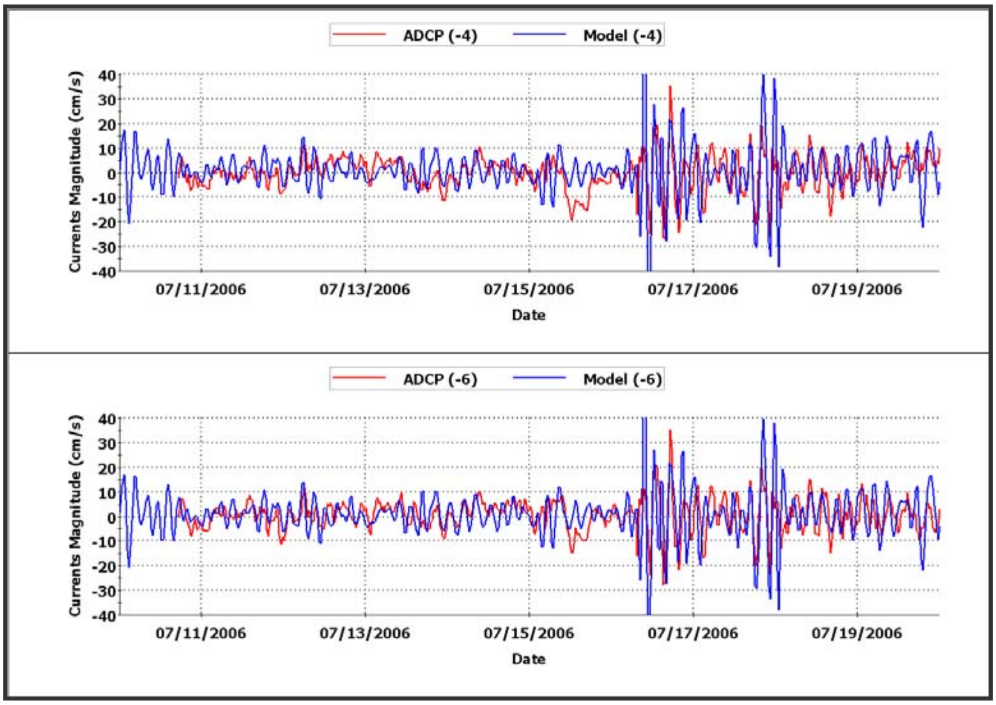

**Figure 7 Modelled vs observed currents at an ADCP location at depths of 4 m and 6m below surface (+ve: towards NNW, -ve: towards SSE)**

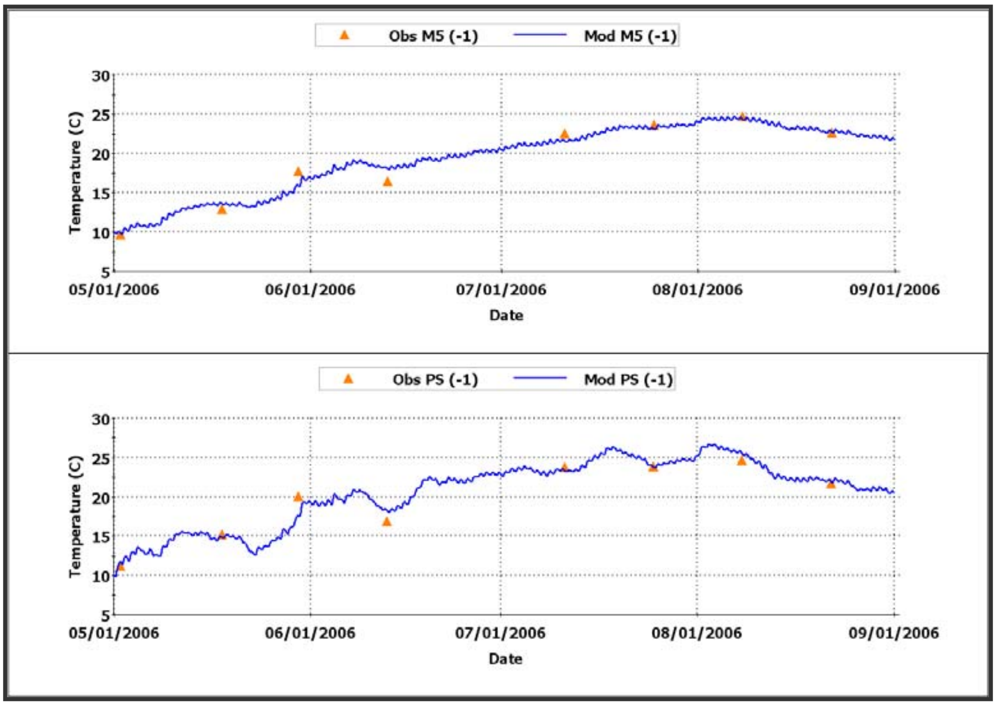


**Figure 8 Modelled vs observed temperatures at two locations within Severn Sound**

**DEVELOPMENT OF IPZ**

Delineation of different IPZs requires a rigorous analysis of the withdrawal zone for the intake and the regional circulation pattern. Circulation in a region is a complex function of bathymetry, meteorological conditions, river discharges, intake operations and other similar forcings. Preliminary withdrawal zone analysis to develop IPZ-1 was done to estimate the probable region of risk for intake contamination. IPZ-1 provided information that was then specified in GEMSS-SPM to develop a more detailed IPZ-2. Finally, the same settings for the regional models were used under extreme event conditions (e.g. storm events) to develop IPZ-3. Due to the extent of the region of interest and the high model grid resolution, the Lagrangian method was adopted to increase computational efficiency. The time of travel for any contaminant to the intake was set at 2 hours and the target dilution of 1000 was adopted. Cluster of 1000 particles were released at each individual model cell within the region of interest and a target number of 1 or more particles was defined as potential threat for contamination. The flow in Georgian Bay is mostly wind driven which leads to the surface velocities being higher than the layers below it. Due to this the particles were only released at the surface. Releasing the particles at the surface with higher velocities will result in a bigger withdrawal zone making the study conservative. Also, the target zone was defined at the intake location with an extent of 50 m in both directions and extending from top to bottom.

**IPZ-1**

IPZ-1 is usually delineated as part of the circulation analysis by developing a possible intake withdrawal zone. The travel time of 2 hours and the current rose plots for the currents modeled at the intake location can be combined to develop a withdrawal distance rose plot which would show the extent and orientation of the withdrawal zone around the intake. These distance rose plots can serve as a preliminary indicator of the zone that may pose risk to the intake. Figure 9 shows these distance rose plots for the three Severn Sound intakes. The orientation of the petals in each rose plot correspond to the direction in which the source water is withdrawn, the length of these petals show the probability of withdrawal from the direction and the color of the petals denote the distance of withdrawal. The IPZ-1 at the Beausoleil intake is oriented north-south. This is due to the shoreline near the intake which is oriented along the same direction resulting in currents that follow the north-south direction. The IPZ-1 for Victoria Harbor is predominantly oriented towards west-east. This is the result of the shoreline to the south suggesting that the source water predominantly is from west or east of the intake. The IPZ-1 for Rope intake is from north or northwest. Severn River enters Severn Sound just north of the Rope intake. This river provides the main source water to the Rope intake due to which the IPZ-1 is predominantly in the north direction.

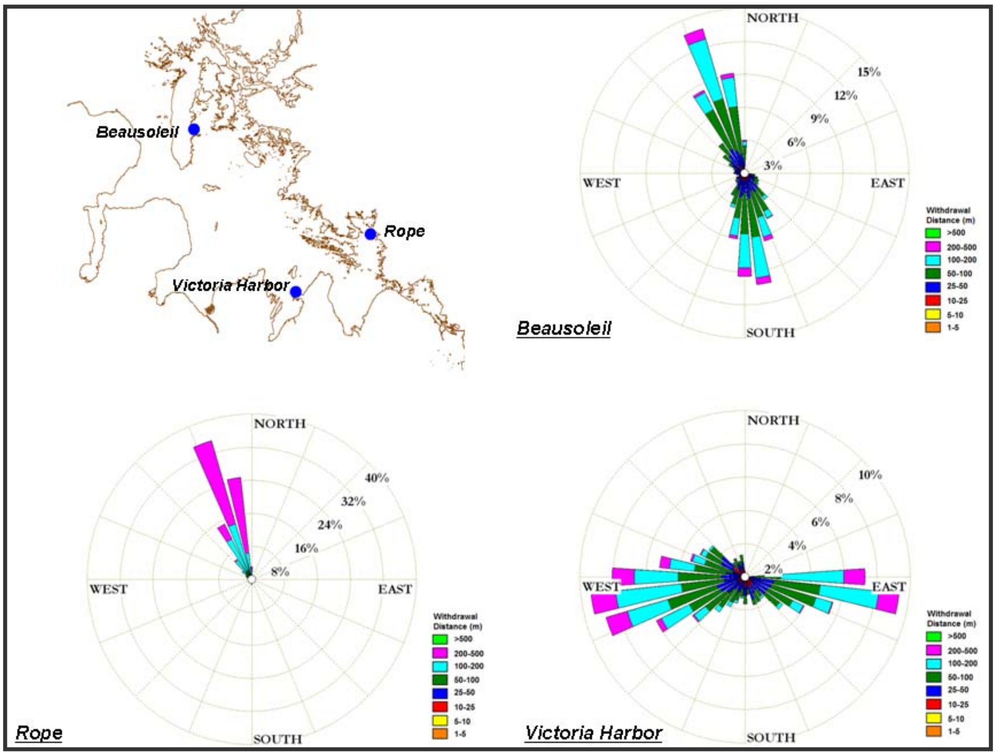


**Figure 9 IPZ-1 delineation in the form of withdrawal distance rose plots for the three Severn Sound intakes**

### IPZ-2

The delineation of IPZ-1 suggested that the extent of the withdrawal zone is within 1000 m with probability of contamination at the intake decreasing due to a spill beyond this zone. The IPZ-1 also suggested that the zones will be elongated along the shorelines near the intakes. Using this information GEMSS-SPM was set up with region of interest defined as an area extending about 2000 m in the alongshore direction and about 500 m in direction of low risk. The simulations were run for a period of 4 months individually for each of the five intakes to obtain the probability contour. The boundary of the region with probability of more than 0.1% was defined as IPZ-2. Figure 10 shows the IPZ-2 obtained for the Collingwood intake for both regular and storm events. The IPZ-2 extends about 1.5 km and 2.5 km in east and west directions, respectively. Beyond this region, the contamination to source water will have a negligible (<0.1%) chance of reaching the intake within the 2 hour travel time.

Similarly, Figure 11 shows the IPZ-2 for the remaining four intakes. The IPZ-2 extends approximately 650 m for in northeast direction for the Beausoleil intake. The extent of this IPZ-2 is approximately 450 m in both east and west direction for the Victoria Harbor intake and approximately 1.1 km in north and the northeast direction for the Rope intake. The IPZ-2 is the largest for Rope intake due to the presence of Severn River that introduces high flows and thus larger withdrawal zone The Christian Island intake IPZ-2 extends approximately 750 m in north-east and south-west directions; 200 m towards the shoreline and 1 km away from the shoreline.

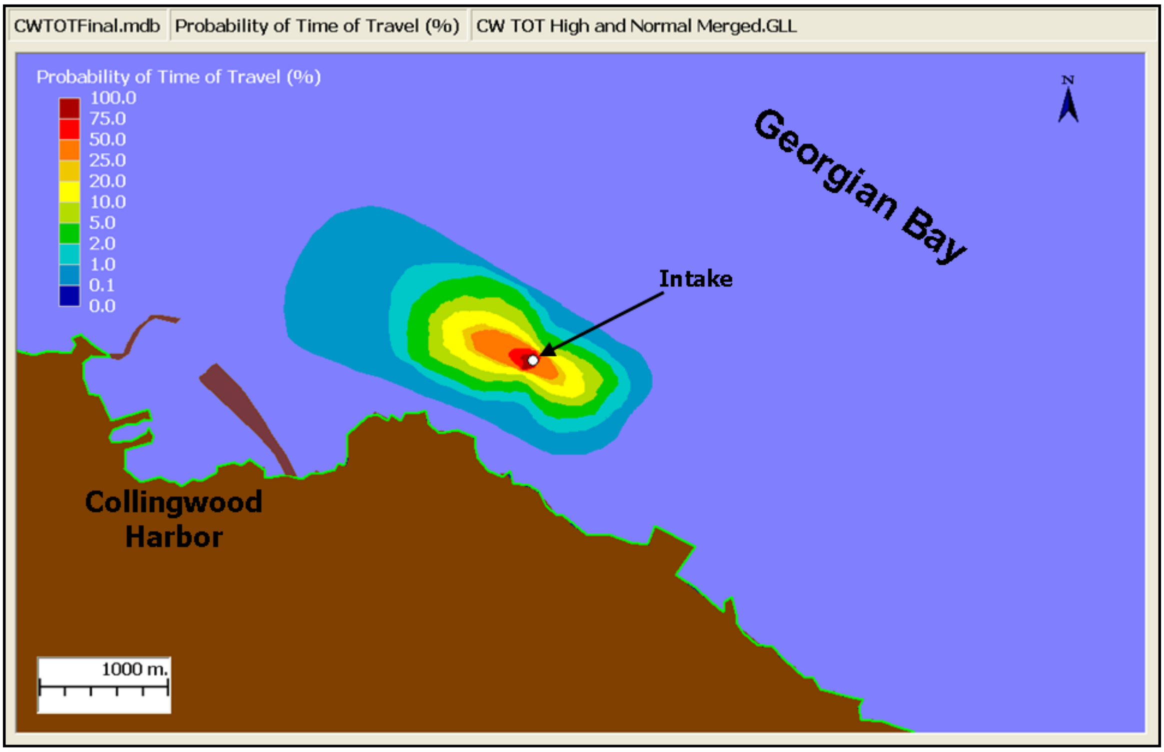


**Figure 10 Probability envelop and IPZ-2 extent for Collingwood intake using the 2 hour time of travel criteria for a target contamination of dilution less than or equal to 1000 (cumulative for the 4 month simulation period with regular and storm events)**

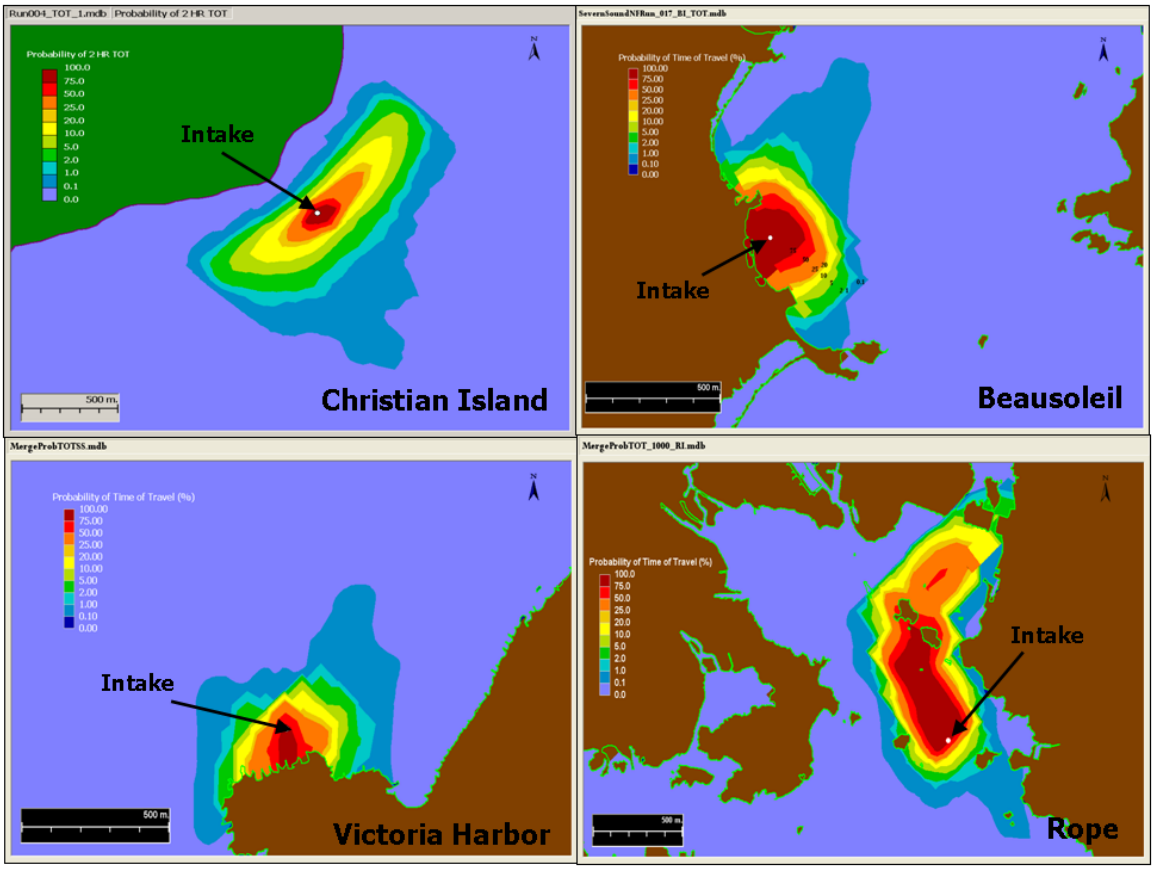


**Figure 11 Probability envelop and IPZ-2 extent for Christian Island, Rope, Beausoleil and Victoria Harbor intake using the 2 hour time of travel criteria for a target contamination of dilution less than or equal to 1000 (cumulative for the 4 month simulation period)**

**IPZ-3**

The delineation of IPZ-3 is done in a similar way as IPZ-2 with special consideration for extreme events such as storms. It is important to study the historical meteorological data for the region of interest to develop a set of extreme conditions. These extreme conditions were evaluated for each intake and used to develop the IPZ-3. The extreme conditions were identified using 1 in 100 year storm or flow event for the study region.

**CONTAMINATION RISK ANALYSIS**

The development of these IPZs relies on information such as response time, ability to respond to such events and knowledge of possible spills. In developing nations where such information may not be available and historical records of meteorological conditions may be sparse, a more comprehensive risk analysis can be done. This risk analysis does not rely on a response time (time of travel), instead it provides the risk of contamination based solely on the time that a spill takes to reach the intake.

The risk analysis approach that determines the time of travel for constituents to reach an intake involves backtracking of contaminants. The approach determines the probable path of constituents/particles to the intake by tracing their path backwards to the probable location of spill origin. This Reverse Particle Modelling (RPM) approach also provides the age of the particles from the point of release. The results are typically presented in time contour maps for a time period such as half or one hour intervals from the intake. Since this approach provides raw information in terms of time of travel, it can be used without an assumption of time of travel. Detailed IPZs can be inferred from these contour plots when a response plan for an intake has been developed.

The RPM approach was also exercised for the five intakes as it provides the possible limits of spill locations that may contaminate the intake. The RPM approach has been used to define some IPZ-2s for intakes in other Lake Simcoe Region studies. Figure 12 shows a time of travel plot developed using the RPM methodology for Collingwood intake under storm conditions. The results show that the regions east and west of the intake have a shorter travel time to the intake when compared to regions north and south of the intake. These results are similar to the ones obtained from IPZ-1 and IPZ-2. They also provide delineation of IPZ-2 at a later date when the facility response plan has been developed.

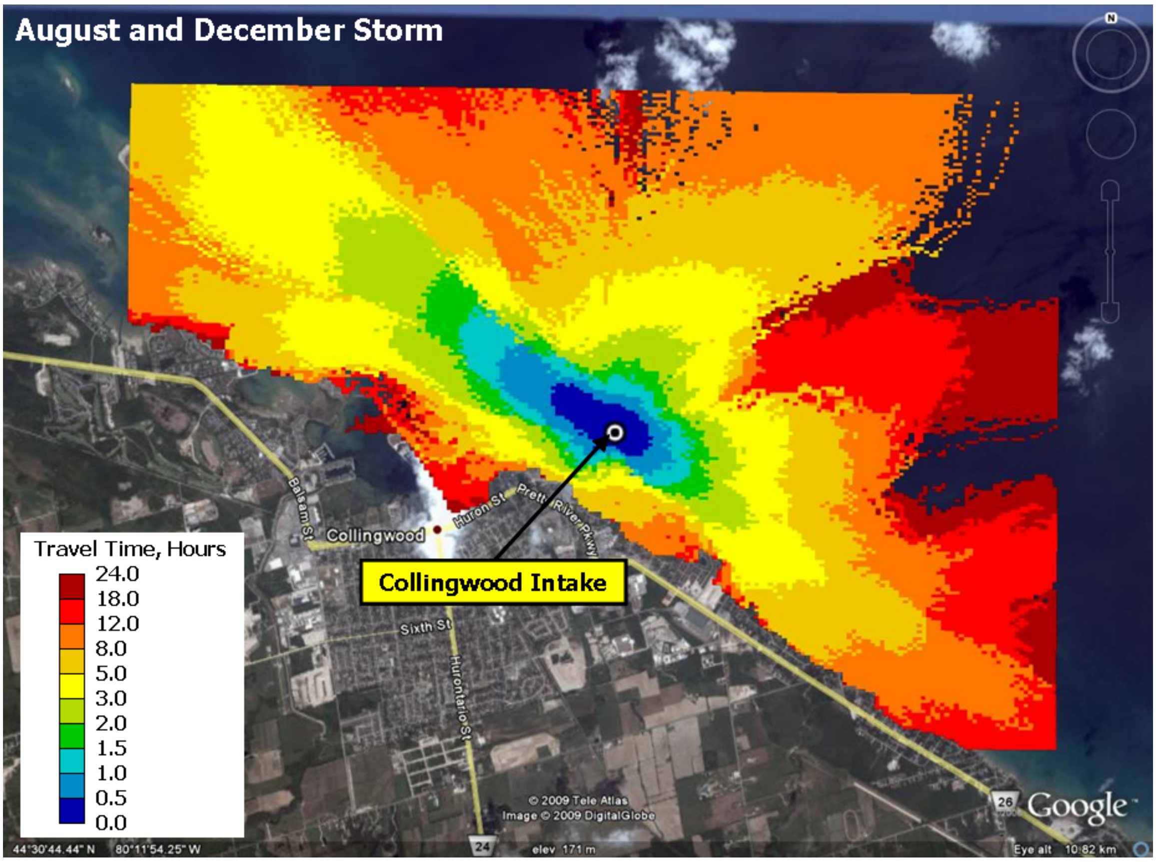


**Figure 12 Time of travel plot for a storm event at Collingwood intake**

## CONCLUSION

The hydrodynamic model was set up for the far-field Georgian Bay nested with three near-field regional models. The far-field model was calibrated against the water surface elevation and temperature data available at several locations within the Georgian Bay. The near-field models were calibrated using temperature measurements, drogue measurements and continuous current measurements using ADCPs. These calibrated near-field models were used to run the GEMSS-SPM module that provided IPZs for the five different intakes. These intakes were developed for typical hydrodynamic conditions and extreme storm events. All of these IPZs considered a TOT of 2 hours. Development of these IPZs is an important measure in protecting our public water supply intakes. Once these IPZs have been defined, frequent water quality measurements can be taken to ensure clean drinking water supply. Additionally, evaluation of risk analysis for intake contamination was done for intakes where facility response plans are not yet available. This risk analysis, providing time of travel and origin of spill for a contaminant that reaches the intake, can be bed to develop IPZs at a later stage.

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**Venkat S. Kolluru** completed his M.S. and Ph.D. degrees in Ocean Engineering from the University of Rhode Island and is the technical director for the Surfacewater Modeling Group of ERM Inc. His experience since 1991 has been in the development and application of 1-D, 2-D, and 3-D hydrodynamic models for water quality, sediment transport, toxic fate, and oil and chemical spill impacts, integrating SMG’s modeling activities within the Generalized Environmental Modeling System for Surfacewaters (GEMSS) framework.

**Shwet Prakash** is a senior project manager in ERM Inc., working extensively with hydrodynamic and transport models. He received his B.S. in Civil Engineering from Indian Institute of Technology Bombay and his M.S. from SUNY Buffalo. Since 2001, Shwet applies, researches, writes and tests improvements to GEMSS® hydrodynamic, transport, water quality, chemical fate, particle tracking, and sediment transport algorithms. Shwet has managed, reviewed, developed and applied models in support of hydropower reservoirs, nuclear and steam power stations, oil spills, LNG facilities, mining lakes, reservoir water quality and load allocation, flushing studies, entrainment studies, dredging and drilling activities, and mixing studies.