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Hydrodynamic and thermal plume modeling for waste heat discharges into coastal waters

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Abstract: The intent of this paper is to present a summary of an impact assessment study of waste heat discharged into a fresh water coastal bay within Canadian shores of the Great Lakes. An existing water cooling system located on the north shores of Lake Ontario draws colder water from the lake and supplies chilled water to an existing air conditioning system. A by-product of the cooling system is waste heat that is discharged into Lake Ontario. Planned upgrades to existing facility require changes to the discharge waste heat discharge characteristics, thus requiring a detailed impact assessment. For the assessment of hydrodynamics and thermal plume dispersion an open source TELEMAC-3D numerical model is used to simulate the effect of mixing of the waste heat with the ambient Lake Ontario coastal waters. TELEMAC-3D is ideally suited for modeling thermal plume discharges since it is able to internally capture the transport-diffusion phenomena (where hydrodynamics and temperature diffusion are dynamically coupled). Numerical modeling carried out evaluated the mixing of the thermal plume for late spring (the start of the cooling season) and late summer conditions (the times when ambient water temperatures peak). Simulation results were used to quantify the impact of the changes in waste heat discharged from existing outfalls, as well as a number of possible outfall relocation scenarios.

1 Introduction

Development and application of numerical models in environmental impact assessment has become commonplace as tools exist to evaluate complex environmental problems without ever adversely impacting the environment in the process. For impact assessments of rivers and coastal waters hydrodynamic models are currently models of choice. A hydrodynamic model solves governing equations for flow and transport phenomena numerically by discretizing the water body into a large number of smaller elements.

Equations used in solving flow and transport phenomena in 2D hydrodynamic models average results over the water column, implying the implicit existence of uniform and fully mixed conditions along the vertical dimension. 2D models therefore do not have the ability to capture vertical variation of transport variables (temperature, density, salinity and contaminants in general). The 2D models are however appropriate for capturing horizontal variation of well mixed bodies of water, or where variation along the water column is not required (such as in dam break inundation analysis or where the objective of the modeling is to predict water levels). The main advantage of the 2D modeling lies in the ease of model set up and relatively fast execution times.

3D hydrodynamic models represent flow and transport phenomena more accurately than 2D models because they capture the variation along the water column for all relevant variables. Implicit in most of the 3D models currently available is the ability to simulate transport of active tracers (where a source of mass added to the flow has the ability to alter water density through temperature, salinity and sediments). Application of such models is most applicable in stratified environments such as "waters receiving cooling water discharges, lakes and estuaries that exhibit thermal stratification and sediment transport studies" (Bedri et. al, 2011).

The objective of this paper is to complete an assessment of the impact of thermal waste heat generated by a facility located on the north shore of Lake Ontario. The core of the study relies on the development of a numerical model able capture hydrodynamics of thermal discharges into coastal waters. Due to the nature of thermal discharges for cooling water projects (discharging water that is typically warmer than ambient conditions), requirements set out in the study were that numerical modeling must capture 3D nature of flow and temperature dispersion. The main tasks of the modeling are to characterize existing conditions, and identify optimal locations of the outfalls should they require relocation.

For confidentiality reasons the exact location of the facility and waste heat discharge characteristics will be omitted from this paper since the project is still ongoing. The methodology and the general patterns of the results obtained will be presented, even though numerical quantities will not be discussed or shown on the output plots.

2 Background

2.1 Existing regulatory framework

Since the project is located within Canadian province of Ontario, the following regulatory framework have been considered in evaluating impacts from waste heat discharges into coastal waters:

- Canadian water quality guidelines for the protection of aquatic life: Temperature (marine), CCME (1999);
- Determining Receiving-Water Based, Point Source Effluent Requirements for Ontario Waters, MOE (1994a);
- Water Management: Policies, Guidelines, Provincial Water Quality Objectives, MOE (1994b)

CCME (1999) state that their interim guideline is that "human activities should not cause changes in ambient temperature of marine and estuarine waters to exceed +/- 1 °C at any time, location or depth" (p.3). Further, the interim guideline states that natural temperature cycles should not be altered in magnitude or frequency, and that the maximum rate of induced temperature change should not exceed 0.5 °C/hr. CCME (1999) also recognizes that by implementing their interim guidelines, allowances can be made for the existence of mixing zones, where higher temperature increases could be permitted in within a defined area.

MOE (1994a) does not provide a set guideline for temperature increase, but does state that discharge of waste heat should ensure rapid mixing in order to minimize the area affected. Further, MOE (1994a) states that waste heat should not affect the water temperature of any water intake or fish spawning area, nor should existing circulation patterns, sedimentation or fishing grounds be affected.

The Provincial Water Quality Objective (PWQO) for temperature, as documented in MOE (1994b), is such that: i) thermal regime of any water body should not be altered to impair the quality of the natural environment, ii) temperature at the edge of the mixing zone at a representative location shall not exceed the natural ambient water by more than 10 °C, iii) maximum temperature of the receiving body, at any point in the thermal plume outside of the mixing zone, shall not exceed 30 °C or the temperature of a representative control location plus 10 °C, or the allowed temperature difference, whichever is less, v) maximum temperatures are to be measured on a mean daily basis from continuous records.

2.2 Literature review

A number of past reports and research papers were reviewed during this study, especially those related to hydrodynamics and circulation patterns at and around the northeastern shores of Lake Ontario, including the Kingston Basin. A brief summary of the past work is provided here for reference purposes only.

Tsanis et. al (1991) report on a deployment of a network of current meters, meteorological buoys, and satellite drifters to study circulation in the Kingston Basin and St. Lawrence River outflow area. The analyses that followed revealed that complicated hydraulic and wind induced circulation patterns exist, especially due to the presence of numerous islands and small bays. It has been documented that waters in the Kingston basin are stratified during the summer months.

In the work by Shore (2009), a 3D hydrodynamic model has been developed for Lake Ontario and the Kingston Basin for the purpose of studying mean circulations. The 3D model was forced with monthly climate (wind and surface heat fluxes) obtained from NOAA’s re-analysis data sets available. Results of the simulations carried out included time histories of temperature and velocities along the water column over a period of multiple months. The results show a double gyre pattern in the lake with average velocity magnitudes consistent with past observations.

As part of Ontario’s Source Water Protection, Paturi et. al (2011) developed a 3D hydrodynamic and temperature model to quantify flow dynamics of eight drinking water intakes within Eastern Lake Ontario and upper St. Lawrence River. The purpose of the modeling was to delineate intake protection zones for a number of intakes within their study area. The 3D model simulated water levels, temperatures, and currents along the water column. Paturi et. al (2011) model domain included areas from the Kingston Basin of Lake Ontario to downstream of Brockville, Ontario on the St. Lawrence River. Simulations showed that circulation was found to be predominantly wind induced in the southwestern portion of their study area (lake portion of their domain), and hydraulically driven in the northeast portion of the domain (river portion).

Comprehensive environmental assessment and extensive numerical modeling efforts have been completed by Golder (2012) related to the proposed upgrades at the Darlington Nuclear Generating Station, located east of Oshawa, Ontario. 3D hydrodynamic numerical modeling and detailed temperature measurements have been prepared that document the impact assessment of thermal discharges from the installation of new units at the existing power plant.

2.3 Historic data

Historic data is required to quantify the climatic factors that influence lake circulation and generate currents around the study area. For coastal waters of the Great Lakes, the primary driver of lake circulation is the wind climate. For areas where hydraulic gradients are evident (such as outflows of interconnected channels), water level differences are also used (Anderson and Schwab, 2011).

Meteorologic data for thus study was obtained from the NOAA's National Climate Data Center, and was used to assess the characteristics of the wind climate required for subsequent numerical modeling. Hourly data for the Kingston airport station was obtained from 1982 to 2011. Meteorological data from Canada's wave buoys positioned along the north shore of Lake Ontario were also obtained, as the wave buoy also collect wind speed and direction data. The wave buoy data was of limited use since most of the collected data is only available for the months between April and November (the buoys are taken out of service during the winter months).

Since the study area is located in the close vicinity of the upper St. Lawrence River, historic data collected from the Fisheries and Oceans Canada water level archives were also obtained. Hourly water level data for stations at Kingston, and Brockville were obtained.

Analysis of the wind climate at the Kingston Airport suggests that wind characteristics are different when comparing all months (Jan to Dec), versus summer months (May to Oct). This distinction is included as the facility's cooling system is operated during the summer months only when air conditioning demand is the highest. Our analysis shows that most of the winds at Kingston can be divided into three dominant directions (northeast, south and southwest). A wind rose plot for the Kingston Airport station is shown in Figure 1.

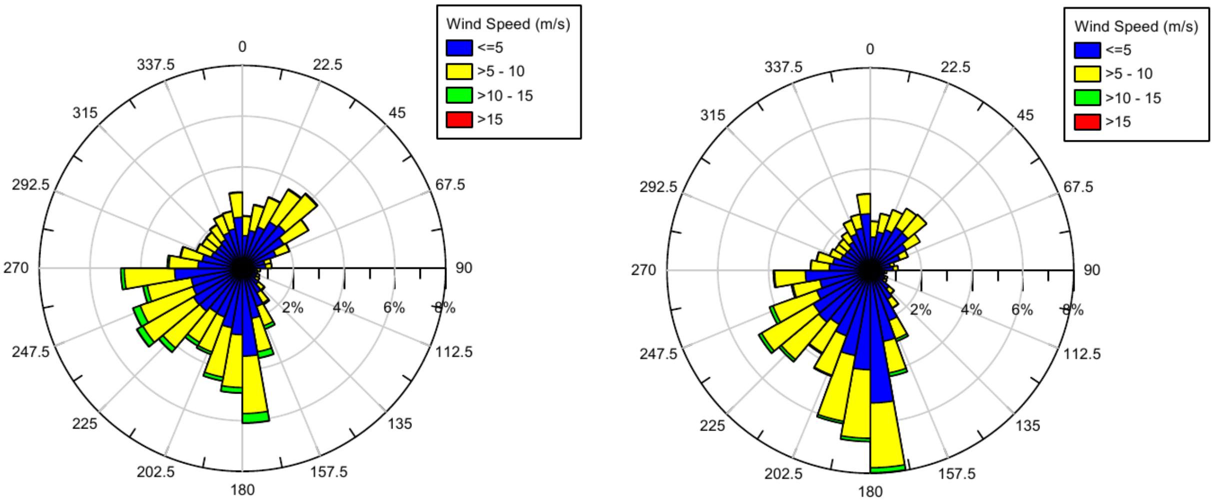

Figure 1: Kingston Airport wind rose (all months left, and summer months right)

Visual inspection of the water levels records from Kingston to Brockville, along with wind records from the Kingston Airport suggest that water levels at the north shore of Lake Ontario is driven by winds blown over Lake Ontario. Further downstream in the St. Lawrence River, hydraulic gradient of the river is responsible for controlling water levels and currents. However for the offshore waters near the inlet of the St. Lawrence, water levels (and thus currents) are heavily influenced through meteorologic forcing especially during periods of calms of most interest when studying dispersion of waste heat.

2.4 Shoreline and bathymetry

Shoreline and bathymetry of Lake Ontario and St. Lawrence River were obtained from navigation charts available from the Canadian Hydrographic Service (CHS) and National Oceanic and Atmospheric Administration (NOAA). Bathymetry data consisted of bottom contours, and individual spot soundings. Shoreline and bathymetry data was assembled into a single data set, and used in the development of the geometry for the hydrodynamic model.

Since the focus of this study is circulation within a small bay located on the northeastern shore of Lake Ontario, and since detailed bathymetric data is not available from CHS or NOAA for this location, Riggs Engineering was tasked to undertake a site specific sounding survey of the area of interest. The survey was completed in August of 2012, using a RESON Navisound 110 echosounder. Horizontal positioning was recorded using a Hemisphere R320 GPS/GLONAS receiver.

2.5 Lake Ontario receiving environment

Lake Ontario’s Kingston Basin is the northeastern most portion of the lake, near the lake’s outlet. It is the Kingston Basin that separates Lake Ontario from the inlet of the St. Lawrence River. Past studies have noted complex circulation patterns within the basin that are in part driven by underwater ridges, channels, and orientation of numerous islands (Paturi et. al, 2011). Due to dominant wind directions and orientation of the main channels around Kingston, flow is generally directed towards the northeast (the flow direction of the St. Lawrence River). However, flow reversals are possible due to strong east winds as is evident in the water level records between Kingston and Brockville gauges.

Waters in the Kingston Basin are stratified during the summer months, implying that solar radiation warms surface waters of the lake throughout the course of the summer. During the winter months large portions of Lake Ontario are frozen, with water temperatures being just above freezing. Starting sometime in March solar radiation provides energy which the lake absorbs, thus gradually raising its temperature along the water column. At the beginning of the cooling season (assumed to take place sometime in May), surface temperatures are generally variable, and can rise to about 15 °C. Temperatures continue to rise until late August (the time when surface and bottom temperatures are equal). Peak surface temperatures in the summer can reach 25 °C (Prince Edward Point buoy). Furthermore, Golder (2012) presents a time series plot of temperature measured at Port Granby (located on the north shore of Lake Ontario between Newcastle and Port Hope) where summer surface temperatures could reach mid 20's.

3 Hydrodynamic and thermal plume modeling

3.1 Telemac-3D model description

For the assessment of hydrodynamics and thermal plume dispersion TELEMAC-3D finite element numerical model was used in this study. TELEMAC-3D is part of the TELEMAC modeling system originally developed by Electricité de France. The code of the TELEMAC system has recently been released as open source, implying that users can freely customize it to suit individual needs and/or projects. The TELEMAC source code is currently maintained by a consortium of established research organizations specializing in hydraulic and coastal research. Further details of the TELEMAC system (governing equations, simplifications, and numerical procedures) are presented in a text by the author of the original version of the source code (Hervouet, 2007).

TELEMAC models (2D and 3D) have been applied to riverine and coastal environments throughout the world. In Canada, recent application of the TELEMAC modeling system by National Research Council (NRC) includes modeling water levels in the St. Clair, Detroit and St. Lawrence Rivers.

3.2 Model domain

3D hydrodynamic model used in the delineation of intake protection zones from Kingston to Brockville (Paturi et. al, 2011) identified that southwestern portion of model domain was influenced by winds, while the northeastern portion by hydraulic gradient of the river. Further support of this finding is the found in the raw water level data between Kingston and Brockville, where flow reversals in the St. Lawrence River are possible during strong east winds. The selection of the model domain used in this study draws on the findings of Paturi et al. (2011).

The model domain is selected from the southwestern tip of Amherst Island to the northeast tip of Grindstone Island, thus capturing the lake portion of the coastal waters. Since the model's main purpose is to study impacts of waste heat discharged into a small bay during periods of relative calms, the extent of the model must be such that enough fetch exists to fully develop hydraulic conditions driven by winds. The domain developed for this work includes approximately 30 km of coastal waters on each side of the site of interest.

The model contains 13,132 triangular elements with 7257 nodes, vertically divided into 5 horizontal planes equally distributed along the water column. The sizes of the elements varies from 8 m to 780 m. Most of the elements within bay of interest are between 30 m to 40 m in length. Remaining elements progressively increase away from the bay. Further offshore, the size of the mesh is kept to 500 m, which is enough to adequately resolve the detail of the five islands included in the domain. Since significant amount of flow passes through the channels around Wolfe, Howe and Carleton Islands, localized mesh refinement was performed to ensure size of the elements was appropriate to convey the large flows present in this reach of the St. Lawrence. A portion of the model's domain containing the small bay into which the waste heat is discharged is shown in Figure 2.

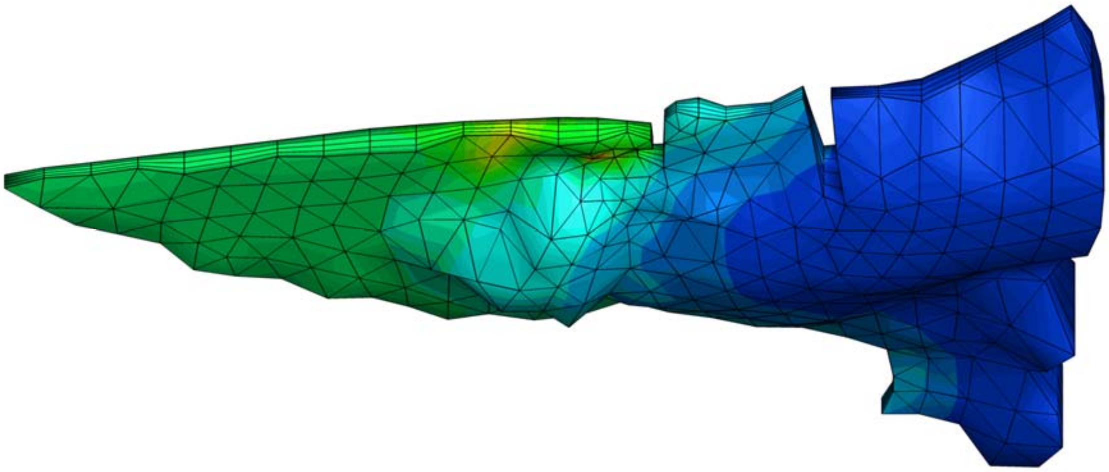

Figure 2: TELEMAC-3D representation of the small bay

3.3 External forcing, initial and boundary conditions

For all simulations we have used surface stress applied by winds to force the TELEMAC-3D hydrodynamic model. Based on the wind rose for the summer season, we have identified three dominant wind directions: i) south, ii) southwest, and iii) northwest. The most dominant wind direction is from the south. Simulations are carried using these wind directions.

The Kingston water level gauge was used to select typical water levels during the summer months (the time during which the cooling system is most likely to be operating). Prior to the start of the simulations initial water level of 0.75 m above chart datum was used. Data available from the Kingston water level gauge suggests this is a typical water level during the summer conditions.

Initial conditions are also specified for temperature just before the waste heat is added to the simulations. For the late spring conditions the model is initialized with uniform temperature of 15 °C. For late summer conditions measurements show that temperatures along the water column in the waters of Lake Ontario are fully mixed, and can reach mid 20’s. For the simulations carried out in this report, we have initialized the late summer cases as having uniform water temperatures of 24 °C.

3.4 Model simulations

The model under each scenario is hot-started in order to develop an initial state of the flow field (wind stress is applied on the surface of the domain until steady state conditions develop.) For wind speeds considered in this study this amounted to approximately two days of simulated time. After development of the steady state hydraulic conditions, waste heat is added at discharge rates, temperatures, and at outfall location according each scenario considered. The simulations are then continued, and the impact of waste heat is identified.

4 Results

4.1 General

The results of the modeling shows the model’s ability to capture wind driven circulation in coastal waters surrounding the small bay located within the northeastern shores of Lake Ontario. Using streamtraces, we have identified that most flow direction is consistent with the downstream direction of the St. Lawrence River for most of the year. The flow direction develops due to orientation of the major islands within our domain. This finding is consistent with previous observational measurements provided by Tsanis et. al (1991), where it is reported that presence of the islands can cause flow to be 180 degrees out of sync with the direction of the wind.

From the plot of streamtraces shown in Figure 3 it is evident that a number of gyres develop with the limits of the small bay. The locations of the gyres are approximate and vary with wind conditions and flows in the main channel. Analysis of model output reveals that velocities in the bay itself are very small, meaning that during calm periods only a nominal amount of mixing is expected to occur between the bay and faster moving offshore waters.

For the sake of brevity results are shown for the simulation run using south winds only (as this was the most dominant wind direction during the cooling season). Results for the late summer condition using existing outfall configurations are presented in Figure 4 (plan view) and Figure 5 (cross sections). The results using other wind directions have been completed, but are not presented as their pattern of behaviour is similar.

Numerical simulations show that under design conditions the waste heat discharged into the small bay causes high localized temperature increases around the outfalls during the late summer conditions due to the shallow depth above the outfall. Outside of the localized increases, temperature in the rest of the bay is computed as being moderately increased. Vertical cross section plots for the existing conditions show that waste heat discharged into the bay causes temperature stratification during the late summer conditions. Because the bay is stagnant during periods of calms, the shallower portions remain vertically well mixed.

4.2 Future model refinements

It is recognized that conservatism in the modeling approach exists for the case representing late spring conditions. Lake Ontario waters in the Kingston basin are stratified during this time, and certainly thermal stratification exists in the small bay prior to start of the air conditioning season. In our simulations, we have conservatively assumed that the entire water column is fully mixed with temperatures of 15 °C, when in fact colder water likely exists near the lake bottom that our initial conditions are not taking advantage of. A refinement in the modeling is required to specify initially stratified conditions for the late spring season prior to the start of the air conditioning season. This refinement is will be possible after temperature profiles are collected prior to the start of the air conditioning season.

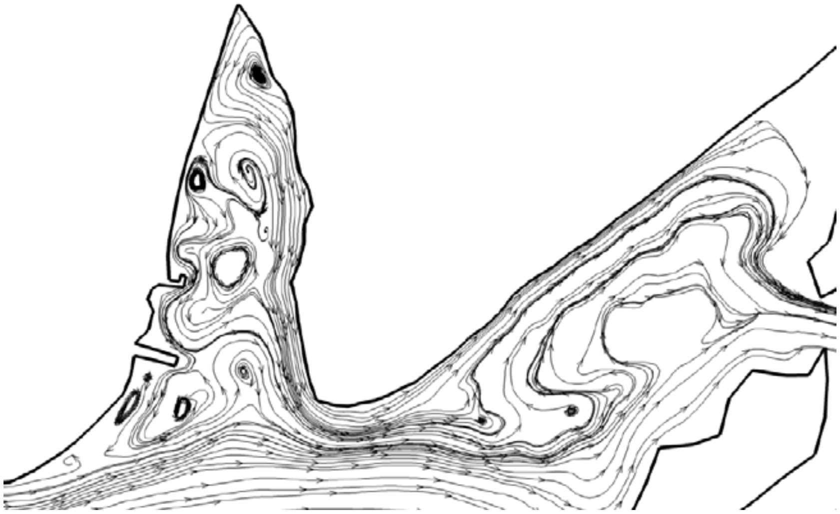

Figure 3: Flow steramtraces around study area

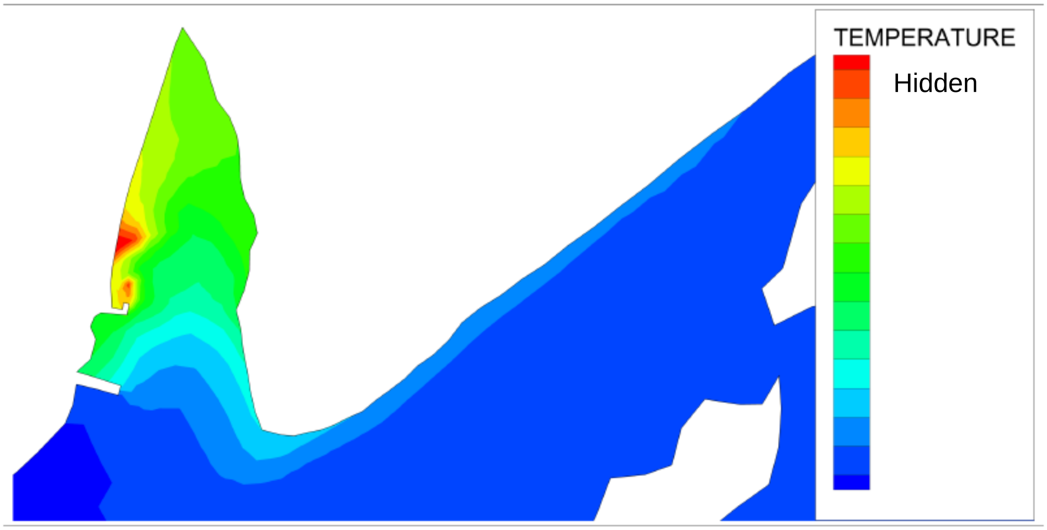

Figure 4: Late summer depth averaged temperature plume

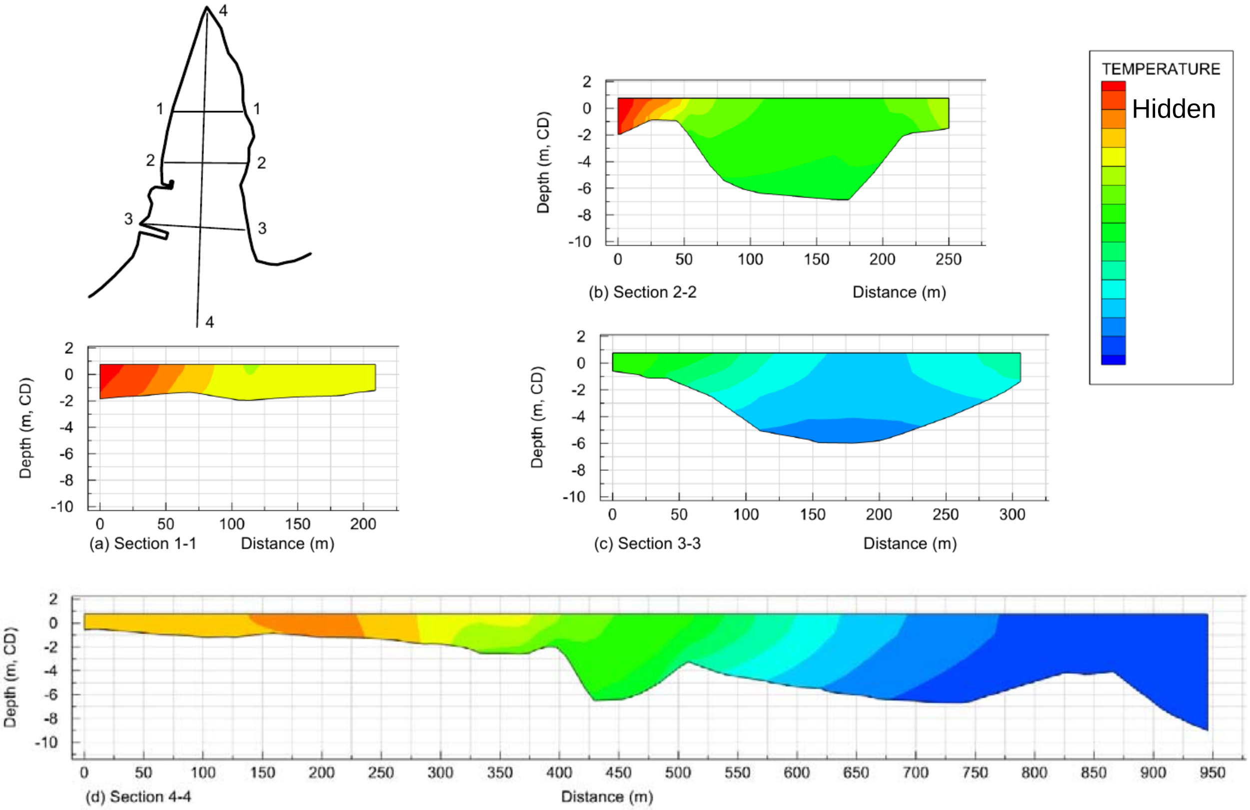

Figure 5: Vertical temperature profiles, late summer conditions

5 Conclusions

A TELEMAC-3D numerical model was applied for a small bay located on the northeastern shore of Lake Ontario for the purpose of assessing impacts of waste heat discharges. Through the simulations carried out it was discovered that thermal gradients exist within the bay resulting from the discharge of waste heat under existing conditions. The TELEMAC-3D simulation model developed in this work was deemed sufficient and appropriate for the assessment of impacts of different scenarios related to possible changes to waste heat characteristics. Future applications of the model will investigate scenarios related to outfall relocations required to meet environmental regulations.

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