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By:
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NWRI Contribution # 03-214

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# Numerical Modelling of the Grand River Plume in Lake Erie during Unstratified Period


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# Numerical modelling of the Grand River Plume in Lake Erie during Unstratified Period

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## Abstract

To better understand the impact of Grand River plume on the surrounding receiving waters, a combined observational and modeling study of the Grand River plume transport in the eastern basin of Lake Erie has been conducted for late spring of 2001 using a high resolution depth-integrated nonlinear barotropic finite element model. Due to the lack of observations needed for specifying the open boundary conditions, an extended domain of receiving waters with closed boundary was applied in this numerical study. The size of closed domain was chosen with consideration of balance between the computing time and preserving the flow hydrodynamic mechanisms. The numerical simulations were focused in particular on the influence of winds on the plume transport especially in the vicinity of the Grand River mouth. A comparison between the simulations and observed currents and conductivity shows a good agreement. This study demonstrates that a well tested two-dimensional numerical model can reasonably predict the river plume transport in a large lake during unstratified periods.

# Modélisation numérique du panache de la rivière Grand dans le lac Érié pendant une période d'absence de stratification

Cheng He, Yerubandi R. Rao, Michael G. Skafel et Todd Howell

## Résumé

Pour mieux comprendre l'impact du panache de la rivière Grand sur les eaux réceptrices avoisinantes, on a effectué, au printemps 2001, une étude combinée d'observation et de modélisation du transport du panache de la rivière Grand dans l'est du bassin du lac Érié à l'aide d'un modèle barotropique non linéaire d'éléments finis à haute résolution, intégrés en fonction de la profondeur. À cause de l'insuffisance des observations nécessaires pour déterminer les conditions avec des limites ouvertes, cette étude numérique portait sur un vaste domaine d'eaux réceptrices à limites fermées. On a choisi la superficie du domaine fermé de façon à équilibrer deux facteurs à effets opposés, le temps nécessaire pour les calculs et la préservation des conditions de base des mécanismes hydrodynamiques d'écoulement. Les simulations numériques ont permis de déterminer notamment l'influence des vents sur le transport du panache, et plus particulièrement dans le voisinage de l'embouchure de la rivière Grand. On a obtenu une bonne concordance entre les valeurs des simulations et les valeurs observées des courants et de la conductivité. Cette étude montre qu'avec un modèle numérique à deux dimensions bien testé, on peut obtenir des prévisions assez exactes du transport du panache des eaux des rivières dans un grand lac pendant les périodes d'absence de stratification.

# NWRI RESEARCH SUMMARY

**Plain language title**

Using numerical model as an alternative tool to investigate the Grand River plume transport in Lake Erie in the spring of 2001

**What is the problem and what do sicentists already know about it?**

The Grand River plume has been identified as one of the sources affecting the water quality of the surrounding area. The average water conductivity from the river discharges was 750 mS/cm, which was much higher than lake value of 250 mS/cm. Especially in the spring, the river conductivity value can go much higher because the runoff or snowmelt brings road salts into the system. However, very little is known about the dispersion of the plume during the spring. Due to the complexity of the physical environment and plume mixing processes, observational data sets are often severely under-resolved in space and time. So, this paper attempts to address this issue using numerical model as an alternative tool.

**Why did NWRI do this study?**

NWRI was invited by Ontario Ministry of Environment to study the Grand River plume time-dependent behaviors in eastern basin of Lake Erie, and to help to answer the questions such as how does plume move after flowing into lake and how much impact it has on surrounding water. It is of critical importance for effective environmental management of these regions to be able to better understand and predict the mixing processes of the plume.

**What were the results?**

From numerical simulation we concluded: (1) A 2D finite element model is capable of predicting the plume transport when the lake was not stratified, which offer an alternative to traditional field measurements. (2) The plumes were mainly carried by alongshore currents, and the alongshore component of wind is responsible for the transport direction of the river plume. (3) With persistent winds, the plume could be traced beyond 10 km in the down-wind direction with water conductivity reaching as high as 400 mS/cm. (4) Frequent reversals of current should effectively limit the plume's along-shore extent. (5) No indication for a strong influence of the earth's rotation on nearfield transport of the Grand River plume in the eastern basin of Lake Erie.

**How will these results be used?**

This contribution will provide valuable scientific knowledge and tools in assessing the threats to sources of drinking water of the Great Lakes. Based on this study the estimation and prediction of impact of Grand River plume on surrounding receiving water under various nature forces become possible.

**Who were our main partners in the study?**

Ontario Ministry of the Environment

# Sommaire des recherches de l'INRE

**Titre en langage clair**

Utilisation d'un nouvel outil, un modèle numérique, pour étudier le transport du panache de la rivière Grand dans le lac Érié au cours du printemps 2001.

**Quel est le problème et que savent les chercheurs à ce sujet?**

On a déterminé que le panache de la rivière Grand est l'une des sources qui dégradent la qualité de l'eau près de l'embouchure. La conductivité moyenne des eaux de la rivière était de 750 mS/cm, ce qui est très supérieur à la valeur du lac (250 mS/cm). Surtout au printemps, la conductivité de la rivière peut être beaucoup plus forte, parce que les eaux de ruissellement et de fonte des neiges transportent des sels de voirie dans le réseau aquatique. Toutefois, on ne connaît que très peu de choses sur la dispersion du panache au printemps et, à cause de la complexité du milieu physique et des processus de mélange du panache, les ensembles de données d'observation n'ont souvent qu'une résolution spatiale et temporelle médiocre. Pour pallier cet inconvénient, les auteurs de cet article expliquent comment ils ont tenté de résoudre le problème à l'aide d'un nouvel outil, un modèle numérique.

**Pourquoi l'INRE a-t-il effectué cette étude?**

Le ministère de l'Environnement de l'Ontario a invité l'INRE à étudier l'évolution du panache de la rivière Grand dans l'est du bassin du lac Érié, afin d'éclaircir certains points, par exemple comment le panache se déplace une fois rendu dans le lac, et quel est son impact sur les eaux avoisinantes. Pour une gestion environnementale efficace de ces secteurs, il est indispensable de mieux comprendre et de mieux prévoir les processus de mélange des panaches.

**Quels sont les résultats?**

La simulation numérique nous a permis de tirer les conclusions suivantes : 1) un modèle d'éléments finis à deux dimensions pouvait décrire le transport du panache quand les eaux du lac n'étaient pas stratifiées; il s'agit donc d'un nouvel outil qui s'ajoute aux mesures habituelles *in situ*; 2) le transport des panaches était surtout dû aux courants riverains, et la composante riveraine du vent était responsable de la direction du panache; 3) dans des conditions de vents persistants, on pouvait suivre le panache à plus de 10 km en aval par rapport au vent, avec des valeurs de conductivité de l'eau pouvant atteindre 400 mS/cm; 4) des inversions fréquentes du courant devraient limiter efficacement l'étendue du panache le long des rives; 5) dans l'est du bassin du lac Érié, on n'a observé qu'une faible influence de la rotation de la Terre sur la trajectoire immédiate du panache de la rivière Grand.

**Comment ces résultats seront-ils utilisés?**

Cette étude doit fournir des connaissances scientifiques et des outils utiles pour évaluer les dangers qui menacent les sources d'eau de boisson des Grands Lacs. Elle montre qu'il est possible d'estimer et de prévoir les impacts du panache de la rivière Grand sur les eaux réceptrices avoisinantes, compte tenu des diverses forces naturelles.

**Quels étaient nos principaux partenaires dans cette étude?**
Ministère de l'Environnement de l'Ontario

**Introduction**

The discharge from ~~the~~ rivers contains sediments, nutrient and pollutant loads that can have significant adverse impacts on water quality near the river mouth in the receiving lake. Horizontal mixing and dispersion of river plume in shallow receiving basins are key processes which affect the distribution and fate of water-borne material, especially for a low buoyant plume traveling in unstratified receiving waters. Understanding these mixing processes is of critical importance for effective environmental management of these regions which often support important biological resources and are heavily impacted by human activities.

Due to the geometrical complexity of most coastal zones, both field observations and numerical models are needed to understand the horizontal mixing processes. The expense of field measurements, combined with the complexity of the physical environment, often results in observational data sets that are severely under-resolved in space and time. In addition, generalization of the field observations must be qualified by the specific condition under which they were made. Numerical models, on the other hand, allow great resolution in space and time, and the ability to predict the future events. The models can also provide an important framework for the design of field studies, identifying key features and processes for examination.

The mixing of river plumes has been widely studied in the past few decades using numerical models (Bowman and Iverson, 1977; Boicourt et al., 1987; Garvine, 1995; Hickey et al., 1998). Most of the numerical modelling work was concentrated on the fresh water plume discharged into salty sea water. In the coastal environment of the oceans the baroclinic and tidal forces dominate the river plume transport, and a 3D numerical model is required in order to resolve the buoyancy term. Surface trapped river plumes are important features, carrying freshwater, nutrients, and pollutants into the coastal ocean. However, there have been relatively few numerical studies on river plume transport in the Great lakes (Paul and Lick, 1974; Murthy et al., 1986; Stepien et al., 1987). One of reasons could be that in numerical modelling of river plume transport, often one has to deal with wide open water boundary without good measurements. It is much more difficult to reconstruct the open boundary conditions for wind induced flow than tide driven current because of irregularity of wind driven current. Obviously, the effects of buoyant force on plume transport in lake are much weaker compared to the oceanographic settings, even though both the positively (Nepf and Oldham, 1997) and negatively (Masse and Murthy, 1990; Churchill et al., 2003) buoyant river plume were observed in large lakes due to temperature and particle concentration of river discharges.

The motivation for this numerical study is mainly to investigate the feasibility of using a two-dimensional (2D) numerical model to predict the spatial and temporal transport of a river plume in a receiving lake during unstratified conditions. The model used in this study is a 2D finite element model developed at National Water Research Institute (NWRI) by He and Hamblin (2000). The finite element model allows us to have a better representation of complex shoreline, which will be important in this numerical study since the plumes, as results from this paper show, travel along the lake shoreline. As mentioned before, one of the potential problems in simulating pollutant transport in the nearshore region of a large scale lake is caused by the wide open boundary area, especially under the situation, where adequately measured data on simulated boundaries is not available. The lack of knowledge about open water is not uncommon in practice, which either because it is too difficult or too expensive to collect them, or because data collection was done before the numerical modelling was planned. In this study, simulations with different sizes of domain were carried out. When the modeled results in study region become independent on the size of the domain, it was assumed that the boundary effects were negligible in the vicinity of the river-mouth.

**Study Area and Observations**

Lake Erie is located between the US and Canada, and is the second smallest lake in the Great Lake system (25633 $km^2$). The Grand River provides the major inflow to the eastern basin of Lake Erie and is the largest river system entering the north shore of Lake Erie. The drainage area of the Grand River includes rural areas, and several urban centers. More than half a million urban residents discharge treated effluents into the Grand River system (source: www.grandriver.ca).

Figure 1 shows Lake Erie with an enlargement of the lake eastern basin adjacent to Grand River mouth. An irregular shoreline underlain by relatively resistant bedrock characterizes the northern shore of the eastern basin. At its mouth the Grand River is about 250 m wide and 6 m deep. Beyond the mouth the bathymetry slopes gently with 20 m depth contour at about 4.5 km from the shore. The Grand River plume has been identified as one of the sources affecting the water quality of the surrounding area. In order to understand its impacts, extensive field data have been collected on different occasions from 1998 to 2002, includingtemperature, velocity profiles, conductivity, wind speed and direction, river discharge and water quality-related parameters at selected locations by either fix-mounted or boat-mounted instruments. The detailed discussion and analysis of field data is not in the scope of this paper, therefore, the only measurements used for this numerical modelling work will be mentioned.

To study the temperature structure and water movements in the vicinity of the Grand River mouth, NWRI installed two 1200 KHz ADCPs (Acoustic Doppler Current Profilers), Two Hydrolab moorings and one meteorological buoy (Figure 1) in support of extensive surveys carried out by OMOE (Ontario Ministry of Environment) during late spring to late fall in 2001. In the same time period OMOE also installed two fixed-point current meters (RCM7) close to the mouth of the river. ADCPs were mounted on the bottom of lake facing up. Measured vertical resolution was set to 1 m and data collected in each depth cell were hourly averaged for this analysis. The long-term accuracy of velocity profiles obtained from broadband ADCP is of the order of ±0.2%. About once a month the OMOE made a field survey for velocity profiles with ship based ADCP, and surface conductivity and temperature. The primary aim of these surveys was to delineate the river plume in the eastern basin

The wind speed and direction were measured from an automatic data recording meteorological buoy, which was deployed at Grand River mouth from 30 April 2001 with the wind sensors about 5m above water surface. The measured wind was, then, converted to surface wind stress using the formula of Wu (1969) for driving the numerical model. The daily flow discharge rate and conductivity information of the Grand River were also recorded by OMOE, which were used as specified inflow boundary condition for the numerical simulations.

**Numerical Model**

As mentioned in the introduction, in this first phase of numerical study we mainly focused on the Grand River plume transport in the late spring of 2001. During this time the water column was not quite stratified as indicated by observations at the river mouth (see Fig. 8 bottom panel). The temperature difference in the water column was less than 5°C during most of the time. The flow pattern was expected to be mainly dominated by wind-induced circulation which consists of many eddies. Regardless of rotational direction and pattern of such eddies; they always generate strong coastal currents, which would carry the river plume away from the river mouth.

Because the shoreline of the eastern basin of Lake Erie is very irregular, and because of the importance of simulating coastal currents accurately, a 2D finite element hydrodynamic and transport model has been chosen for this study. Mathematical models were based on the depth integrated equations of continuity and momentum, subject to the incompressibility, Boussinesq and hydrostatic pressure approximations. The governing equations and boundary conditions can be expressed as:

Momentum equation:

$$\partial \mathbf{U} / \partial t + (\mathbf{U} \bullet \nabla)\mathbf{U} + \mathbf{f} \times \mathbf{U} = -g\nabla\zeta + \upsilon\nabla^2\mathbf{U} + \mathbf{S} \quad (1)$$

Continuity equation:

$$\partial \zeta / \partial t + \nabla \bullet (H\mathbf{U}) = 0 \quad (2)$$

Transport equation:

$$\partial C / \partial t + \mathbf{U} \bullet \nabla C = \mathbf{D} \bullet \nabla^2 C \quad (3)$$

The notations are as follows:

**U** $= (U_1, U_2)$, where $U_i$ is the depth-averaged velocity component in the $x_i$ direction.

$\zeta$ is the water elevation.

$H = h + \zeta$, where h is the water depth measured from the mean surface.

$f$ is the Coriolis parameter.

$S_i = (\tau_{si} - \tau_{bi})/(\rho H)$ is the source term.

$\tau_{si}$ and $\tau_{bi}$ are the surface and bottom stress in the $x_i$ direction.

$\upsilon$ is a diffusion coefficient of flow that is assumed to be constant here.

$\rho$ is the fluid density.

**D** is diffusion coefficient of transported substance that is assumed to be constant here.

The boundary conditions applied are:

Open boundary: flow flux in normal direction was specified through line integral on the open boundary; and in along boundary direction was zero.

Closed boundary: the normal velocity $U_n = 0$.

On the bottom: $\tau_{bi} = g|U|/C^2$, where $C^2$ is the Chezy coefficient.

On the surface: $\tau_{si} = \rho_a C_D |W| W_i$, where W is wind speed at 10 m above water. $C_D$ and $\rho_a$ are the surface wind drag coefficient and air density respectively.

At the river inlet observed concentrations and discharges were prescribed.

The above equations were solved by means of decomposition in fractional steps. In this way each numerical operator can be treated independently with an appropriate method. The resolution is achieved in three steps: In the advection step the Eulerian-Lagrangian method was implemented. The quadratic basis function of Galerkin schemes was used to solve diffusion term. The free surface-pressure-continuity step was solved with implicit method. Since the nonlinear term was treated with the Eulerian-Lagrangian approach, the transport equation was solved with hydrodynamic equations together with little extra computing cost.

**Results**

The model described in the previous section has been verified and applied to study the circulation and exchange flows in Hamilton Harbour (He and Hamblin, 2001; Hamblin and He, 2003). However, the model results will be verified with the current observations near the Grand River mouth before using it for contaminant transport. In this study the x and y-axes were chosen in west-east and south-north directions, respectively. So the main direction of shoreline of the eastern basin in our numerical simulations is parallel to the x- axis.

Figure 2 shows the x and y components of surface winds near the river mouth. It suggests that there was no obvious prevailing wind during the period from Julian day 120 to 160 of 2001 except for two episodes, each having duration of 3 days. During JD 125-128 and JD 147-150 the strong north-east and north-west winds dominated this region, respectively. To illustrate the variability of the river discharges throughout the year the measured river discharge and conductivity were presented in Figures 3a and 3b, respectively. The annual mean flow of the Grand River was about 40 $m^3/s$ with a maximum peak of 450 $m^3/s$ during the spring season. The river discharge and conductivity show a typical behavior of flow from runoff or snowmelt during the spring.

It may be noticed that with every major discharge the conductivity would increase sharply because rain runoff or snowmelt flushes the heavily contaminated substances from land surface into the river, and after that, the conductivity drops sharply. The average water conductivity in the river was 750 $\mu$S/cm, which was much higher than lake value of 250 $\mu$S/cm.

The mixing associated with the inflow can be parametrized by a densimetric Froude number F (Chu and Baddour 1984):

$$F^2 = u^2/d\,g'$$

where d and u are river depth and vertical integrated velocity, respectively; and $g'$ is the reduced gravitational acceleration given by $g' = (\Delta\rho/\rho_o)g$, where $\Delta\rho$ is the density difference between the river water and lake water of density $\rho_o$, and g is the acceleration due to gravity. The parameterization indicates the magnitude of inertia relative to the stability provided by buoyancy. $F<3$ indicates that the river inflow does not act in a jet like fashion, rather river acts like a mixing layer. Taking values typical of late spring conditions, particularly for the high discharge of 150 $m^3/s$ ($d = 6$ m, $u = 0.1$ m/s, $g' = 0.0048\ ms^{-2}$), $F = 0.59$. Thus, for late spring conditions the river plume does not behave like a jet, and flow is mixed and remains at its depth of neutral buoyancy. For the typical values considered representative for late spring conditions the Kelvin number is less than 1, indicating that Coriolis effects are not important in plume dynamics.

As mentioned earlier it is difficult and costly to collect data along the long open-boundary such as the case in this study. The most common way to deal with lack of measurements on the boundary is either to re-construct one according to certain physical and mathematical principles (Chu et al., 1996), or to use the output from larger scale model with a coarse mesh (Murthy et al., 1986; Amin and Flather, 1995). In this study we use a simpler approach to examine the influence of boundaries. We place the open boundaries very far from the region of interest, and treat them as closed boundaries. To examine the ideal size of the domain, we conducted experiments with different sizes. When the modeled results of study area were independent of the size of simulated region, it was assumed that the effects of open boundaries on currents near the river mouth were negligible. The final mesh used in this study was shown in Figure 4, which consists of 1688 nodal points and 2955 triangular elements. The element size is proportional to the square root of depth in regions away from shore, where more detailed resolution is not needed. The mesh covers a domain around 40 km in X direction and 22 km in Y direction. The results using this mesh and a larger mesh (not shown here) covering an area of 70 x 35 $km^2$ are shown in Figures 5 and 6 for comparison. It can be seen that the differences between the outputs from two different meshes were almost negligible, which indicates that the smaller closed boundary was far enough away not to have any strong influence on the flow near the mouth of the river.

The period of numerical simulation for the Grand River plume transport in the eastern basin of Lake Erie was chosen from JD 120 (April 30) to JD 160 (May 10) because wind information was only available from JD 120, and after JD 160 the lake became stratified and the 2D model is not suitable. The 10 s time-step used in numerical simulations is found to be consistent for stability criteria. The initial conditions for the model were the state of rest, with imposed winds and discharge at the river mouth. Because of the effect of numerical damping in the model, a small value of 0.1 $m^2/s$ of constant eddy viscosity and diffusion coefficients were found to be adequate for both hydrodynamic and transport simulations.

Figure 7 shows an example of modeled velocity and free surface at 1:00 pm on day 137 (May 17, 2001). This result was chosen because of the availability of field survey data of water conductivity on this day which will be discussed later. Figure 7 provides a typical 2D wind induced flow pattern in a closed basin. It can be seen that there were several small eddies inside a large eddy circulating along the boundary. This strong boundary current has been observed in most of the large lakes. On day 137, wind came from the north-east driving shallow water along shoreline with the wind and piling water at the western end of the basin, as indicated by contour lines of free surface. At the same time the barotropic pressure generated from tilted free surface would push water back to the east, flowing along the deeper offshore boundary. This is consistent with wind induced currents in closed basins. In general, the flow behavior showed in Figure 7 is reasonable without obvious numerical noise.

The time-dependent behavior of simulated and observed vertically averaged currents at measurement stations 38 and 40 were presented earlier in Figures 6 and 7. The high frequency oscillations in the measured currents have been removed by applying a 6-h low-pass filter. Both simulations and observations show the alongshore (x-component) currents were stronger than cross-shore (y-component) currents. In general, they show a good agreement between observations and simulations in both x and y velocity components during the 40 days simulation period except on day 148. The observations on day 148 indicate that the model under-predicted currents on this day. The winds on this day were moderate to high (10-15 m/s) coming from the west or south-west. This has resulted in a coastal upwelling type of situation along the shoreline (Fig. 8b). The surface currents at both ADCP stations show clear response of currents to this prevailing wind, and buoyant surface discharge from the river (Fig. 8a). The model-simulated flows are depth-averaged, and therefore do not clearly indicate this type of complicated flow arising from the interaction of the river and baroclinic flow induced by upwelling. Although the strengths of the model simulated currents are weaker, the direction seems to be accurate. However, to accurately simulate the currents in the stratified season a three-dimensional model is more appropriate.

As mentioned in the previous section the main goal of this study was to examine the behavior of the Grand River plume and its impact on the surrounding area. Two hydrolab stations H1 and H2 were deployed near the river mouth as shown in Fig. 1 for continuous monitoring of conductivity during the year of 2001. Figure 9 shows a comparison of measured and predicted conductivity values at stations H1 and H2. In general, the numerical model was able to simulate the major events of high values of conductivity. The reasons for discrepancy between observed and computed conductivity values could be due to the fact that the observations were point measurements and the computations were depth-averaged.

On 17 May, a field survey was conducted to trace the Grand River plume near the mouth of the river with a boat mounted instruments. The boat tracks and the area covered by the survey were shown in Figure 10. The observed and modeled water conductivity on 17 May was displayed in Figures 11a and 11b, respectively. The observed and modeled plumes have similar shapes, especially near the river mouth. However, the observed plume traveled closer to the shoreline and also further away from the river-mouth than computed river-plume. One of the possible explanations for the wider plume shape from numerical simulations can be attributed to the numerical damping, even though a small diffusion coefficient was chosen in this simulation. Another possibility for wider and shorter plume is that since the numerical simulations are depth-averaged and limited to a much smaller closed basin instead of the whole eastern basin of Lake Erie. In the model the alongshore currents were forced to turn in much shorter distance, which could reduce the simulated current speeds. In order to conserve the flow flux the alongshore currents have to become wider, which may increase the width of the river plume. Unfortunately, there is only one day of survey data available and no long term measurements of horizontal current distribution are available during the 40 days of numerical simulation period. The comparisons between simulations and observations have demonstrated that the 2D numerical model was capable to reproduce most of the physical features of the measurements. Therefore, it was reasonable to believe that the model could be used to predict the mixing of plume under different wind conditions and its impact on the surrounding environment.

In order to examine the relationship between wind and plume transport in the eastern basin of Lake Erie, the low-pass filtered x-and y-components of wind were re-plotted in panel A of Figure 12. The computed conductivity values during the 40 days simulation along the western and eastern shoreline at different locations (see Fig. 4 and Table 1) were given in panels B and C, respectively. The comparison between wind and conductivity reveals that the alongshore (x-component) of wind is mainly responsible for the transport direction of river plume. The correlation coefficients between negative and positive x-component wind and plume transport through locations 1 and 5 were given in panel D as solid and dashed lines, respectively. The x-axis in panel D is the time lag between wind and conductivity transport in panels B and C. The maximum correlation coefficients were found to be at a lag of 3 hrs. This indicates that it took around 3 hours for the wind to change the direction of plume to travel 1.25 km from the river mouth. The correlation coefficients between cross-shore (y-component) of the wind and plume transport were close to zero.

Therefore the simulations for 40 days during the spring of 2001 show that the plumes were mainly carried by alongshore currents, and the travel direction was determined by persistent winds. With persistent winds (for example from day 148 to 152), the plume could be traced beyond 10 km in the down-wind direction with water conductivity reaching as high as 400 $\mu$S/cm at that location. Both simulations and observations have not indicated a strong influence of the earth's rotation on nearfield transport of the Grand River plume in the eastern basin of Lake Erie. If the earth's rotation had a strong influence on the plume transport, the plume would indeed turn right and travel westwards more often, which was neither observed from the measurements nor from the simulations.

## Conclusions

The results of the numerical simulation of the Grand River plume suggest that the 2D finite element model is capable of predicting the plume transport when the lake was not stratified, even though the observations at open boundaries are not available. With increased computational power, the lack of observed boundary conditions could be overcome by increasing the size of the domain. The simulations compare favorably with the observations for vertically averaged velocity and plume distribution in the vicinity of Grand River mouth and offer an alternative to traditional field measurements. Numerical modeling results also provided a good insight into the relationship among wind force, currents and plume distribution, which helped to better understand and predict the mixing processes of the plume, which is of critical importance for effective environmental management of these regions. Both measurements and simulations have not shown strong earth's rotational effects on the plume transport. Its movement appeared to have been primarily controlled by the wind-driven coastal current. Our simulations indicate that the frequent reversals of this current should effectively limit the plume's along-shore extent and may result in a continuous coastal band of turbid water extending alongshore in either direction in the vicinity of the river mouth.

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List of Figures:

**Table 1: The station points in finite-element mesh, and their distance from the river-mouth**

| | To the east | | | | To the west | | | |
|---|---|---|---|---|---|---|---|---|
| Point | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Dist.(km) | 1.3 | 4.1 | 6.7 | 9.9 | 1.2 | 3.1 | 5.1 | 7.9 |

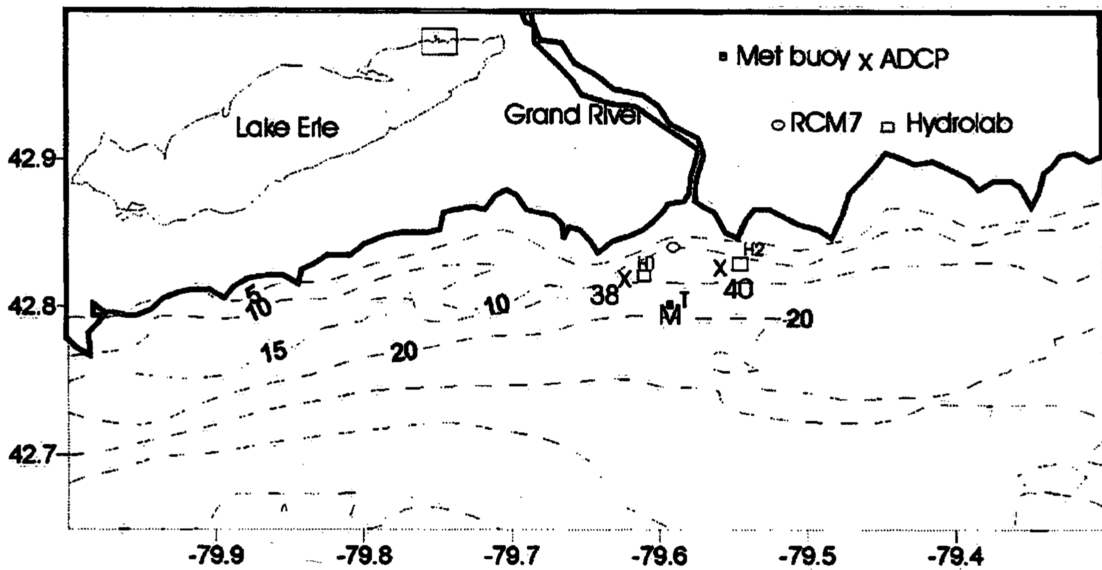

Met buoy
ADCP
RCM7
Hydrolab
Lake Erie
Grand River
42.9
42.8
42.7
-79.9
-79.8
-79.7
-79.6
-79.5
-79.4
5
10
15
20
10
38
40
20
H1
H2
M
T

Fig. 1

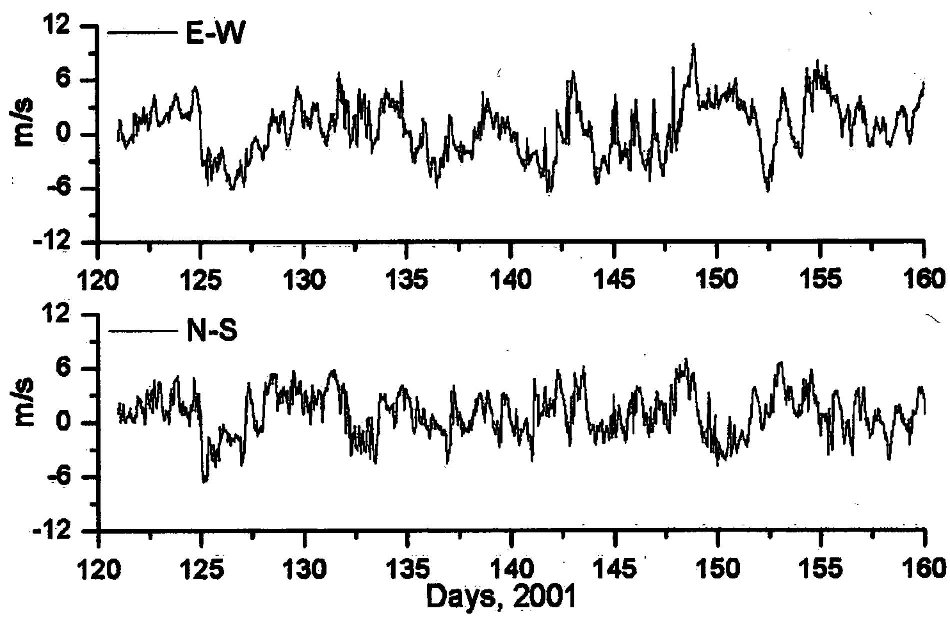
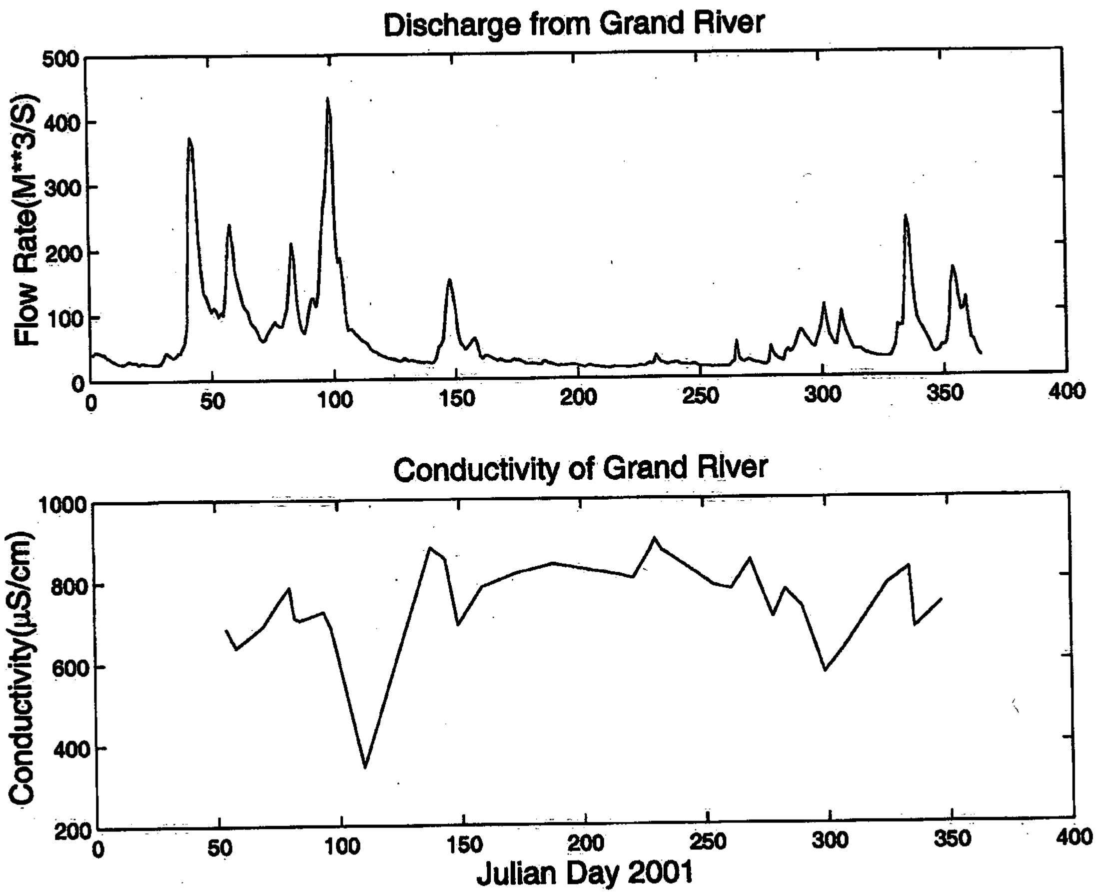



Fig. 2



Discharge from Grand River
Flow Rate(M**3/S)
500
400
300
200
100
0
0
50
100
150
200
250
300
350
400
Conductivity of Grand River
Conductivity(µS/cm)
1000
800
600
400
200
0
50
100
150
200
250
300
350
400
Julian Day 2001


Fig. 3

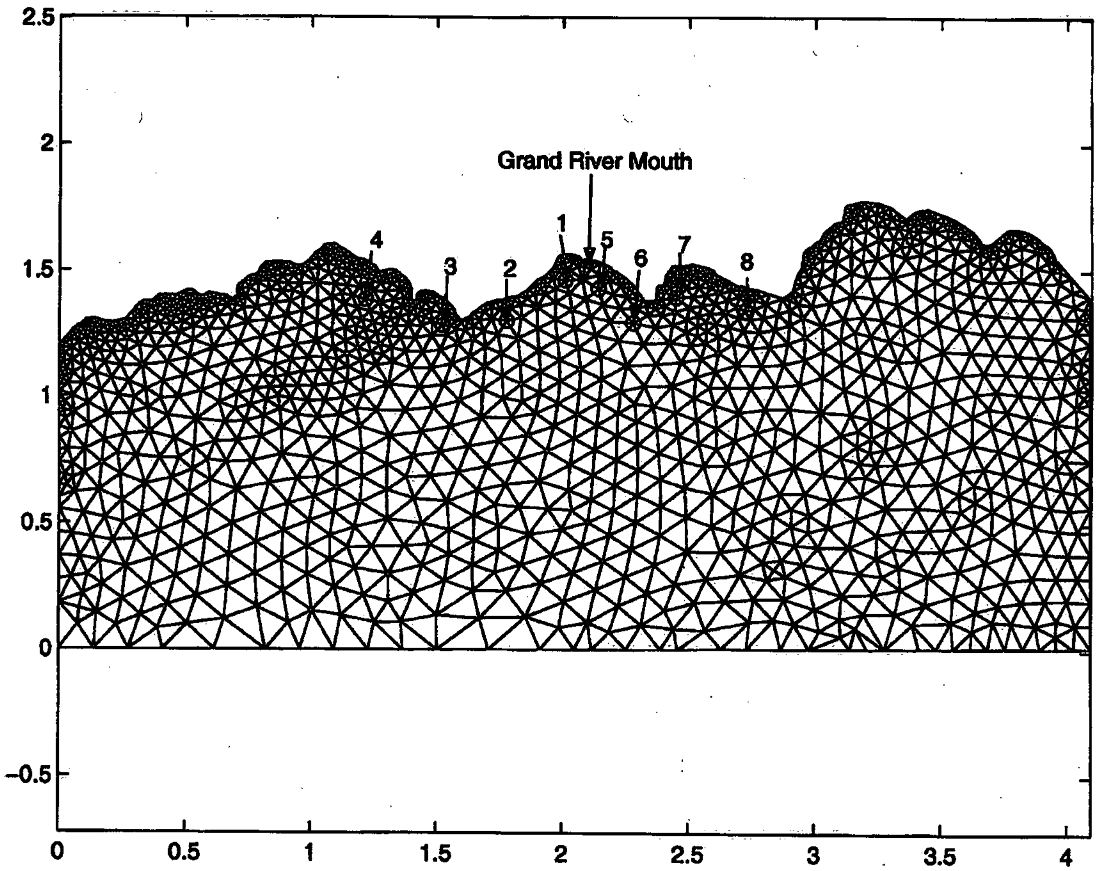



Fig. 4

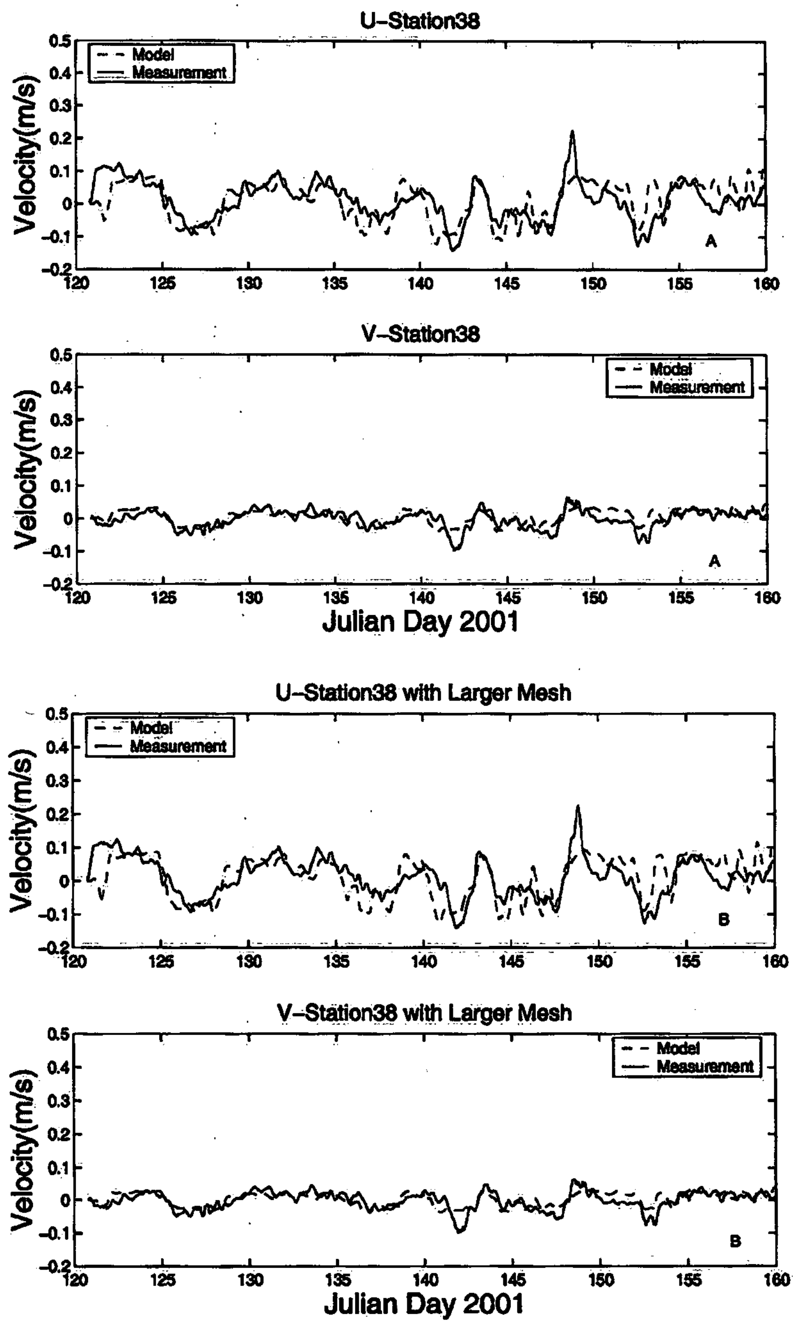

U-Station38
Model
Measurement
Velocity(m/s)
A
V-Station38
Model
Measurement
Velocity(m/s)
A
Julian Day 2001
U-Station38 with Larger Mesh
Model
Measurement
Velocity(m/s)
B
V-Station38 with Larger Mesh
Model
Measurement
Velocity(m/s)
B
Julian Day 2001

Fig. 5

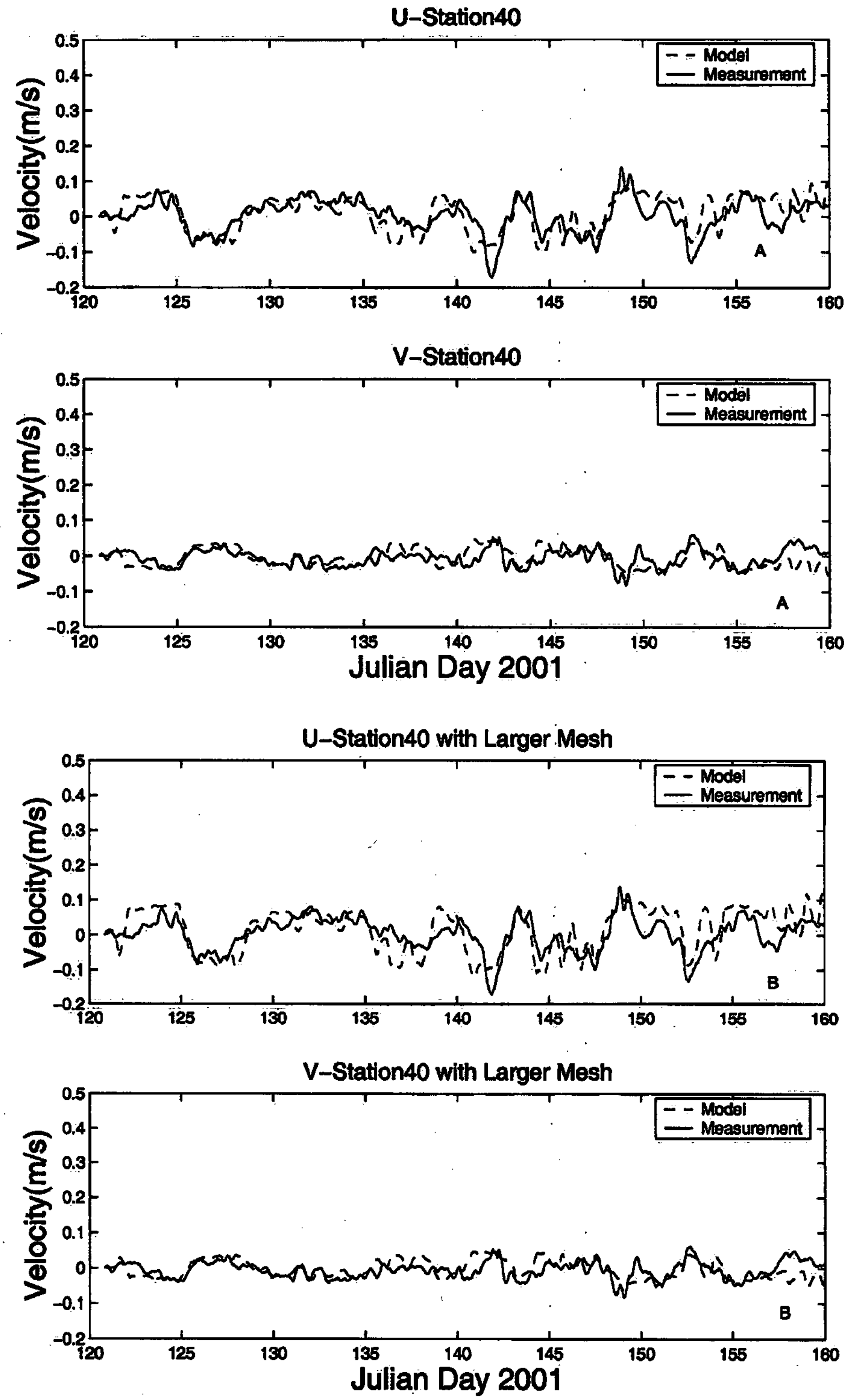
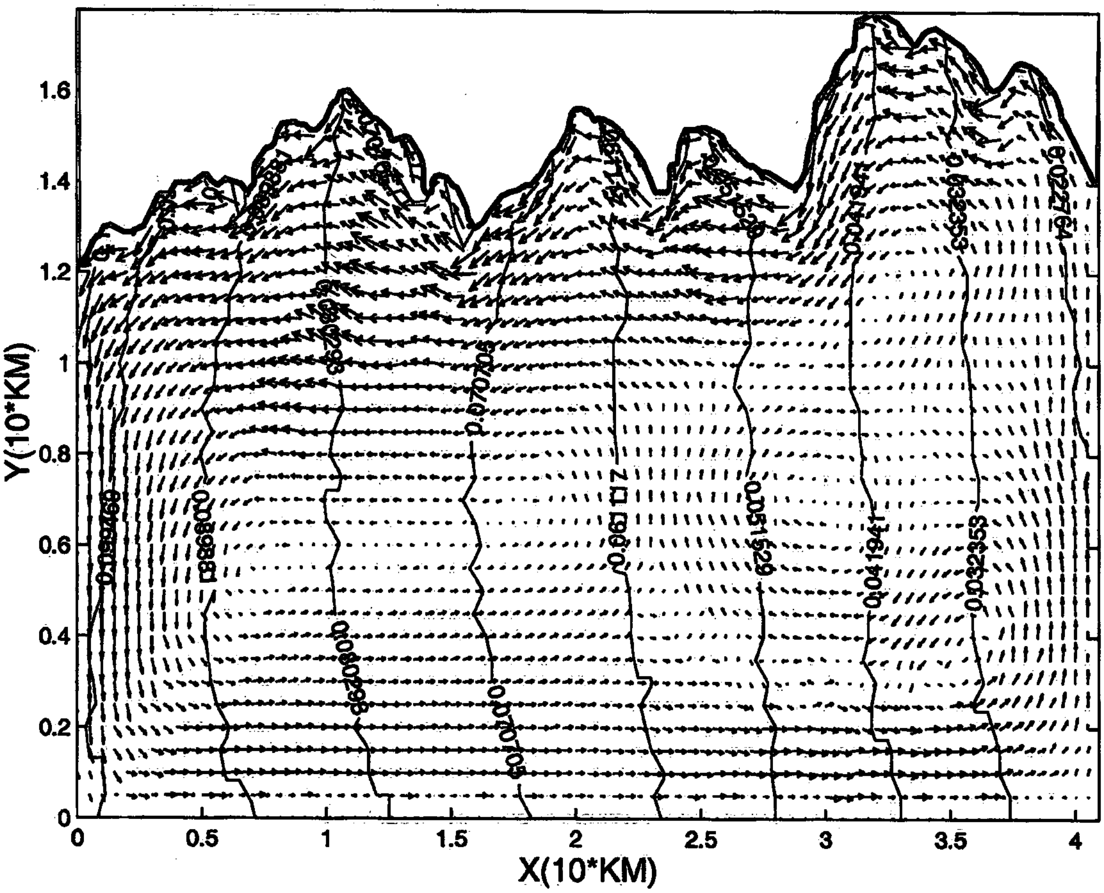

U-Station40
V-Station40
U-Station40 with Larger Mesh
V-Station40 with Larger Mesh
Model
Measurement
Velocity(m/s)
Julian Day 2001
A
B
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
120
125
130
135
140
145
150
155
160

Fig. 6



Y(10*KM)
X(10*KM)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.5
1.5
2
2.5
3
3.5
4
0.080298
0.07705
0.061117
0.051529
0.041941
0.032353
0.070705
0.09469


Fig. 7

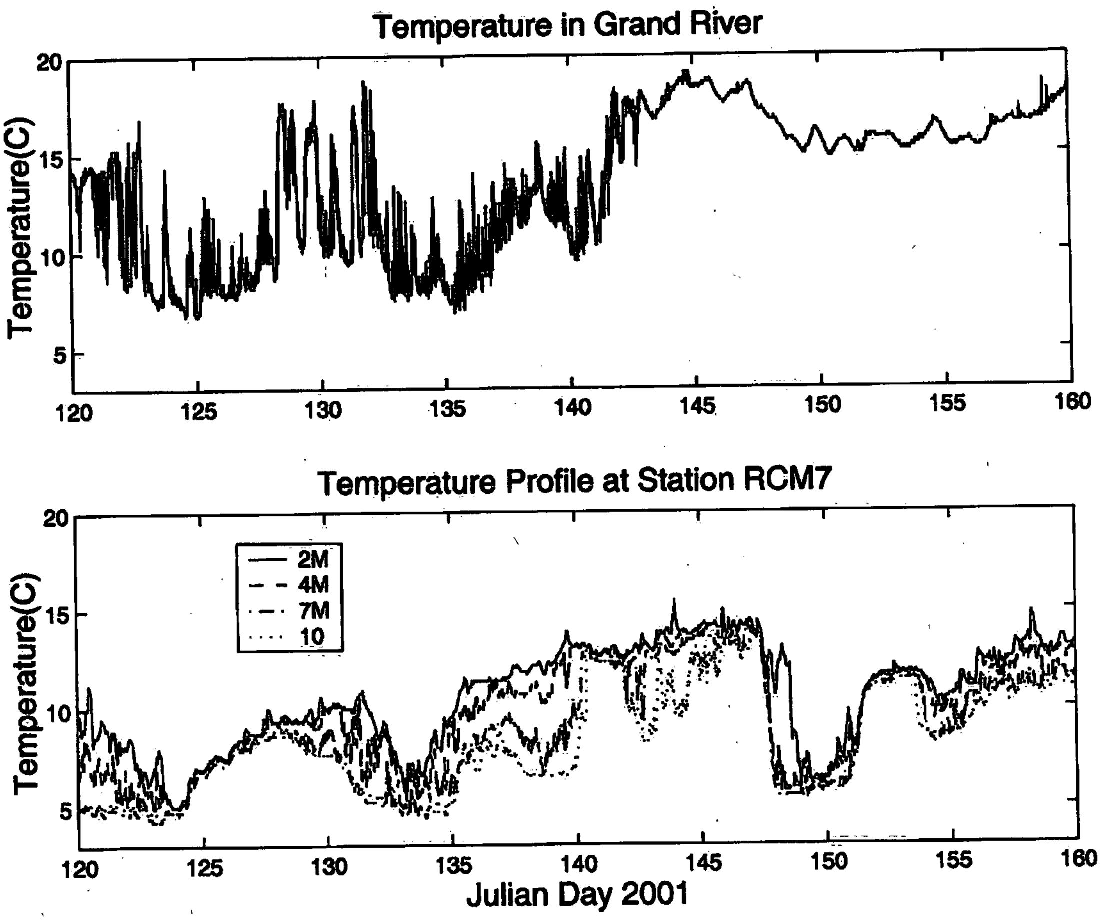

Temperature in Grand River
Temperature(C)
Temperature Profile at Station RCM7
2M
4M
7M
10
Temperature(C)
Julian Day 2001

Fig. 8

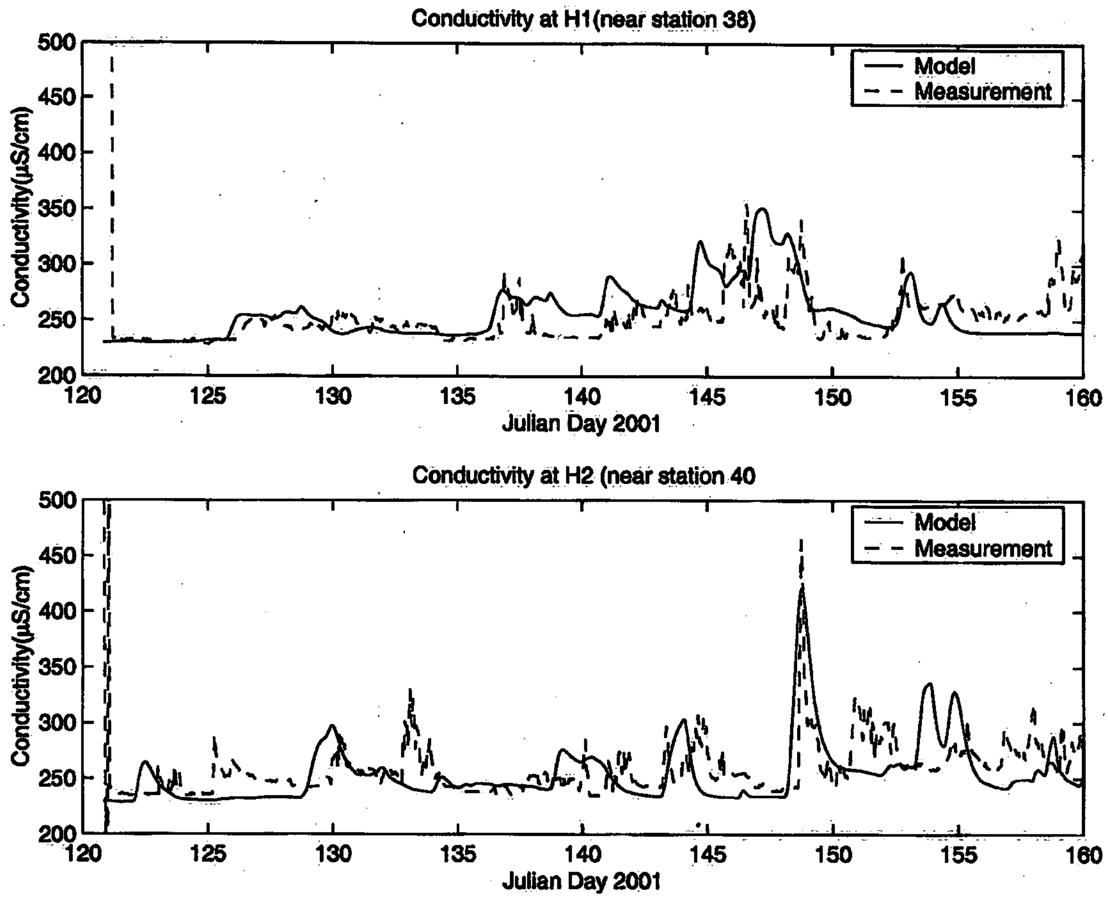
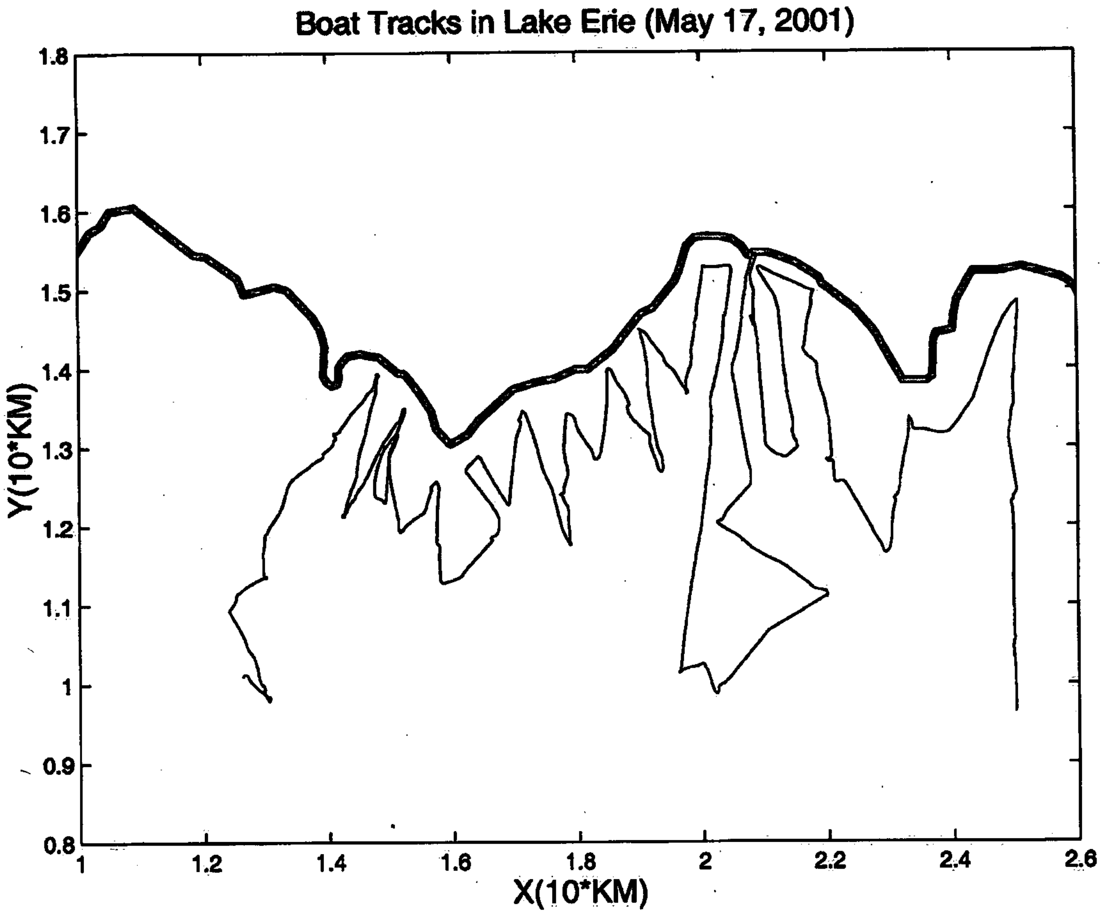
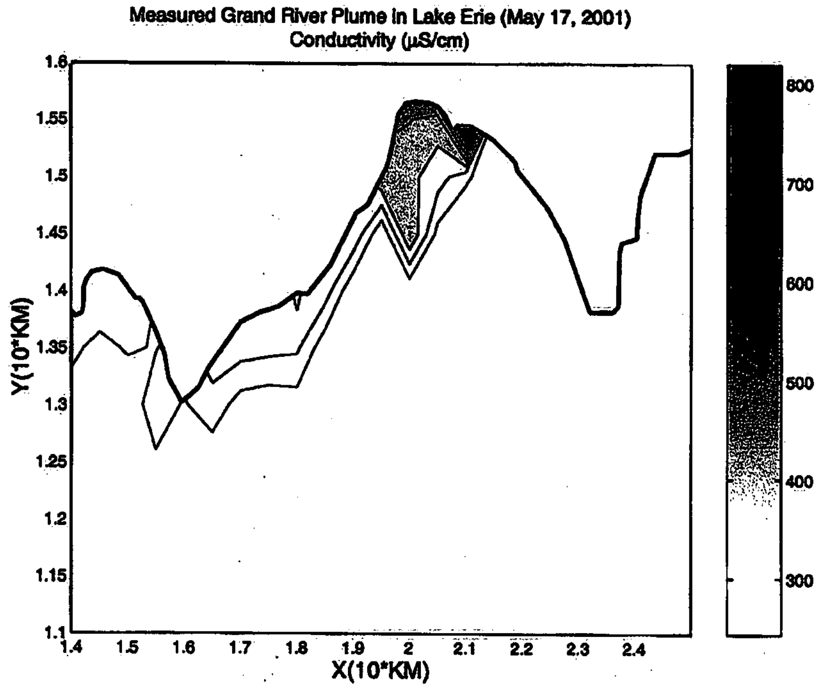

Conductivity at H1(near station 38)
Model
Measurement
Conductivity(µS/cm)
500
450
400
350
300
250
200
120
125
130
135
140
145
150
155
160
Julian Day 2001
Conductivity at H2 (near station 40
Model
Measurement
Conductivity(µS/cm)
500
450
400
350
300
250
200
120
125
130
135
140
145
150
155
160
Julian Day 2001

Fig. 9



Boat Tracks in Lake Erie (May 17, 2001)
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
Y(10*KM)
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
X(10*KM)


Fig. 10


Measured Grand River Plume in Lake Erie (May 17, 2001)
Conductivity (µS/cm)
Y(10*KM)
X(10*KM)
1.6
1.55
1.5
1.45
1.4
1.35
1.3
1.25
1.2
1.15
1.1
1.4
1.5
1.6
1.7
1.8
1.9
2
2.1
2.2
2.3
2.4
800
700
600
500
400
300

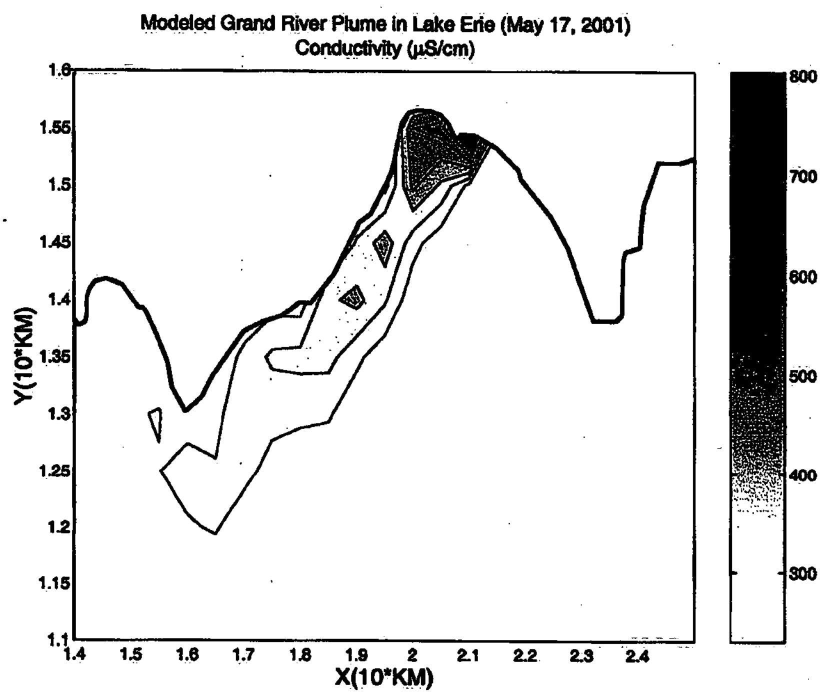
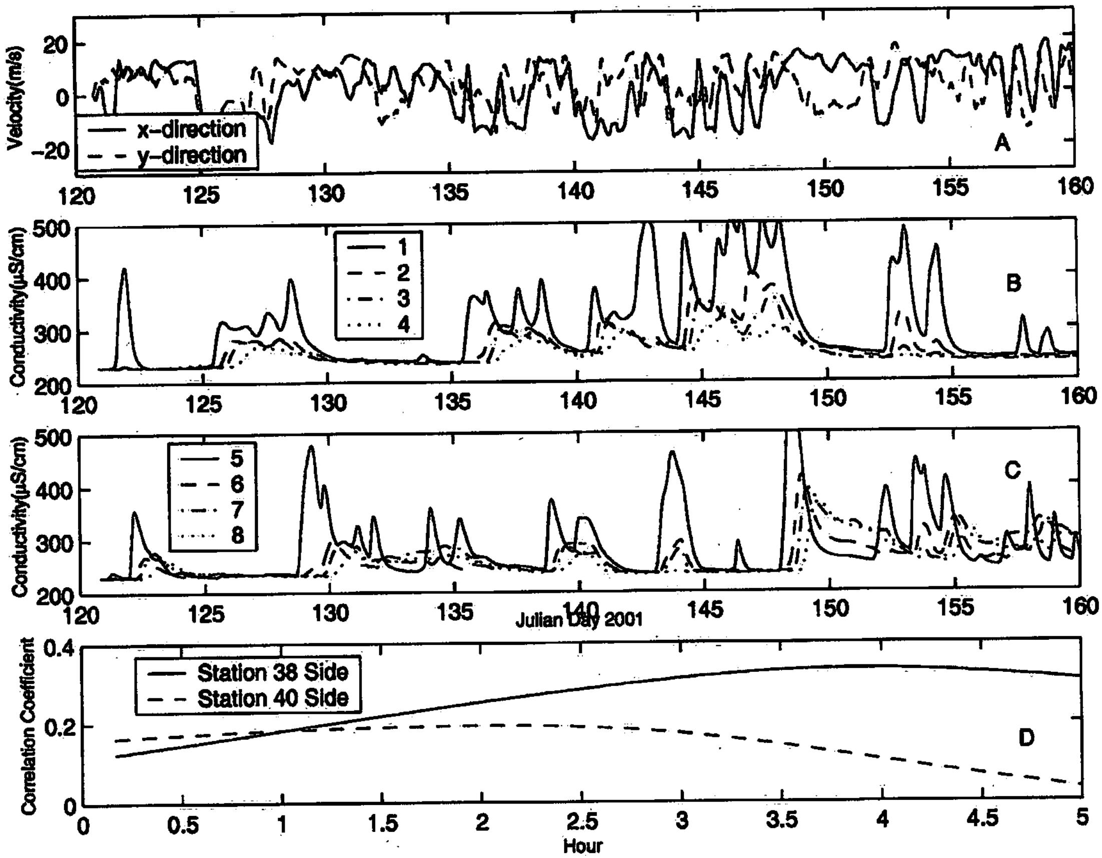

Modeled Grand River Plume in Lake Erie (May 17, 2001)
Conductivity (µS/cm)
Y(10*KM)
X(10*KM)
1.6
1.55
1.5
1.45
1.4
1.35
1.3
1.25
1.2
1.15
1.1
1.4
1.5
1.6
1.7
1.8
1.9
2
2.1
2.2
2.3
2.4
800
700
600
500
400
300

Fig. 11



Velocity(m/s)
20
0
-20
x-direction
y-direction
A
120
125
130
135
140
145
150
155
160
Conductivity(μS/cm)
500
400
300
200
1
2
3
4
B
Conductivity(μS/cm)
5
6
7
8
C
Julian Day 2001
Correlation Coefficient
0.4
0.2
0
Station 38 Side
Station 40 Side
D
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Hour


Fig. 12

Environment Canada Environnement Canada

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