Real-Time Hydraulic and Hydrodynamic Model of the St. Clair River, Lake St. Clair, Detroit River System

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Abstract: The Huron-Erie Corridor serves as a major waterway in the Great Lakes and is the connecting channel between Lake Huron and Lake Erie. The system consists of the St. Clair River, Lake St. Clair, and the Detroit River, and serves as a recreational waterway, source of drinking water for Detroit and surrounding cities, as well as the only shipping channel to Lakes Huron, Michigan, and Superior. This paper describes a three-dimensional unsteady model of the combined system and its application to real-time predictions of physical conditions over the corridor. The hydrodynamic model produces nowcasts eight times per day and 48 h forecasts twice a day. Comparisons between model simulations and observed values show average differences of 3 cm for water levels and 12 cm/s for along-channel currents in the St. Clair River (compared to mean current values of 1.7 m/s) for the period of September 2007 to August 2008. Simulations reveal a spatially and temporally variable circulation in Lake St. Clair as well as significant changes in flow rate and distribution through the St. Clair Delta not accounted for in previous models.

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Background

River Models

Several models have been developed to characterize the discharge and flow distribution in the St. Clair and Detroit Rivers for a variety of scenarios. Initially, one-dimensional transient models (Quinn and Wylie 1972; Quinn and Hagman 1977; Derecki and Kelley 1981; Derecki 1982) aimed to replace the empirical stage-fall discharge equations employed to estimate flow in the Huron-Erie Corridor (HEC). These models used daily, weekly, and monthly forecasted water levels, and eventually implemented wind stress forcing (Quinn 1980) to provide flow magnitude predictions for each river. These models gave reasonably accurate estimates of discharge for both rivers, but were not able to describe details of the hydrodynamics in the system. A steady two-dimensional hydrodynamic model (RMA2) was developed to predict the spatial distribution of currents in the St. Clair and Detroit Rivers by Tsanis et al. (1996) for constant inflow and downstream water level boundary condition. Results were compared to drifter buoy experiments. However, unlike the one-dimensional models, which used varying Manning's n roughness coefficients between water level gauges, the two-dimensional model implemented a constant Manning's n coefficient in each river. The main limitations of this model were the steady-state conditions and nonvariable roughness parameter. Using the discharge predictions and steady-state distributions from these studies, other subsequent studies were able to investigate flow reversal in the Detroit River (Quinn 1988), the effects of weed growth on flow magnitude (Sellinger and Quinn 2001), flow distribution in branches of the Detroit and St. Clair Rivers (Holtschlag and Koschik 2002b), and flow paths as a function of depth in the St. Clair River (Holtschlag and Koschik 2005). In all cases, variation of flow or velocity with depth was not described.

Lake St. Clair Models

In contrast to the discharge focus of the river model, hydrodynamic models of Lake St. Clair have primarily focused on the effects of wind on lake circulation and water levels. The first numerical model (Schwab et al. 1981) used a two-dimensional, unsteady finite-difference scheme to describe the hydrodynamics for a constant inflow/outflow and temporally varying wind. However, in order to describe both circulation and changes in elevation, a rigid lid circulation model and a free surface model were employed. The rigid lid model was applied to Lake St. Clair to study the effect of wind on lake circulation (Schwab et al. 1989) using wind data from 1985 and constant flow conditions. These results were compared with current meter observations and drifter buoy tracks for the selected time period. Two-dimensional models were also used to investigate wave-current interactions within the

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lake in order to validate field measurements (Tsanis and Wu 1990; Brissette et al. 1993). The first three-dimensional (3D) model of Lake St. Clair (Ibrahim and McCorquodale 1985) used finite elements to predict the current patterns for a variety of steady-state flow and uniform wind conditions. In addition, they also investigated the effects of ice on lake currents by reducing wind stress as a function of ice coverage. However, the steady-state model could only provide general circulation patterns in the lake. Variability due to hydraulic flow and wind stress was not included. In addition to circulation in Lake St. Clair, water-level setup was also modeled as a function of wind stress (Simons and Schertzer 1989) using an unsteady, two-dimensional model, validated with water level gauges at the shoreline. This study also compared hydrodynamic model results to those of an empirical model of the lake, pointing out that although the results were similar, the hydrodynamic model was able to calculate water level for any location without the extensive history necessary for empirical models. Thus far, hydrodynamic models of Lake St. Clair have described current patterns in the lake using either an (1) unsteady, two-dimensional or (2) steady, 3D model, but in all cases uniform wind and constant inflow/outflow conditions have been applied, thus failing to take into account the temporal variation of hydraulic flow through the lake in combination with variable winds.

Combined-System Models

As Lake St. Clair and the St. Clair and Detroit Rivers are hydraulically linked, variations in water level and flow are interdependent between sections, and thus for accurate hydraulic and hydrodynamic predictions, a single model is essential. Furthermore, due to the population density near the HEC, and the cities served by the waterway, a combined-system model is also necessary to predict transport of pollutants, sediment, toxins, etc. throughout the waterway. Based on prototype models of the entire HEC by the United States Army Corps of Engineers and Environment Canada, a steady-state two-dimensional, finite-element model of the HEC was developed by Holtschlag and Koschik (2002a), as part of the Michigan Dept. of Environmental Quality source water assessment program. Their model used the RMA-2 hydrodynamic model to predict velocity and water level throughout the corridor based on an upstream flow condition at the St. Clair River and downstream water level in the Detroit River near Bar Point, Ontario, as well as constant flows at seven tributaries along the system. Steady-state scenarios were used to calibrate the model for elevation and flow with nonuniform Manning's n coefficients, in order to provide flow paths for a given steady-state physical scenario. However, wind forcing was not included in the model, and thus currents and circulations in the HEC are purely hydraulically driven. As such, velocities at specific points within the model were not validated with observations.

Overall, neither the combined-system model nor a combination of sectional models provide a complete, unsteady 3D description of the HEC, which is necessary for producing real-time nowcasts and forecasts of the hydrodynamics. The purpose of this study is to provide such a combined-system model, in which the hydrodynamic processes of the combined St. Clair River, Lake St. Clair, and the Detroit River can be predicted in an operational setting and support search and rescue operations, toxic spill response, drinking water quality, invasive species investigations, commercial shipping, and beach closure forecasting.

Model

In order to produce hydrodynamic forecasts for the HEC, a wide geometric range of length scales in the combined system must be resolved. Unlike the open Great Lakes and the models of the Great Lakes coastal forecasting system (GLCFS) (Schwab and Bedford 1994), the HEC consists of a variety of lake, river, and tributary length scales that are critical to the system dynamics. Thus, to resolve the geometry without great computational expense, an unstructured grid is employed to simulate the fluid dynamics in the HEC using the finite volume coastal ocean model (FVCOM) (Chen et al. 2003; Chen et al. 2006).

FVCOM Background

FVCOM is a 3D hydrostatic free surface circulation model that solves continuity [Eq. (1)], momentum [Eq. (2)], and temperature equations [Eq. (3)] with second order accuracy on a horizontally unstructured grid of triangular elements and a sigma coordinate system in the vertical direction

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{1}$$

$$\frac{Du}{Dt} - fv = -\frac{1}{\rho_0}\frac{\partial P}{\partial x} + \frac{\partial}{\partial z}\left(K_m\frac{\partial u}{\partial z}\right) + F_u$$

$$\frac{Dv}{Dt} - fu = -\frac{1}{\rho_0}\frac{\partial P}{\partial y} + \frac{\partial}{\partial z}\left(K_m\frac{\partial v}{\partial z}\right) + F_v \tag{2}$$

$$\frac{\partial P}{\partial z} = -\rho g$$

$$\frac{DT}{Dt} = \frac{\partial}{\partial z}\left(K_h\frac{\partial T}{\partial z}\right) + F_T \tag{3}$$

where x, y, and z=Cartesian coordinates; u, v, and w=velocity components; T=temperature; ρ=density; ρ_0=reference density; P=pressure; f=Coriolis parameter; g=gravitational acceleration; K_m=vertical eddy viscosity coefficient; K_h=thermal vertical eddy diffusion coefficient; F_u and F_v=horizontal momentum diffusion terms; and F_T=horizontal thermal diffusion term.

Unlike finite-difference and finite-element schemes, FVCOM solves the integral forms of the governing equations to better satisfy the conservation laws. In addition, the unstructured grid uses triangular volumes to resolve complex geometry, and thus is able to accurately portray the hydrodynamics near complex areas with a reduced number of grid cells as compared to structured grids. In previous studies, FVCOM has demonstrated better resolution of both geometry and hydrodynamics (velocity, temperature, circulations) than finite-difference schemes, and has been validated through analytical, numerical, and experimental means (Chen et al. 2003; Chen et al. 2007; Chen et al. 2008; Huang et al. 2008). In particular, FVCOM has been validated with success in the cases of the wind-driven circular basin (Chen et al. 2007; Huang et al. 2008) and coastal rivers/creeks (Chen et al. 2003), both of which exhibit similar hydrodynamics to Lake St. Clair and the St. Clair and Detroit Rivers, respectively.

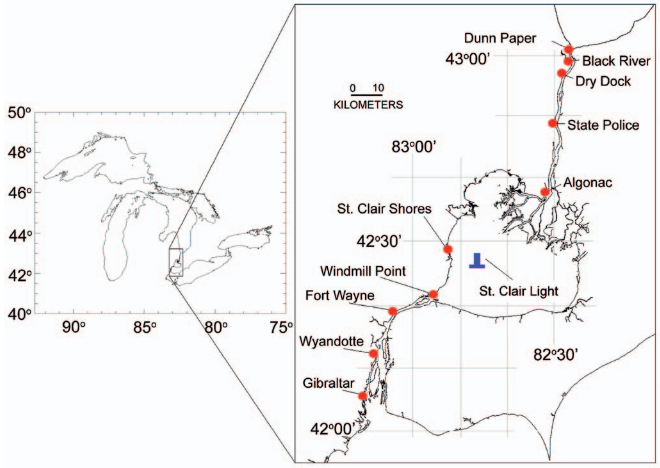

Fig. 1. (Color) Location map of the HEC, containing the NOS water level gauges (red dots) along the HEC and the CMAN wind station at the Lake St. Clair Lighthouse (blue rectangle). The gauge at Dunn Paper, Mich. is used as the boundary condition for inlet of the model, and the Gibraltar and Fermi Power Plant, Mich. gauges are used for the outlet of the model. The remaining gauges are used in model calibration as well as in validation during real-time runs. The lighthouse is the location of the C-MAN station that provides hourly wind data to the model.

HEC Specifics

The HEC stretches over 90 mi (150 km) from Lake Huron to Lake Erie, and has a surface area of 480 mi^2 (1250 km^2) (Fig. 1). To resolve this geometry, an unstructured grid is created for the hydrodynamic model consisting of 25,050 triangular elements and 14,659 nodes (Fig. 2). Grid resolution varies within the model from an average grid resolution of 100 m in the rivers to 300 m in Lake St. Clair, and 50 m in the tributaries. Provision for wetting/drying of volumes is included in the model. The model contains 7 uniformly distributed sigma layers in the vertical direction. A 3D model is chosen to capture the vertical velocity profile in order to support toxic spill response and drinking water intake predictions. As this operational model has been developed as a predictive tool for use in spill response, in addition to other user communities, there is a need to understand the vertical diffusion of contaminant releases that can occur from a variety of scenarios (e.g., surface release, bottom release, water quality at intake level or surface beach areas). Therefore, the model has been implemented as 3D to resolve the horizontal and vertical velocities and enable lateral and vertical tracking. The number of sigma layers chosen in this model (7) was the result of balancing the need for an efficient simulation time for operations and the need to adequately predict the vertical distribution of velocity. It was determined from several iterations of sigma layers that seven layers was able to capture vertical velocity profiles seen in models with more layers and from the limited observations without a drastic increase in computation time. This model does not incorporate temperature stratification since the entire system is shallow enough to be predominantly well-mixed in the vertical direction. Additionally, eddies and other characteristics that are smaller than the resolved lateral and vertical scales will not be captured by the resultant model grid.

In order to smooth the transition at the boundaries, the grid is artificially extended at both the inlet and outlet of the model and reduced to a single element at the northern and southern boundaries. An iterative process was used to design the inlet and outlet boundary so that a single element could be used to represent a boundary condition that provides stability and the correct flow in the realistic geometry. The shoreline and bathymetry applied to the grid are realistic (from Dunn Paper, Michigan to Bar Point, Ont.) for the entire model except for the boundary extensions (reductions in elements), where artificial shorelines and bathymetry were created by extruding the conditions at Dunn Paper and Bar Point. These extensions are implemented to stabilize the model for the use of water level boundary conditions (in contrast to flow/water-level conditions) and eliminate flow anomalies that can occur near the open-boundaries of unstructured grids, but they are not expected to affect the results in the realistic grid geometry. Hence, results are reported for the model grid from Dunn Paper, Mich. (inlet) to Bar Point, Ont. (outlet). The time-step is four seconds (internal and external) for all simulations.

The driving forces behind the hydrodynamics in the HEC differ from those of the Great Lakes (Schwab and Bedford 1994) as the rivers form a major component of the system, necessitating the use of open-boundaries at the mouths of the St. Clair and the Detroit Rivers to allow for the inflow and outflow of the system. The dynamics in the HEC are both hydraulically driven by the water levels at Lake Huron and Lake Erie, as well as driven by the wind stress on Lake St. Clair. In addition, the inflow from tributaries connected to the system can have a noticeable effect on downstream water levels and consequently the hydrodynamics. The set of boundary conditions applied to the model consists of: (1) the water levels near Lake Huron and Lake Erie; (2) the wind stress over the entire model provided by a station on Lake St. Clair; and (3) the tributary inflows along the system.

Initialization

Using the stated boundary conditions, the model is initialized with a steady-state water level profile and constant flow. In contrast to the flat water-surface initial condition applied to hydrodynamic models of the Great Lakes, the drop in water elevation along the entire span of the HEC varies between 1.5 and 2.0 m from Lake Huron to Lake Erie, producing an average flow of $5{,}200\ m^3/s$ (Holtschlag and Koschik 2002a). In order to obtain this water-level profile as an initial condition, the model is first given a flat water-surface elevation for the entire system equivalent to the water level at Lake Huron, near the mouth of the St. Clair River. Then the water is allowed to 'drain' through the outlet at the bottom of the Detroit River by incrementally decreasing the water level at the outlet (maintaining the water level at the inlet) until it matches the level at Lake Erie. The resulting steady-state flow, interior velocities, and water levels become the initial conditions for the model. In addition to the initial hydrodynamic and hydraulic conditions, the bottom roughness (z_0) for various sections of the model is specified. This parameter is critical to hydrodynamics in the rivers, and since it cannot be measured physically, roughness is determined through calibration to water level and flows. Therefore, as an initial condition, the entire model is given a uniform bottom roughness, and then a separate value of roughness is determined for individual reaches of the model by calibration between water-level gauges.

Model calibration is carried out through seven steady-state scenarios adopted from the work of Holtschlag and Koschik (2002a,b). Each scenario consists of three-day averages of flow at several cross sections of the model as well as water level at ten water level gauges maintained by the National Oceanic and Atmospheric Administration (NOAA) National Ocean Service

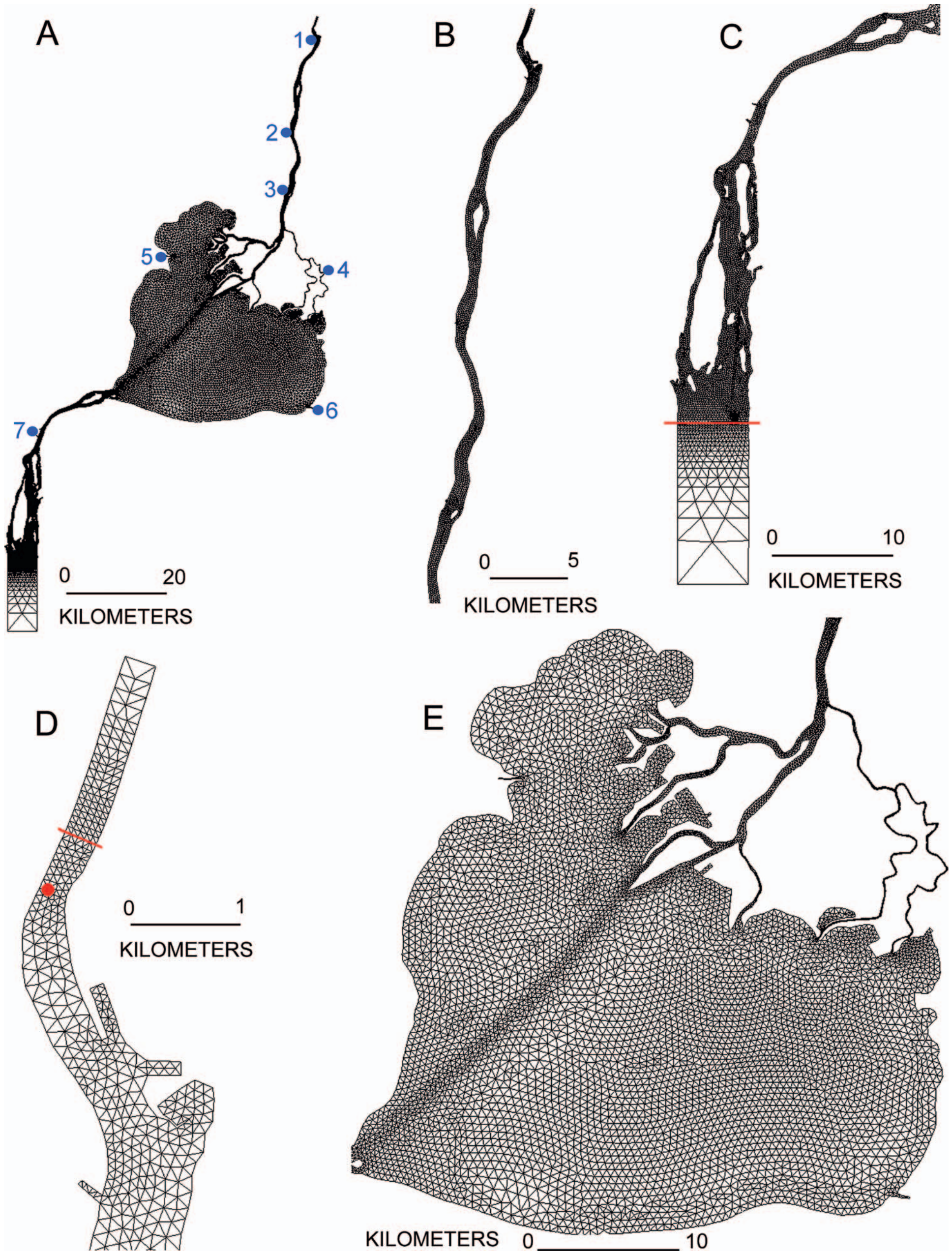

Fig. 2. (Color) (a) Unstructured grid of the HEC; (b) St. Clair River; (c) Detroit River; (d) the model inlet at the St. Clair River; and (e) Lake St. Clair. The red point represents the location of the ADCP gauge near the Blue Water Bridge and the red lines represent the border between the HEC geometry and the artificial extensions. Seven tributaries are included in the model (shown in blue): (1) Black River; (2) Pine River; (3) Belle River; (4) Sydenham River; (5) Clinton River; (6) Thames River; and (7) River Rouge.

(NOS). The scenarios were chosen based on availability of flow measurements by reach throughout the system (Fig. 1; reaches defined between each water level gauge), as carried out in fieldwork for the years 1996–1999. The average drop in elevation between the model inlet and outlet is on the order of 2 m, with up to 1 m variation in the water levels at the inlet and outlet for the seven scenarios. In addition, the inflows to the system for each scenario range from 4,905 to 6,302 m^3/s. To begin the calibration, a value of the uniform z_0 is first determined that yields a flow through the inlet equivalent to the scenario measurement. The model is run using the boundary conditions for Scenario 1, where the steady-state inlet flow is compared to observed flows while the uniform z_0 is adjusted in order to match the desired inflow. Following this adjustment, the seven scenarios are run with the appropriate boundary conditions for each case, using the uniform z_0 as found previously. In each scenario, the interior water levels and flows (through branching cross sections) are compared to the respective observed values. Beginning with the model outlet at the mouth of the Detroit River the bottom roughness is adjusted by reach, where reaches are determined by zones that lie between the gauge locations [zones adapted from the work of Holtschlag and Koschik (2002a)]. The mean differences between the observed and model water levels at the gauge upstream of the zone are found for the seven scenarios, and the z_0 is adjusted accordingly. This procedure is repeated until the mean differences between observed and modeled elevation are minimized across the scenarios, yielding an optimal calibration for the given scenarios. After the bottom roughness (z_0) is determined for a specific reach, the next upstream reach is investigated and the process is repeated to find the appropriate roughness until the water levels are satisfied for the entire model. Finally, calibration is completed by again comparing model and observed flows for the scenarios, as adjustments to the zonal roughness could shift the inflow. The mean difference between observed and modeled flow across all scenarios is used to adjust roughness equally for all zones within the model, in which the calibrated water levels will be maintained while the flow is satisfied. After calibration, the z_0 for each zone in the model yields the best set of water levels and flows for the seven steady-state scenarios.

Nowcast Boundary Conditions

Simulations of the hydrodynamics in the HEC require real-time boundary conditions in order to provide an operational nowcast of the system. As stated previously, the model inputs consist of water level at the inlet and outlet, the wind velocity, and tributary inflows.

Water levels supplied at the inlet and outlet of the model are provided by NOAA/NOS gauges, and are located near Dunn Paper, Mich. for the St. Clair River, and near Gibraltar and the Fermi Power Plant, Mich. for the Detroit River (Fig. 1). Real-time levels are obtained every six minutes and become the driving force for the model nowcast. As the model grid extends above the Dunn Paper gauge, an adjustment must be made to the gauge water level (used as a boundary condition at the inlet) in order to provide accurate flow and water levels within the model. This adjustment is found by calibration, and thus water level supplied at the model inlet is the 6-min level from Dunn Paper plus the adjustment. Similarly, the model outlet extends beyond the Gibraltar gauge, and thus an adjustment must be made to provide the correct downstream boundary condition as well. In this case, in order to properly provide the water level and flow at the mouth of the Detroit River, both the Gibraltar (upstream of the outlet) and Fermi Power Plant (downstream of the outlet) gauges are used to calculate the necessary outlet boundary condition (found by calibration). In the event that a water level gauge fails to provide data in real-time (nonoperational or erroneous data), the next closest gauge is used to provide the inlet/outlet boundary conditions, where the necessary adjustments are again found by calibration. In this case, the model is still able to produce real-time nowcasts.

Wind forcing on the HEC is also a critical boundary condition, particularly for determining circulation in Lake St. Clair. For the wind condition, data are obtained hourly by a NOAA coastal-marine automated network (C-MAN) station at the Lake St. Clair lighthouse (Fig. 1), and is applied uniformly over the entire model. For wind conditions between the hours, values are estimated by interpolation.

Finally, tributary flows are included for seven tributaries along the HEC (Fig. 2). All rivers are given "real-time" daily averages for flow as calculated by the large basin runoff model (LBRM) for the Great Lakes (Croley 2002), in which river-mouth flow is determined as a function of daily precipitation, temperature, insulation, snow pack, snow melt, and evaporation. The LBRM has been extensively calibrated against the USGS tributary flow data for tributaries across the entire Great Lakes basin. Nowcast model runs are performed every 3 h.

Forecast Boundary Conditions

Forecasts of flows and levels for the HEC are also performed for conditions out to 48 h into the future, starting at the end of the nowcast. In this case, model forecasts require the same input conditions as the nowcast model runs, namely wind, water level, and tributary flow. Forecasted winds are obtained from the National Weather Service national digital forecast database (NDFD) for every third hour in the forecast simulation (Glahn and Ruth 2003). Again, wind speed and direction are applied uniformly over the entire model, with the NDFD values taken from the location of the St. Clair lighthouse. Forecasted water levels for the inlet and outlet are acquired hourly from the GLCFS model output for Lake Huron and Lake Erie. GLCFS forecasted water levels near the Dunn Paper gauge on Lake Huron and levels from the Gibraltar and Fermi gauges on Lake Erie are used. For both the wind and water level boundary conditions, interpolation is used to estimate values between forecast hours. Finally, tributary flows are applied as constants based on the last LBRM output. Hence, the last flow for a particular tributary in the latest nowcast simulation is applied for the 48 h forecasted period. Forecast model runs are performed every 12 h, providing a new 48 h forecast for the HEC. The initial conditions for each forecast run are taken from the end-point of the most recent nowcast run. Forecasts are, thus, independent of previous forecasts.

Results

Calibration

The HEC hydrodynamic model is calibrated with seven steady-state scenarios, where the roughness lengths (z_0) for reaches between water level gauges are adjusted to provide the best set of flows and water levels within the model (z_0 range from 0.0001 to 0.01 m). For seven scenarios and 10 water level gauges (70 data points total), the maximum difference in water level between the model and observed values is 4 cm [Fig. 3(a)]. The majority of the computed water levels are less than 2 cm from the observed level (data points on the diagonal line represent a perfect match between the computed and observed level). Comparisons are also reported by water level gauge and scenario (Fig. 4), in which levels in the Detroit River, and in particular at Gibraltar, yield the largest variance. Similarly, computed volumetric flows at various cross sections throughout the system are compared to observations [Fig. 3(b), Table 1], where inlet flows at the head of the St. Clair River are within 5% of the measured average flow the scenario time period. This result is representative of other flow comparisons made throughout the system (outlet, other branches, etc.), and thus only results for the inlet are reported. Differences in both water levels and flows are comparable to those described in Holtschlag and Koschik (2002a,b), where such differences are not surprising as the scenarios represent averaged measured flow and water level data instead of actual steady-state conditions.

Nowcast

Following calibration, nowcast simulations are carried out to predict water levels and currents for the period of September 2007 through August 2008 using observed boundary conditions for water level, wind, and tributary flow. A time series of the water levels, computed and observed, display the model performance for the periods of September–December 2007 and January–August 2008 (Fig. 5). As the model does not include ice conditions, performance during the period of ice-cover (January–March 2008) is worse than in nonice months. The ice period is shown only to provide an indication of system sensitivity to the ice con-

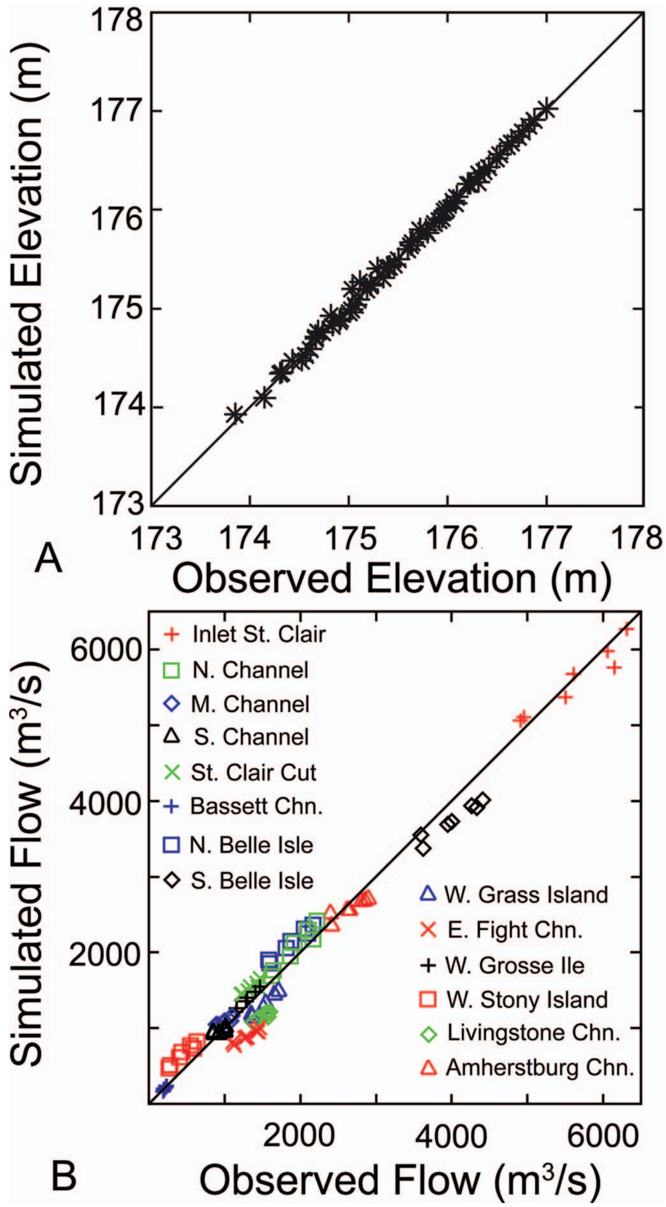

Fig. 3. (Color) Comparison of model and observed: (a) water levels for each gauge; (b) flows at various cross sections throughout the system for the seven steady-state calibration scenarios. The line of agreement (plotted diagonally) represents a perfect match between model and observed values.

ditions. Results during this time are not included in the analysis. As seen in the time series, the model is able to predict both the small- and large-scale fluctuations in water levels for the observed period, including during high-wind events, with accuracy within the ranges defined by the calibration. The months of November and December yield the highest daily fluctuations in water levels, in which December shows the largest differences between modeled and observed water levels (outside of the ice months). Statistical analysis for the entire year shows the mean water level for each gauge to be within 3 cm, where the average root mean square difference (RMSD) between the observed and model level is under 4 cm (Table 2). These differences in water level can yield consequent changes in flow magnitude through the rivers, where the exact magnitude is dependent on the specific water levels and reach. For the RMSD values in Table 2, the river flow can vary

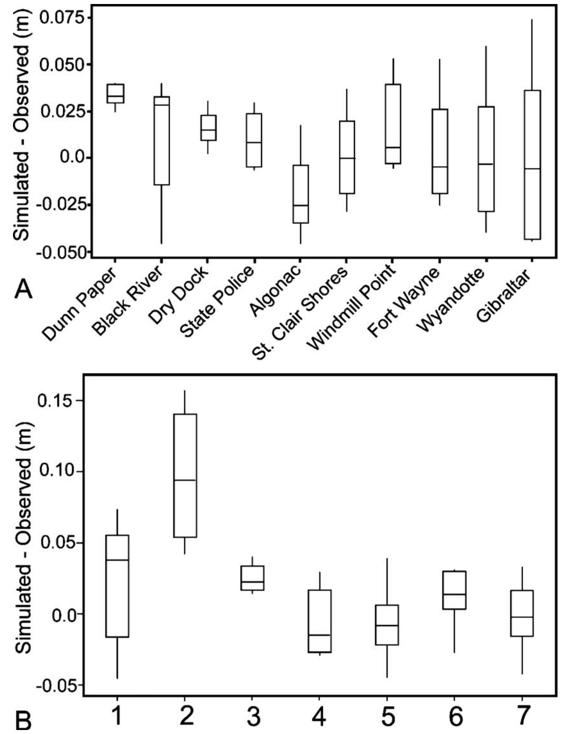

Fig. 4. Difference between simulated and observed water levels for: (a) each gauge; (b) each steady-state scenario

between 5 and 12%, depending on the conditions and reach. The largest RMSD occurs at the mouth of the Detroit River near the Gibraltar gauge, where it reaches over 6 cm. An increased value here is most likely due to the high-frequency fluctuations in Lake Erie levels as well as the method of using both the Gibraltar and Fermi Power Plant gauges to derive the outlet boundary condition. However, even at this increased RMSD for water level, the effect on flow at Gibraltar is only 5–6%. Sensitivity of the system to ice conditions is apparent during the first 70 days of 2008, where water level differences between the model and observations can approach 20 cm (primarily near-uniform decreases in modeled water level with respect to observations), with the largest differences found in the St. Clair River. Although the observed water levels are not always correct during ice conditions, noted by

Table 1. Locations of Flow Transects Used in Model Calibration

Section	Transect	Latitude	Longitude
St. Clair River	St. Clair Inlet	43°0′12″N	82°25′14″W
St. Clair River Delta	North Channel	42°37′19″N	82°36′60″W
	Middle Channel	42°35′36″N	82°37′34″W
	South Channel	42°32′50″N	82°39′9″W
	St. Clair Cut	42°32′30″N	82°36′51″W
	Bassett Channel	42°32′36″N	82°35′3″W
Detroit River	N. Belle Isle	42°21′10″N	82°57′41″W
	S. Belle Isle	42°19′58″N	82°58′45″W
	W. Grass Island	42°13′24″N	83°8′25″W
	E. Fighting Channel	42°14′10″N	83°6′29″W
	W. Grosse Ile	42°11′27″N	83°8′58″W
	W. Stony Island	42°7′37″N	83°8′18″W
	Livingstone Channel	42°7′36″N	83°7′28″W
	Amherstburg Channel	42°7′46″N	83°7′4″W

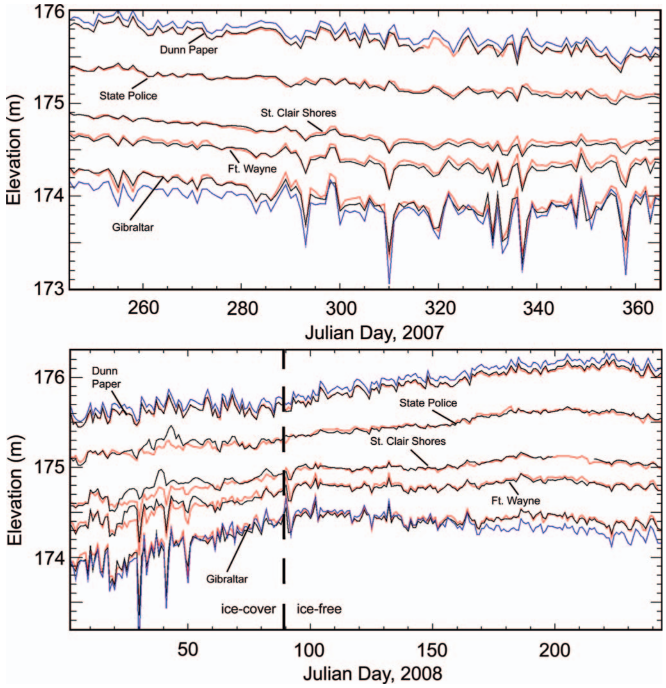

Fig. 5. (Color) Nowcast water level for select gauges along the HEC for (top) September–December 2007, and (bottom) January–August 2008. Results are shown for daily averages of water level at each gauge. Observed water levels are shown in black, modeled water levels in red, and blue lines indicate the water level boundary conditions applied at the inlet and outlet. In the 2008 plot (bottom), the dashed vertical line marks the transfer from ice-cover to ice-free months.

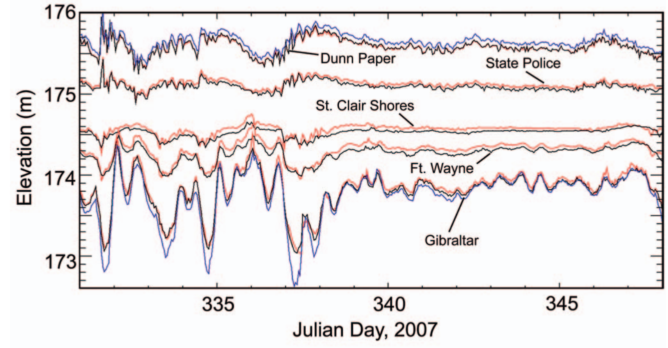

Fig. 6. (Color) Nowcast water level tracking for transient period in December 2007. Results are plotted as hourly averages for each gauge. Observed water levels are shown in black, modeled water levels in red, and blue lines indicate the water level boundary conditions applied at the inlet and outlet.

the gaps in observed data where erroneous levels were removed, the comparison with the model demonstrates the possible effect on flow in the HEC due to ice formation in the rivers. Comparing the modeled and observed levels, the decrease in flow as a result of ice in early 2008 is as great as 31%.

Results for a single month, December 2007, with particularly transient periods are also displayed (Fig. 6). Here, hourly averages of water level show sub-24 h fluctuations not shown in the daily-averages plot. In some wind events the model overpredicts the change (increase or decrease) in water level, however, all significant water level fluctuations are captured by the model. For example, the large changes in water level at the Gibraltar gauge approach a meter over a period of a few hours, in which the model remains stable and maintains prediction accuracy. Similarly, fluctuations also occur near the inlet (Dunn Paper gauge) on sub-24 h scales. However, in contrast to Gibraltar, these changes occur over a much smaller time-scale and with less variability. In this case, as found previously, the model is able to simulate the event and remain stable.

In addition to water level nowcasts, the 3D currents throughout the HEC are simulated in a real-time operational setting. In Lake St. Clair, hydraulically driven and wind-induced currents are present, where the dominating forcing mechanism is found to vary with time and space, for instance in the presence of a storm. The annual mean currents [Fig. 7(a)] show the velocity in the St. Clair River and St. Clair Delta to decrease from the order of 1 to 0.05 m/s in the center of Lake St. Clair. This drop in the current speed tends to occur within 2 or 3 km of the mouths of the St. Clair Delta channels as they enter the lake. Similarly, the currents increase again as they come within 6 km of the head of the Detroit River. It is interesting to note that once the water is carried away from the delta channels there is no discernable difference in the current speeds between the navigational channel and the other sections of the lake, at least for the annual mean currents. A similar current distribution is found for the bottom currents [Fig. 7(b)], where currents drop off quickly from the channel mouths with little difference in current speeds across the lake regions. Differences between the surface and bottom annual mean currents are apparent throughout most of the lake, however, in the eastern portion of Lake St. Clair, there is a noticeable area where the mean surface currents approach zero and appear to even drop below the mean bottom current speed. This phenomenon in the eastern portion of the lake has not been found in the past with vertically averaged lake currents and poses an interesting mean circulation pattern for the lake. Additionally, it also suggests that the eastern region of low annual mean currents may have a wind-induced dominance with only a small component of the current due to hydraulic forcing. This is in contrast to the central and western regions where annual means currents, and possibly hydraulically driven currents, are larger.

Further, the peak currents (maximum speeds during the entire period) in Lake St. Clair are found to be highest near the delta channels, with speeds up to 2 m/s [Fig. 7(c)]. However, at the convergence zone near the head of the Detroit River, the peak

Table 2. Nowcast Water Level Statistical Comparisons for the Nonice-Cover Months (September 2007–August 2008)

Station	Observed	Model	Difference	RMSD
1	175.857	175.848	0.008	0.039
2	175.805	175.795	0.010	0.041
3	175.676	175.675	0.001	0.034
4	175.379	175.388	−0.009	0.032
5	175.037	175.043	−0.006	0.037
6	174.872	174.878	−0.006	0.032
7	174.782	174.794	−0.012	0.037
8	174.630	174.656	−0.025	0.042
9	174.534	174.542	−0.008	0.036
10	174.228	174.246	−0.017	0.064

Note: Stations numbered from inlet (Dunn Paper, Mich.) to outlet (Gibraltar, Mich.), and results reported in meters.

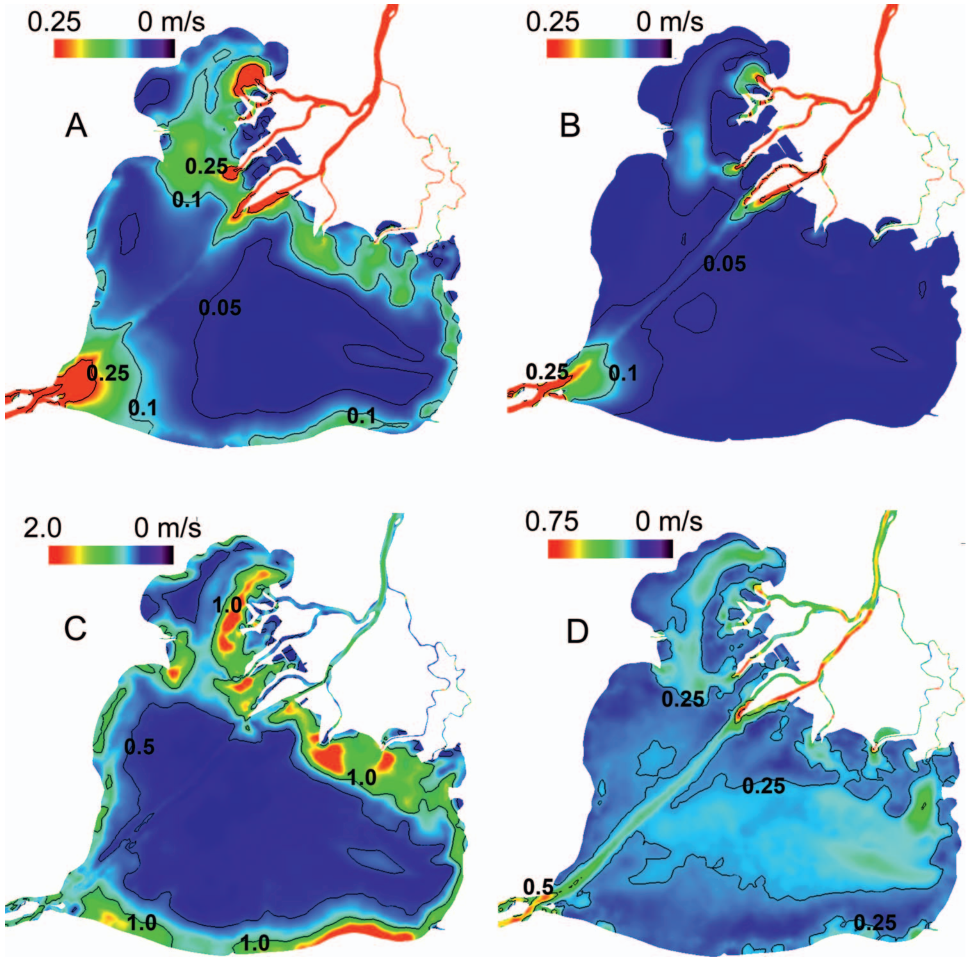

Fig. 7. (Color) Current speeds in Lake St. Clair for: (a) annual mean surface currents; (b) annual mean bottom currents; (c) peak surface currents; and (d) peak bottom currents for the simulated period. Currents greater than the scale bar limits are colored red.

currents are only about half as strong as at the channel mouths, contrasting with the similarities between the two zones in the annual mean surface currents. Again, much of the central area of the lake experiences similar peak current speeds (0.2–0.4 m/s), with the highest values found in peripheral areas. For the bottom peak current speeds [Fig. 7(d)], the majority of the lake, even peripheral areas, experiences peak current speeds between 0.1 and 0.5 m/s. However, there is an obvious difference between the peak bottom current in the navigational channel (0.3–0.5 m/s) and the surrounding lake regions (0.1–0.3 m/s). In addition, higher bottom peak currents are found near Anchor Bay in the northwestern part of the lake and in the eastern region. As these increased current speeds are not found in the annual means, it suggests that peak bottom currents in the channel and eastern zones, which may be important to resuspension and distribution of particles, occur during high-wind events. This further supports the notion that currents in the eastern region might be dominated by wind stress as opposed to hydraulically forcing from the St. Clair River. It should be noted that the frequency of high currents (i.e., the number of hours over the course of the year in which currents exceeded a specific speed), which can be a marker of zones that feel a greater effect from storm events, are not shown. However, we have found that the peak currents at the surface and bottom layers are a proxy for frequency of high currents, or in other words the areas which experience higher peak currents also experience a greater frequency of higher currents than other regions of the lake.

The hydraulic flow through the St. Clair Delta Channels, which seems to be the primary mechanism for mean annual flow in Lake St. Clair, is found to vary with time (Fig. 8). In past models, the inflows for each of the 5 channels (North, Middle, South, St. Clair Cut, and Bassett) were given as constants. Using the real-time nowcast model of the combined system, in which flows are determined as a function of water levels and wind stress, the daily averaged flow in each channel changes slightly during the period. However, the distribution of flow from the St. Clair River through the channels is not constant (mean distribution: North=31%, Middle=20%, South=18%, St. Clair Cut =28%, and Bassett=3%). The North Channel, which normally experiences the greatest flow, exchanges places as greatest flow input to the lake with the St. Clair Cutoff Channel. Furthermore, in storm periods (noted by sharp drops in the flow) the North Channel even drops below the Middle and South Channels in volumetric discharge into the lake. Although the mean discharge and distribution is similar to previous studies [North=35%, Middle=20%, South=20%, St. Clair Cut=20%, Bassett=5%; Schwab et al. (1989)], this variation in flow input to Lake St. Clair could potentially have a significant impact on the lake hy-

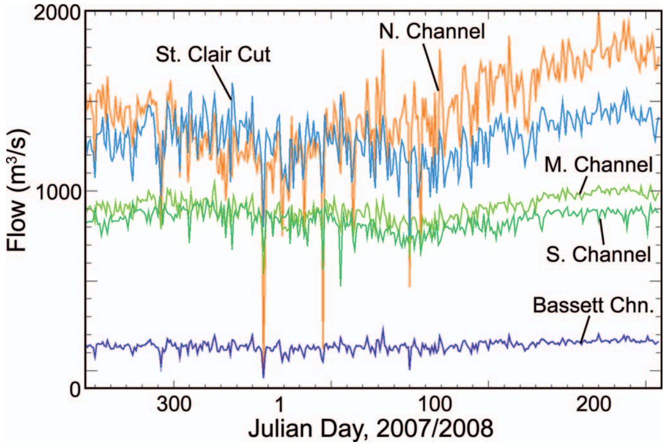

Fig. 8. (Color) Predicted daily average flow in the five major channels of the St. Clair River Delta for September 2007–August 2008

drodynamics and consequent processes in the lake. In addition, these storm events may even yield storm surges and flooding conditions in the delta that need further investigation.

For the currents, real-time observations in the system are limited to one acoustic Doppler current profiler (ADCP) located near the Blue Water Bridge in the St. Clair River (Fig. 2). Comparisons are made between the observed and computed currents for the months of May–August 2008, the only period in which the current meter was operational during the model run times. The ADCP is maintained by NOAA's Center for Operational Oceanographic Products and Services, where near-surface currents are reported for a location in the river 64 m from the western shore. For the observation period, the along-channel and cross-channel currents are compared between the current meter and model output, with a representative period shown for 10 days in August

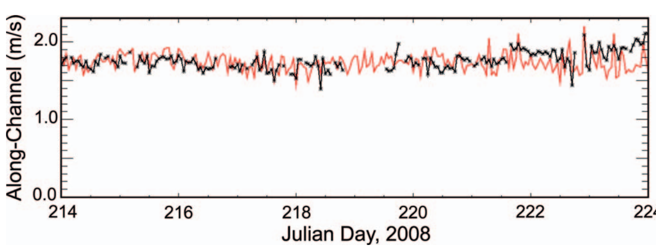

Fig. 9. (Color) Nowcast surface current (hourly averages) comparisons between model output (red) and ADCP observations (black) in the St. Clair River (43°00′45.01″N, 82°25′44.83″W) for a representative 10-day period from August 2008

2008 (Fig. 9). The model is able to successfully predict the mean velocity as well as most fluctuations in the along-channel velocity. Statistical analysis shows that the model tends to underpredict along-channel currents for the entire period, though the mean difference is less than 10% (Table 3). Fourier norms are used to analyze model performance, where the Fourier norm of a time series for observed currents v_o and computed currents v_c is defined as (Beletsky and Schwab 2001)

$$\|v_o, v_c\| = \left(\frac{1}{n} \sum_{t=1}^{n} |v_o - v_c|^2 \right)^{1/2} \tag{4}$$

$$F_n = \frac{\|v_o, v_c\|}{\|v_o, 0\|} \tag{5}$$

As in the work of Beletsky and Schwab (2001), normalized Fourier norms [Eq. (5)] are employed, where F_n represents the uncertainty in the computed currents relative to the variance in the observed currents. If model predictions match the observed currents, then $F_n = 0$, where as values between 0 and 1 indicate improvement over the no-prediction case (greater than 1 indicates no improvement). In the along-channel currents, the model performs well with a mean $F_n = 0.116$, which can be equated to 11.6% uncertainty in along-channel predictions, or computed velocities are able to explain up to 88% of the variance of the observed currents. However, river current predictions are likely to be more successful than those in the open lakes simply because there is much less uncertainty in boundary conditions provided by hydraulic water level data in river models compared to boundary conditions provided by overlake wind conditions in lake models. For example, Beletsky and Schwab (2001) found computed currents in Lake Michigan yielded $0.75 < F_n < 1.01$. Similarly, in cross-channel current predictions the model performs successfully, although the uncertainty is increased in cross-channel predictions. Computed velocities tend to overpredict currents in this case, where flow is directed toward the western shore. The absolute difference in means between the observed and computed currents is smaller in this case, but the mean difference is close to 30% as opposed to the 10% the along-channel comparisons. Consequently, for the cross-channel current predictions $F_n = 0.365$ (3 times the along-channel uncertainty). Yet, even with an increased uncertainty, the cross-channel magnitudes are less than 10% of the along-channel velocities, and hence make only a small contribution to the overall channel flow.

Table 3. Nowcast Current Statistical Comparison between Model Velocities and Measured ADCP Velocities near the Blue Water Bridge in the St. Clair River, for the Period May–August 2008

	Along-channel current			Cross-channel current				
Period	Mean (observed)	Mean (model)	Difference in means	Mean (observed)	Mean (model)	Difference in means	F_n (along)	F_n (cross)
May	1.532	1.494	0.038	−0.112	−0.164	0.052	0.105	0.498
June	1.707	1.540	0.167	−0.141	−0.170	0.029	0.130	0.273
July	1.712	1.626	0.087	−0.140	−0.181	0.041	0.096	0.349
August	1.795	1.629	0.166	−0.136	−0.181	0.045	0.123	0.374
Total	1.695	1.575	0.121	−0.133	−0.174	0.041	0.116	0.365

Note: Velocities are reported in along- and cross-channel magnitudes in units of meters per second, where positive values are downstream and toward the western shore for the along- and cross-channel currents, respectively. Normalized Fourier norms represent the relative percentage of uncertainty in the computed currents.

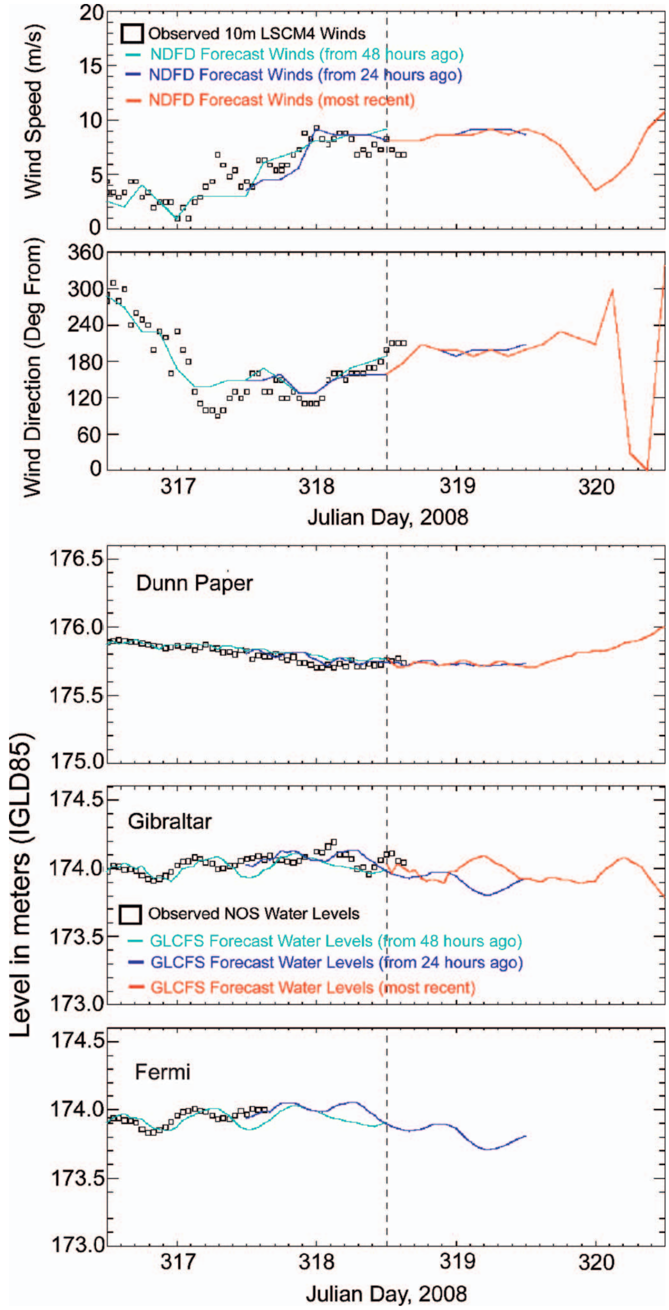

Fig. 10. (Color) Forecasted (top) NDFD wind for Lake St. Clair, and (bottom) GLCFS water levels for Lake Huron (Dunn Paper) and Lake Erie (Gibraltar and Fermi). Plots show previous and the most recent 48 h forecast.

Forecast

Similar to the nowcast simulations, forecasts in the HEC are completely dependent on the accuracy of the applied boundary conditions. As such, if the supplied forecasted winds, water levels, and tributary flows are an accurate representation of the conditions in the next 48 h, then model forecasts are as successful as the nowcasts, and results are identical to those reported above. In order to evaluate the performance of the forecast simulations, one only needs to investigate how well forecasted boundary conditions compare with those actually observed.

For both water level and wind, the observed and forecasted values are compared in real-time (Fig. 10). Overall, the reliability of the forecasted wind speed and direction decreases with increasing time from the current conditions. However, for a 48 h forecast period, the predicted winds are able to follow trends in speed and direction. Real-time plots of the previous forecasted winds and the actual observations from the previous 48 h, become a dynamic validation of the forecast accuracy. For example, if the winds were underestimated in the previous 48 h forecast, one may assume that the future 48 h forecast would also follow this trend. Similarly, water level forecasts show a decreasing reliability with increasing time from current conditions, however, in general water levels tend to be more accurate than the wind forecasts in any given time period. Again, comparisons from the previous 48 h are used to estimate the reliability of the future forecasted water levels, and hence the accuracy of the forecast model simulations.

As tributary flows are held constant for the forecasted period, error is inherently introduced if the flows deviate from the latest nowcast, for example in the event of a storm. However, as a new forecast is provided every 12 h, the error due to tributary flows is only introduced during the first forecast simulation that overlaps with the storm event. In subsequent forecasts, when the tributary flow is updated to represent storm flow, the model essentially "catches up" as each forecast is based on the latest nowcast, which always receives the latest tributary flow conditions. Overall, the net effect of the tributary inflows is much less than the primary flow of the system and the effect of wind forcing, and thus errors in the forecast simulations introduced through constant tributary inflows are considered negligible outside of the extreme storm events.

Summary and Conclusions

In order to provide operational nowcast and forecast simulations for water levels and flows in Lake St. Clair, the St. Clair River, and the Detroit River, a 3D combined-system model of the HEC has been created. The unstructured grid model of the HEC allows the rivers, tributaries, and open lake to be represented with high resolution for the first time as a combined system. Simulations for the period September 2007–August 2008 show the mean difference between observed and simulated water level to be under 3 cm, and the RMSD is less than 4 cm, which corresponds to possible differences in flow between 5 and 12%.

In addition to water levels, 3D currents are also simulated for the corridor. Current comparisons made in the St. Clair River show the average uncertainty in simulated currents is 11% in the along-channel velocity and 37% in the cross-channel velocity. In Lake St. Clair, the annual mean current in the shipping channel tends to be similar to shallower parts of the lake for both the surface and bottom layers. However, peak bottom currents experienced along the channel can possibly be more than 3 times the speed of the surrounding area. Furthermore, the currents in Lake St. Clair show that there may be significant differences between sections of the lake in regard to whether currents are hydraulically driven or wind-induced. There are noticeable differences in the annual mean currents between the western and eastern regions of the lake, where the eastern portion has a near zero velocity for both the surface and bottom layers. In contrast, the peak currents experienced in the eastern region are of similar magnitude to the western region, suggesting that during wind events as in the case of a storm, the currents in eastern Lake St. Clair can be as great as the their hydraulically driven counterparts in the west, making the eastern section into much more of an episodic, if not a dynamic, zone.

An important aspect of this combined hydrodynamic system, is the interface between the rivers and the lake, where the flow through the delta channels and into the Detroit River are driven by a more natural method, that is, the elevation drop from Lake Huron to Lake Erie, in addition to the wind stress. In this pursuit, results show that long-term changes in flow rate through the delta channels are relatively small (up to 30%); however, there tends to be frequent episodes where very quick and drastic changes (50 to 80%) in the channel flows occur, though not always uniformly. Therefore, the use of static flow rates and distribution in the channels is not appropriate, particularly during storm events, where channel flow and redistribution may significantly alter the hydrodynamics in the lake.

One of the main limitations of the model is the assumption of uniform bottom roughness zones between the water level gauge locations. Although we were able to successfully calibrate the model against observed water levels by adjusting the z_0 values in these zones, we do not have sufficient information to further describe the spatial variability of z_0 within a zone. The bottom roughness depends not only on the physical characteristics of the bottom but also on any seasonal vegetation. So there may be changes in bottom roughness within a zone, or changes in time that are not included in our model. This could affect the details of current patterns within a region, but should not have a significant effect on the overall results. Another limitation of the model is the assumption of a spatially uniform wind condition. However, wind has a much lower effect in the rivers than in Lake St. Clair and thus, the error introduced through supplying Lake St. Clair winds in the St. Clair and Detroit Rivers is small.

Although ice is not included in the model, and thus no attempt is made to support the model results during the ice-cover months (January–March 2008), comparison of the modeled and observed water levels can still provide insight into the system. During ice conditions, the observed water levels are considerably different than the model-predicted nonice equivalents. These differences can point to the reduction in flow through the HEC due to ice formation in the rivers, where comparisons with modeled nonice levels show flow can be reduced by up to 31% of its nonice magnitude. This significance of the ice-cover on the hydraulics beckons further investigation into ice formation in the HEC, and highlights the need for an ice model in the winter months in order to maintain accuracy of the model predictions.

Overall, the Huron-Erie connecting waterways forecasting system provides an essential missing link in the operational models of the Great Lakes. Nowcasts are provided every 3 and 48 h forecasts every 12 h. It also presents the first application of FVCOM to the Great Lakes in an operational setting, and additionally as part of an open river flow system. These results show the validity of the HEC operational system as well as the capability of FVCOM in river models and the Great Lakes, and provide the basis for future coupled physical-ecological-chemical models and a means for contaminant tracking, beach closure forecasting, spill response, and search and rescue efforts in the HEC.

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