PAPER

Contaminant Transport and Spill Reference Tables for the St. Clair River

AUTHORS

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ABSTRACT

The goal of this work is to calibrate a real-time hydrodynamic model for spill tracking in the St. Clair River and to provide decision makers with information for response planning and in the event of a spill. In order to provide experimental validation data, three dye releases were carried out to simulate movement of a potential contaminant in the river. Measurements of dye concentration were used to provide estimates of lateral and vertical mixing as well as travel time of the dye cloud. Model simulations were able to recreate the dye movement and concentrations with model-estimated arrival times within 14 min of the observed plume arrival times and concentrations within 0.005 normalized concentration units of the observed concentrations (which ranged from 0.06 to 0.004).

Following model calibration, a set of spill scenarios was chosen to encompass the types and locations of spills commonly experienced in the St. Clair River. These spill scenarios were then simulated with the HECWFS model to predict transport characteristics such as plume leading edge travel time, duration, concentration, and cross-channel mixing. Results from the scenarios were compiled into reference tables in which spill characteristics are listed at several downstream transects. These spill reference tables provide water intake operators with information before the event of a spill, enabling decision makers to plan for potential or common spills as well as providing a quick reference library that can be accessed immediately after a spill is detected to aid in mitigating the effects on drinking water supply.

Keywords: dye experiments, Huron-Erie Corridor, Great Lakes, toxic spill, dye experiments

Introduction

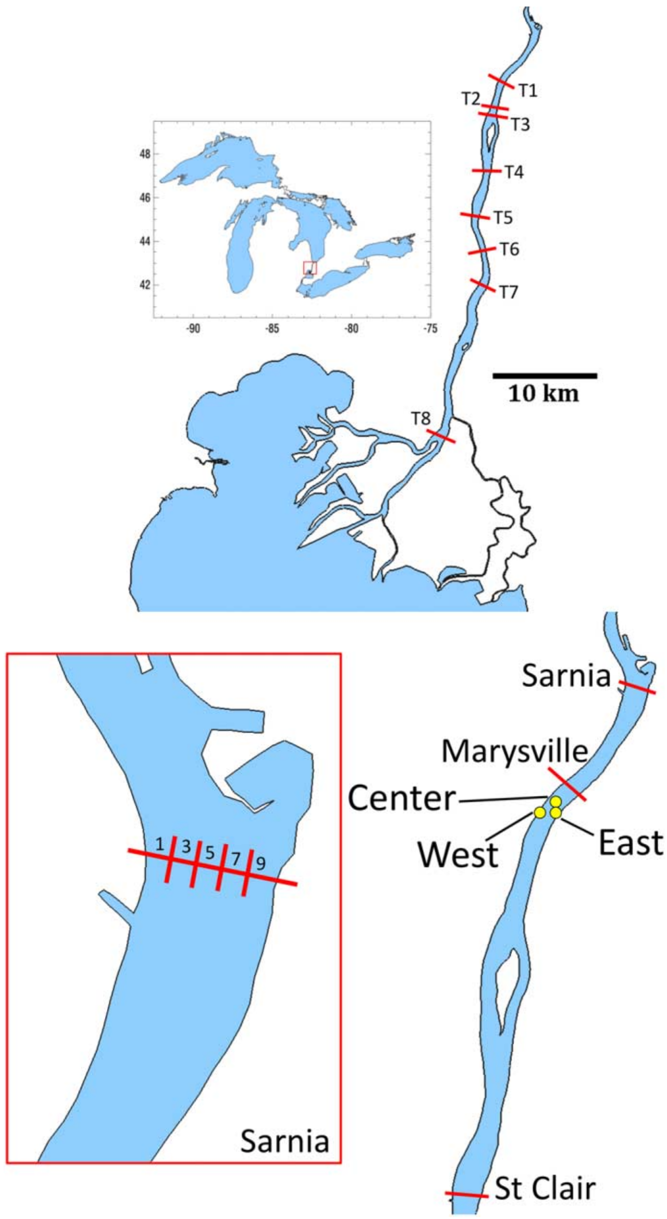
The St. Clair River plays an integral role as a major shipping channel, a source of drinking water, and a popular recreation area in the Great Lakes. It also serves as the only navigable connection from the lower lakes to Lakes Huron, Michigan, and Superior (Figure 1). It forms the upstream reach of the Huron-Erie Corridor, which is an international border between the United States and Canada and is the connecting waterway between Lakes Huron and Erie. The Huron-Erie Corridor includes the St. Clair River, Lake St. Clair, and Detroit River. In addition to being an important waterway for the shipping industry, granting passage to more than $80 billion in cargo each year, the Huron-Erie Corridor provides drinking water to over 3 million people via 20 public water intakes, nine within the St. Clair River (International Joint Commission, 2006).

By hydraulic standards, the river is considered large (width/depth > 50; Parsons et al., 2007), measuring nearly 65 km long (40 miles), with widths between 500 and 1,000 m and depths up to 10 m. The mean discharge is 5,200 m^3/s, which is driven primarily by differences between the water levels at the southern end of Lake Huron and the northern end of Lake St. Clair. Strong winter storms with sustained southerly winds have been shown to dramatically reduce flow during the wind event (Anderson et al., 2010). Currents in the river can reach up to 2 m/s during certain events, though average surface currents near 1 m/s are common. Given the mean flow in the river and the topography, travel times from Lake Huron to Lake St. Clair have been estimated to be around 21 h (Derecki, 1983), though nearshore travel times have been shown to be much greater (Sun et al., 2012). Due to the strong currents in the river, the transport of contaminants resulting from a spill can be rapid, moving between water intakes within minutes. This travel time, in conjunction with the time taken to report a spill, can be detrimental to water intake plant operation and public health within the corridor.

Although the number of contaminant spills in the Great Lakes has declined within the last 20 years, the St. Clair River continues to be an

FIGURE 1

The St. Clair River (top right) connects Lake Huron and Lake St. Clair, as part of the Huron-Erie Corridor of the Great Lakes (top left inset). Sampling transects are shown in red along the St. Clair River. Locations of the three dye releases are shown by yellow circles: center, east, and west (bottom right). Spill scenario locations used in the reference library are shown by red transects (on the bottom right): Sarnia, Marysville, and St. Clair. (bottom left) Zoomed-in view of the Sarnia spill scenario release locations, showing the five release locations per transect. The numbers refer to the normalized distance across the river from the U.S. shore (1 = 10%, 3 = 30%, etc.) (Color versions of figures available online at: http://www.ingentaconnect.com/content/mts/mtsj/2012/00000046/00000005.)



area with one of the highest number of reported spills (International Joint Commission, 2006). Industrial sources along the river include oil refineries, power plants, and chemical plants, primarily located near Sarnia, Ontario. These industrial plants have been the largest contributor to spills in the St. Clair River and are located just upstream of several public water intakes that supply drinking water to surrounding communities in the United States, although spills have originated from both countries throughout the corridor. Between 1990 and 2004, the number of reported spills decreased from roughly 150 to 70 incidents per year in the Huron-Erie Corridor (International Joint Commission, 2006). Data from a subset of reported spills from 2002 to 2005 estimate that for 11 known spills in the St. Clair River, more than 50,000 gallons of contaminants were released in the river, primarily made up of oil and hydrocarbons.

In the event of a spill, water quality monitoring and hydrodynamic modeling are used to estimate the movement and impact of the spill as well as to enable decision makers to respond appropriately. However, often spills go unreported until detected by a monitoring station downstream, leaving much of the river and lake community unprotected in the first minutes or hours after a spill. Furthermore, monitoring capabilities along the St. Clair River are limited to a volunteer network made up of the water intake monitoring stations and a lone real-time monitoring system operated by the Sarnia-Lambton Environmental Association. In all cases, only a limited number of chemicals and other water quality parameters are monitored, and thus this network cannot detect all spills. Even when a spill is identified, there is often a communication lag or only a limited set of details is shared with other interested parties, and that can delay proper response. As a result of unreported spills, travel times in the river, and the lack of a robust monitoring system, spill response in the St. Clair River may not be as quick and extensive as required to fully inform water intake operators and decision makers in downstream communities.

Several studies of the St. Clair River and Lake St. Clair have focused on the hydraulics and hydrodynamics in the system, including determination of travel times and source waters for public intakes (Derecki, 1983; Tsanis et al., 1996; Holtschlag & Koschik, 2002, 2005; Anderson et al., 2010; Anderson & Schwab, 2011; Anderson & Phanikumar, 2011; Sun et al., 2012; Shen et al., 2010; Holtschlag et al., 2008). A variety of models have been developed to understand different dynamics and scales in the river using one-, two-, and three-dimensional approaches. A combined system model that included the entire Huron-Erie Corridor (Holtschlag & Koschik, 2002) was the first to couple lake dynamics with river conditions and provide a comprehensive model of the system. This work led to development of an operational real-time hydrodynamic model of the combined system known as the Huron-Erie Connecting Waterways Forecasting System (HECWFS; Anderson et al., 2010). The HECWFS model is run every 3 h at the National Oceanic and Atmospheric Administration's (NOAA) Great Lakes Environmental Research Laboratory and predicts three-dimensional currents and water levels for the entire corridor. Since its implementation in 2008, HECWFS output has been used to aid in investigations of river mixing, ballast water discharge, transient storage zones, and contaminant distribution (Sun et al., 2012; Anderson & Phanikumar, 2011; Szalinska et al., 2011). In the event of a spill, the model is set up to provide currents to NOAA for contaminant forecasting; however, the model itself has not been calibrated for spill modeling nor has it been integrated into the real-time monitoring network operated on the St. Clair River. Hence, the goal of this work is to calibrate the real-time hydrodynamic model for spill tracking and to provide decision makers such as water intake operators with information that can be used for response planning and in the event of a spill.

In order to extend modeling capability to serve in spill tracking, dye releases were carried out in the St. Clair River to simulate movement of a potential contaminant in the river. Rhodamine dye was released from three locations to represent a spill near the U.S. shore, in the center of the river, and near the Canadian shore. Measurements of concentration at several downstream transects illustrated the diffusion and dilution of the dye as it traveled downstream (Table 1). These measurements were used to provide estimates of lateral and vertical mixing as well as travel time of the dye cloud.

Following model calibration, a set of spill scenarios were chosen that encompass the types and locations of spills commonly experienced in the St. Clair River. These spill scenarios were then simulated with the HECWFS model to predict transport characteristics such as plume leading edge travel time, duration, concentration, and cross-channel mixing. Results from the scenarios were compiled into reference tables, organized by spill

TABLE 1

Example spill reference table (spill reference library) for the Marysville spill location. Plume characteristics are shown for a surface release 30% ("3") across the river (from the U.S. shore). Peak concentrations are normalized with initial concentration (C/C_o). West edge, peak location, and east edge are shown in normalized coordinates (distance from western shore-U.S. shore).

Marysville	"3"	Surface	Floating							
Transect	Leading Edge (hr)	Distance (km)	Avg. Depth (m)	Peak Conc.	Time Peak Conc. (min)	Trailing Edge (min)	Trailing Edge 90% (min)	West Edge	Peak Location	East Edge
1	0.7	2.6	8.76	0.1622	4	20	12	0.13	0.15	0.49
2	1.25	4.48	9.12	0.1109	11	32	21	0.12	0.21	0.53
3	1.4	5.01	6.85	0.0885	15	39	25	0.16	0.21	0.49
4	2.78	9.48	7.82	0.0401	27	78	50	0.07	0.16	0.46
5	4.3	14.17	8.07	0.0268	43	139	79	0.05	0.14	0.54
6	5.28	17.35	8.66	0.0212	49	158	91	0.05	0.23	0.71
7	6.43	21.02	7.88	0.0198	63	192	109	0.09	0.28	0.76
8	11.67	36.47	7.86	0.0076	197	479	245	0.02	0.13	0.96

location/type, in which spill characteristics are listed at several downstream transects. These spill reference tables provide water intake operators with information before the event of a spill, enabling decision makers to plan for potential or common spills as well as providing a quick reference library that can be accessed immediately after a spill is detected.

Through dye experiments and development of a spill reference library, HECWFS is able to play a vital role in spill prediction and response in the St. Clair River and strengthen the real-time monitoring and modeling network in the corridor. As a result, this work enables two additional steps in protecting Great Lakes waters against contaminant spills: (1) decision makers have generalized information for several different spill scenarios, which they can use for planning purposes before a spill event, and (2) an intermediary step between spill detection and spill modeling, in which water intake operators can quickly determine when they will be impacted by a spill, the duration of its impact, and the magnitude to which they will be impacted. This intermediary step is crucial due to the current speed and the consequent travel times in the river, which can be on the order of minutes between intakes. In this case, rapid response is critical and spill reference tables can provide the necessary information to act before the spill reaches the area of interest.

Methods

Dye Experiments

In order to understand contaminant transport in the river and to validate spill predictions in the hydrodynamic model, three dye releases were carried out in the St. Clair River on August 18, 19, and 20, 2009, respectively (Figure 1). The dye release locations were chosen to represent surface spills near the channel center, Canadian shore, and U.S. shore and were chosen due to the density of petrochemical plants in the area (near Sarnia, Ontario), presence of historical spills in the area, the distance from Lake St. Clair, and the presence of several downstream public water intakes that would potentially be affected in the event of an actual spill. In each case, 33.5 liters of a 21% solution of Rhodamine WT dye was poured onto the surface of the river, in essence representing a near-instantaneous surface spill.

Three boats were deployed to measure and track the plumes as they traveled downstream at eight downstream sampling transects (Figure 1, Table 1). Each boat was instrumented with two flow-through fluorometers (Turner 10-AU field fluorometer and Turner SCUFA fluorometer, in series) and a submersible pump placed 0.5 m below the surface. As the plume traveled downstream, the boats drove along the transect pumping surface water through the fluorometers to obtain samples every 5 s. During this process, the boats were able to make several passes across the dye plume to provide a measure of plume shape and concentration. Other parameters such as time, GPS position, temperature, and absorbance data were collected for each sample as well.

In addition to the horizontal transects, vertical profiles of fluorescence were collected for the three upstream transects. For these measurements, the boat was allowed to drift with the current and the dye plume as it moved downstream. In each case, the pump was lowered through the water column, taking samples at roughly every 0.5–1.0 m.

Throughout the sampling period, calibration solutions were acquired and stored in a closed box. These solutions were collected daily with each fluorometer to correlate fluorescence and dye concentration (temperature corrected) and correct for instrument drift (though no evidence was found). In addition, the effect of sunlight on dye degradation was tested by sealing two dye samples in two containers, one was sheltered from sunlight and the other was placed in the sun during the dye releases. It was found that the potential degradation was up to 12% over the period of 12 h as compared to the sealed sample; however, this is considered an upper limit, as dye within the water column of the river would not necessarily receive the same amount of sunlight. As a result, dye was sampled below the surface as an attempt to minimize these effects.

Data Processing

Fluorescence samples from each dye release were corrected for temperature to obtain measures of dye concentration as a function of time and location (lateral distance) for several passes along each transect. A reference velocity from each transect, determined as the mean downstream current at each cross-section, was used to transform the measurement time into a longitudinal distance, thus yielding a spatial representation of the dye plume. For each sample, the difference between that sample's measurement time and the measurement time associated with the plume leading edge sample was multiplied by the reference velocity to achieve a longitudinal or along-channel distance. The resulting data set, containing concentration as a function of location only, was interpolated to a rectangular grid to provide an approximation of the full shape and concentration of the plume (another example of this approach is explained in Anderson & Phanikumar, 2011). Through this approach, plume characteristics such as peak concentration, lateral spread and overall plume shape, leading edge time, trailing edge time, and peak concentration location can be determined (Figure 2). In addition, break-through curves (BTC) are computed for each transect (concentration vs. time) using cross-sectional averages of concentration as the plume moves downstream. BTCs are beneficial for model comparison and calibration as well as for providing generalized plume information for the spill reference tables discussed later.

Hydrodynamic Model (HECWFS)

The HECWFS is a real-time forecasting model of the St. Clair River, the Lake St. Clair, and the Detroit River that produces nowcasts and forecasts of currents and water levels throughout the corridor every 3 h (Anderson et al., 2010). The HECWFS model is housed and operated within the NOAA's Great Lakes Environmental Research Laboratory (NOAA/GLERL) through collaboration with the Great Lakes Observing System (GLOS), which is the regional node of the Integrated Ocean Observing System (IOOS) for the Great Lakes (Read et al., 2010). The model has been in real-time operation since 2008 with continued improvements to grid resolution and nearshore predictions (horizontal resolution: 30–300 m; vertical resolution: 7 sigma layers, uniformly distributed within the water column).

HECWFS uses the Finite Volume Coastal Ocean Model (FVCOM; Chen et al., 2006) a three-dimensional, primitive equation, sigma-coordinate oceanographic model that solves the continuity (Eq. 1), momentum (Eq. 2), and energy equations (not reported in this study) on an unstructured grid. Turbulent closure schemes are given by the Smagorinsky formulation (Smagorinsky, 1963) and the Mellor-Yamada level 2.5 (MY-2.5; Mellor & Yamada, 1982) for the horizontal and vertical diffusion, respectively. In addition, the FVCOM Lagrangian Particle model is used to simulate contaminant movement in the system (Eq. 3) by solving a nonlinear system of ordinary differential equations using a 4th order, 4-stage Runge-Kutta method. In this mode, the horizontal and vertical diffusion is provided by Smagorinsky and a random-walk scheme, respectively.

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

$$\frac{Du}{Dt}-fv=-\frac{1}{\rho_0}\frac{\partial P}{\partial x}+\frac{\partial}{\partial z}\left(K_m\frac{\partial u}{\partial z}\right)+F_u \tag{2}$$

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

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

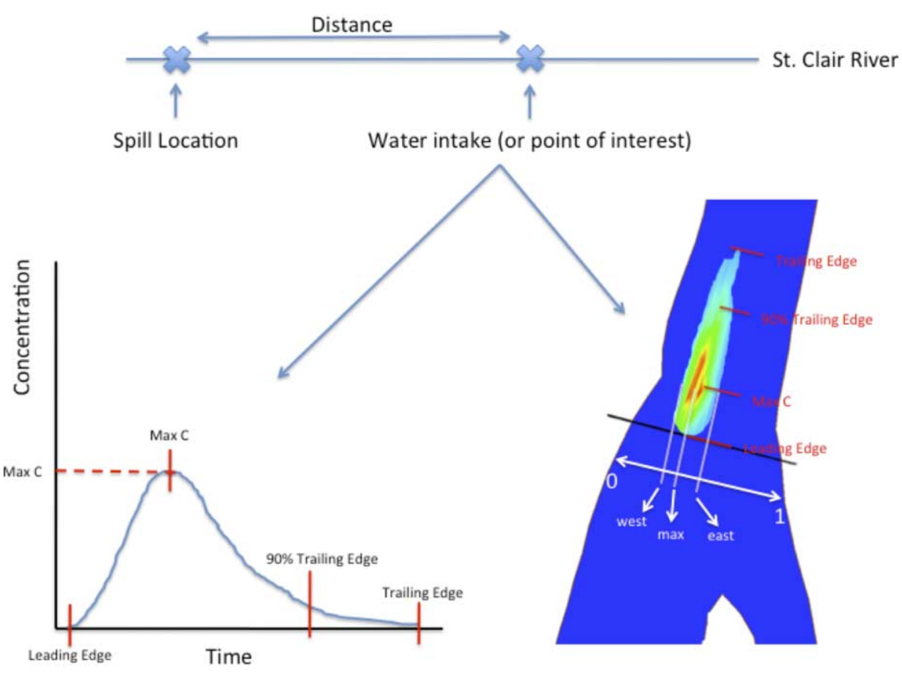
$$\frac{d\vec{x}}{dt}=\vec{v}(\vec{x}(t),t) \tag{3}$$

$$\vec{x}(t)=\vec{x}(t_n)+\int_{t_n}^{t}\vec{v}(\vec{x}(t),\tau)d\tau$$

In Eqs. 1–3, x, y, and z are the Cartesian coordinates, u, v, and w are the velocity components, ρ is density, P is pressure, f is the Coriolis parameter, g is the gravitational acceleration, K_m is

FIGURE 2

Plume characteristics used in analysis of the dye releases and in the spill reference library. For a given spill location/type, users can determine the leading edge time, trailing edge time, peak concentration, peak timing, and lateral spread of the plume. The information is derived from BTCs of dye concentration (C vs. t) for several downstream transects.



the vertical eddy viscosity, F_u and F_v are the horizontal diffusion terms, and t is time.

Forcing conditions are provided by water levels at open boundaries at the inlet and outlet, wind stress distributed across the model surface, and tributary inflows along the system. Water levels at the inlet (head of St. Clair River, near Lake Huron) and outlet (mouth of Detroit River, near Lake Erie) are specified from 6-min observations at National Ocean Service (NOS) operational water level gauges at Dunn Paper, MI, and Gibraltar, MI, respectively. Hourly wind conditions are taken from a meteorological station at the St. Clair Lighthouse in Lake St. Clair (CMAN LSCM4) and applied uniformly over the model grid. Daily tributary flows acquired from the NOAA/GLERL Large Basin Runoff Model (LBRM), a real-time lumped-parameter hydrologic model, are applied to seven tributaries along the entire system (Black, Pine, Belle, Sydenham, Thames, Clinton, and Rouge Rivers). The combined flow of the tributaries that feed into the St. Clair River (Black River: 14 m^3/s, Pine River: 3 m^3/s, and Belle River: 14 m^3/s) make up only 0.6% of its average discharge (5,200 m^3/s).

Descriptions of previous work on HECWFS development and calibration can be found in Anderson et al. (2010) and Anderson and Schwab (2011). The model has been calibrated to 10 water level gauges and 12 current meters in the system. Root mean square differences (RMSD) in water levels have been found to be within 3 cm in the St. Clair River, where levels are only considered valid in the ice-free period. Current comparisons in the river between the model and a permanent horizontal current meter show RMSD for along-channel currents to be 11% and cross-channel currents to be 37%. Additional comparison to flow distributions around islands in the St. Clair River, into the St. Clair River delta, and inflow from Lake Huron have been carried out for seven steady state scenarios taken from Holtschlag and Koschik (2002).

Dye Release Simulations

To recreate the conditions during the dye experiments, the HECWFS model was applied for the period August 15–22, 2009 using observed water levels, winds, and tributary flows as described above. For each release, tracer particles (n = 100,000) were placed in the model in a patch at the recorded location (roughly a 5-m circle) and spread over the top 0.5 m of the water column. The particles were released at the recorded dye initiation time and allowed to move in three dimensions with the simulated currents. A particle-based concentration was determined for each patch by scaling the particle density to the initial concentration as recorded in the experiments.

Particle densities were computed and converted to concentration for each time step. Surface concentrations of the particle-plume were extracted for each transect in order to compare with the processed experimental data. BTCs and plume characteristics were computed as described above using cross-sectional weighted averages of particle concentration in each model grid cell (see Anderson & Phanikumar, 2011). Differences between the modeled and observed leading edge times, concentration, lateral and vertical mixing, and trailing edge times were used to calibrate the model diffusion based on the data at each transect.

Spill Reference Tables and Simulations

Following model calibration to the experimental dye releases, several spill scenarios were chosen in order to categorize the transport and impact of spills at specific locations. The spill scenarios were chosen through public workshops led by the GLOS, in which several community stakeholders and decision makers provided input on the locations and types of spills that are of the most concern. After several workshops, three primary spill locations were chosen near Sarnia, Marysville, and St. Clair (Figure 1). For each primary location, spill releases were divided into different cross-channel locations, representing a spill 10%, 30%, 50%, 70%, and 90% of the distance across the river (defined as 1, 3, 5, 7, and 9; distances based on measurement from the U.S. shore). Then within each subset of spill locations, two kinds of releases were initiated to represent (1) surface/neutrally buoyant and (2) bottom/sinking contaminants. Therefore, 30 total spill scenarios were chosen and simulated using the HECWFS model.

For each scenario, constant boundary conditions were used based on daily-averaged water levels from August 19, 2009, with no wind conditions, and constant tributary inflows. Using steady-state conditions, the results can be scaled to higher or lower flows in the St. Clair River, extending the ability to estimate plume characteristics for a variety of conditions. In each case, 100,000 particles were released instantaneously over a 5-m radius patch, for the surface and bottom releases. Particle densities and concentrations were computed for each time step, as well as BTC for each transect as described above. Using the simulated contaminant plume, characteristics were recorded for (1) leading edge time, (2) trailing edge time, (3) 90% trailing edge time (defined as the time taken for 90% of the concentration-based plume to pass the transect), (4) peak concentration, (5) time of peak concentration, (6) western plume edge, (7) peak concentration location, and (8) eastern plume edge at each transect (Figure 2). The simulated river flow (5,600 m^3/s) for the specified conditions is given as a scaling factor, in which the above time-based plume characteristics can be scaled by a given flow condition divided by the scaling factor in order to estimate travel times for a specific day.

Results

Dye Experiments

On August 18–20, 2009, three dye releases were carried out (1 release/day) to represent a spill in the center channel, east shore (Canadian), and west shore (United States), respectively. The average discharges in the St. Clair River on the days of these three releases were 5,053, 5,198, and 4,740 m^3/s, respectively. Using concentration sampling data from each dye release, interpolated plumes were created for each transect (Figure 3). In each case, "zig-zag" boat tracks in space and time were used to estimate the plume shape and concentration as it passed the sampling transect. Taking cross-sectional averages of concentration over the length of the plume and normalizing the data with the initial concentration (105 ppb) BTCs were derived, illustrating the slug of dye as it moved downstream (Figure 4).

Plots of averaged concentration suggest the plumes remained concentrated upstream of Stag Island, where BTCs at T1, T3, and T2 show comparable magnitudes for each release. Following the flow split around Stag Island, longitudinal diffusion becomes more apparent as the dye plume lengthens and decreases in peak concentration, following a gradual dilution pattern as it travels downstream (more in Anderson & Phanikumar, 2011). Total travel times for each release (time taken to reach T7) were 6.06, 6.0, and 6.52 h (center, east, west). An additional sampling transect was acquired for the center release (T8), illustrating an elongated and flattened BTC that took 8.1 h to travel from the spill origin. For several transects, a power–law relationship is observed in the dye BTCs; however, evidence of multimodal behavior is apparent as well, such as in T4, T5, and T6 of the east release.

Vertical mixing occurred by T2 (< 3 km downstream) for each release (Figure 5). Several samples throughout the water column were taken as the boat drifted with the plume as to ensure capture of the vertical profile near the first three transects. At the first transect (T1), peak concentrations were measured at the surface, roughly an order of magnitude greater than subsurface concentration. The surface layer was also found to contain the widest range of concentrations, suggesting anisotropy in the dye plume from very early stages. By the second and third transects (T2 and T3), concentrations in the water column had equalized, signifying strong vertical diffusion in the river. Modeled dye concentrations were averaged (at each sample depth) along the sampling pathway near each transect. The model shows a much more diffuse concentration profile near the first transect (T1) than the observed dye cloud, most likely due to assumptions in the initial conditions and coarse resolution of the vertical sigma layers. However, the model shows mixing to occur over the entire water column by the second transect, similar to the observed dye cloud. As a result, model predictions of vertical dye distribution might not be accurate for first few kilometers downstream of the release point, given the limited vertical

FIGURE 3

(left) An example transect sample data track showing the zig-zag pattern used for plume interpolation. (right) Interpolated dye plume using a reference velocity and grid interpolation approach.

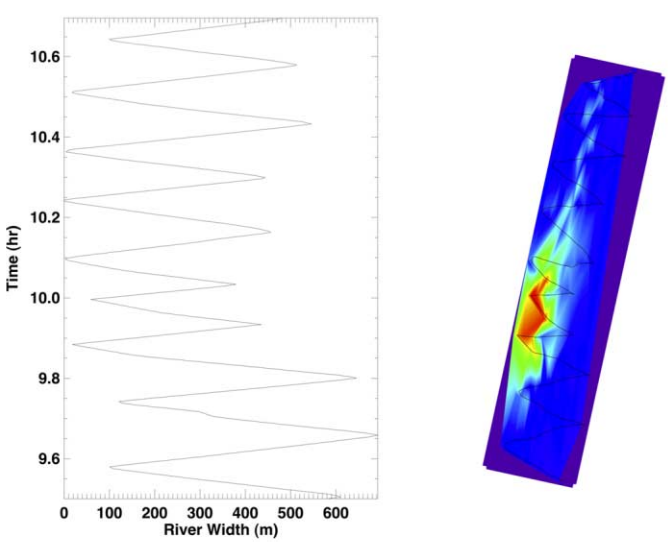
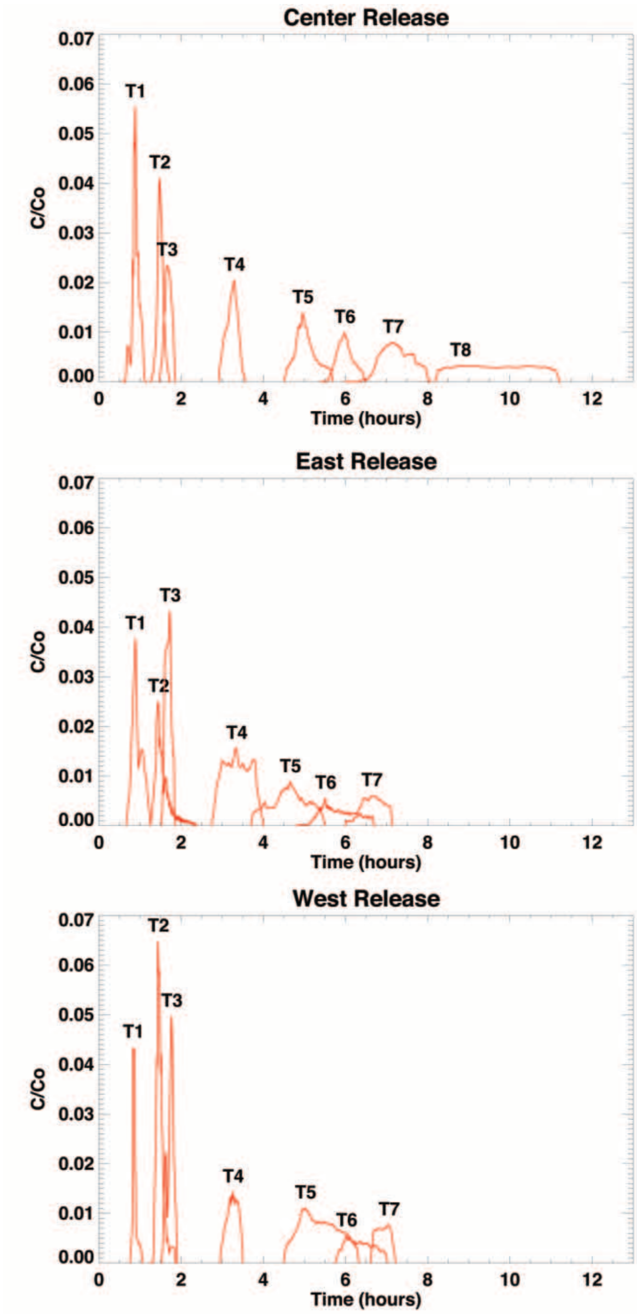


FIGURE 4

BTCs for the three dye releases, shown by transect. Normalized concentrations are plotted in reference to the initial release concentration and BTCs are shown for cross-sectional averages of dye concentration.



resolution and knowledge of the initial conditions.

Conversely, lateral or transverse mixing was constrained to only 25–30% of the river width by T3 (Figure 6). Using the interpolated dye plumes to detect the western and eastern edges of the cloud ($C/C_o < 0.005$), the lateral mixing of each release is plotted against downstream distance. West and east releases tended to follow their respective shorelines; however, both releases crossed over the center of the channel after 11 and 7 km downstream. The center channel release experienced the greatest lateral diffusion, spreading across more than 70% of the river width by the last transect. Fluctuations in the plume edge locations or lateral mixing boundaries are caused by topographical influences such as bathymetric changes or islands but might also suggest small-scale phenomena such as transient storage zones caused by eddies or other hydrodynamic processes.

Similar paths and lateral mixing are observed for the center and west releases, largely due to the initial locations of the release and the current patterns in the area. The east release experienced a large lateral diffusion near 5 km downstream of its release. The presence of Stag Island and in particular the disparity in flow distribution around the island due to channel geometry likely result in much of the dye passing on the western side of the island. Thus by T4, the east dye plume has been spread laterally by both channels.

Simulated Particle Releases

Currents and water levels were simulated for the dye release period using the HECWFS model (Figure 7). Simulated water levels tracked gauged observations within 4 cm for the center and east dye releases (Julian Day 230–231). During the west release, storm conditions in the evening increased model error over the entire corridor. However, predictions in the St. Clair River, the upper four line plots in Figure 7, remained within 8 cm during the storm. In addition, current comparisons were made between the model and a horizontal acoustic Doppler current profiler (H-ADCP) near the head of the river (NOAA National Ocean Service GL0301). The real-time H-ADCP measured surface currents (midchannel)

FIGURE 5

Measured vertical structure of the dye plume (asterisks) and the model simulation (solid line) for the first three transects. Plots show normalized concentration as a function of normalized depth (sigma).

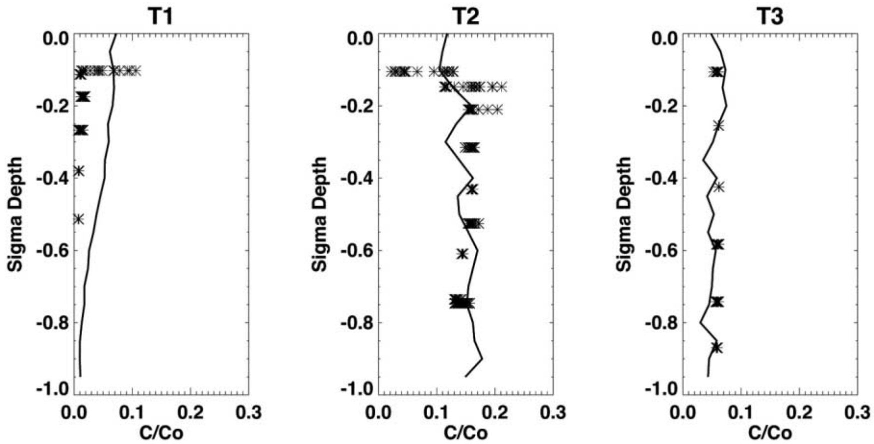
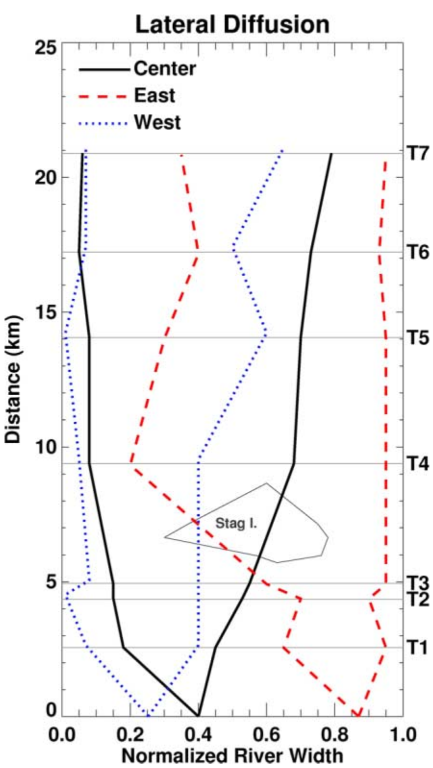


FIGURE 6

Lateral diffusion of the dye releases, shown as a function of normalized river width (from western to eastern shore). Plots are drawn from the detected plume edge. Approximate transect locations and the extent of Stag Island are marked.



between 1.5 and 2.2 m/s during the release period. Model predictions of 6-min currents are within 12% of the gauge observations. However, the ADCP failed to report during the west dye release, leaving model performance during the storm event to remain unclear.

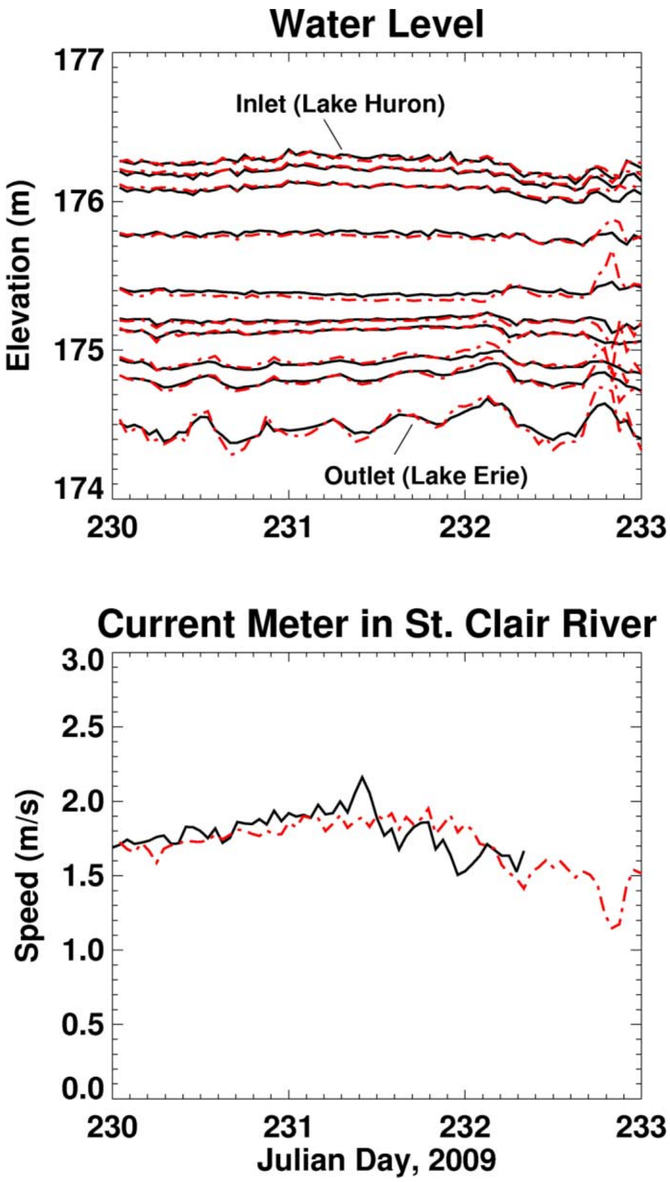
Using 6-min model output, the Lagrangian particle model was used to simulate dye transport for each release. Particle-based densities were converted to concentration for each time step and cross-sectional weighted averages were computed for each transect (Figure 8). Comparison between the model BTCs and the observed curves reveal that the predicted plume magnitude and timing are in agreement with the dye experiment, where the center release is used as a representative case, though the west and east experiments revealed similar results. Leading edge times show the model predicted plume arrives within 2–5 min of the observed plume for the first three transects (Figure 9). However, at the downstream transects, the model plume arrives before the observed dye, particularly at T8, where it reaches the transect 36 min before the observed dye. The RMSD for the leading times is within 13.5 min for all transects.

Trailing edge times, used as a measure of spill duration or plume length, show the modeled plumes are predicted to extend much further than the observed dye clouds (Figure 9). Calculated in hours after the plume leading edge, the model plume arrives within 4 min up to nearly 2 h after the observed plume edge, with the disparity increasing with downstream distance. RMSD between the model and observations show model plumes to last for 56 min longer than the experimental dye. However, if we assume that the field observations may not have fully sample the plume, due to instrument thresholds or oversight, we find that a 90% threshold of the model plume gives better results (RMSD = 34 min). This 90% threshold is described as the time taken for 90% of the plume (concentration-based) to pass the transect and is given for comparison.

Peak concentration times, which might be a critical parameter to water intake operators, show excellent agreement between modeled plumes and the observed dye cloud (RMSD = 0.005). However, the location of the peak concentration may be of more importance as the point of highest concentration may be confined to a small area that can travel over key points of interest such as water intakes (Figure 9). The lateral mixing in the predicted plume is comparable to the observed dye edge, where RMSD is 0.036 and 0.073 for the western and eastern edges, respectively. Values are given in percentage of river width; thus for a 600-m-wide river section, the error in the model predicted edge

FIGURE 7

HECWFS model (red dashed line) comparisons with gauge observations (black solid line) for the simulated dye release period.



would be 21.6 and 43.8 m for western and eastern edges. The location of the peak concentration within the plume is found to vary laterally as a function of downstream distance as well. In the case of the center channel, the peak concentration moves closer to the western edge of the river (U.S. shore) immediately after release. Predicted plume location for the peak concentration follows this path as well with RMSD of 0.073. Furthermore, vertical mixing in the simulated plume occurs by the second transect (T2; Figure 5). Although the vertical stratification in the plume is not as pronounced as in observed dye plume at the first downstream transect (T1), both the model and the observations suggest that the plume is completely mixed in the water column within 3 km of the release point.

Spill Reference Tables

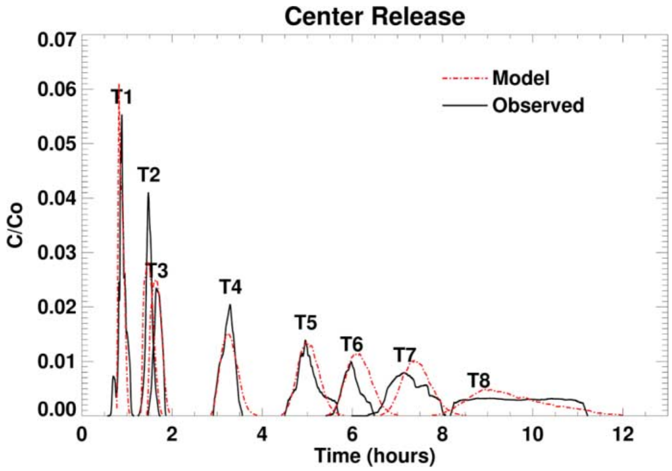
Spill scenario simulations for 30 different spill locations/types were carried out using the calibrated particle-spill model of HECWFS. Results for key plume characteristics such as leading edge time, trailing edge time, peak concentration, time of peak concentration, and plume shape have been compiled into a set of reference tables, referred to as the spill reference library (Table 1). A representative release location, Marysville, illustrates the variability in spill transport due to the location and type of spill.

Comparisons between lateral-location and type for a representative spill show leading edge times of the plume are highly dependent on release location (Figure 10). Lateral variation within the Marysville spill transect shows the plume speed can vary up to 1.4 times between the fastest and slowest surface release locations, in case spills (7) and (1). This difference can increase the arrival time of the plume at T8 up to 1.2 times, in this case 1.9 h. At the T4, which is 5 km downstream of the release, differences in arrival time can be up to 0.8 h. If bottom releases are considered, in the case of a substance that is denser than water the difference in speed can be more than half for identical lateral locations. As a result, arrival times at the last transect T8 can be 6 and 13 h later than a corresponding surface release, suggesting the lateral and vertical location of the release and the spill type can have a profound influence on the plume arrival time.

Peak concentrations are also found to be dependent on spill type (Figure 10). Surface releases show an exponential decay as a function of distance, with sharp decline over the first few kilometers downstream and then a gradual decrease over the remainder of the river.

FIGURE 8

BTC for the HECWFS model simulation and the dye observation for the center release. Shown as normalized concentration, calculated as cross-sectional averages of the dye/particle plume.



However, the majority of the bottom releases exhibit limited longitudinal mixing, causing high concentrations in the plume to extend much further downstream. In this case, releases (7) and (9) maintain concentrations greater than 0.5 for over 15 km. Even at the final transect, over 35 km downstream, four of the five bottom releases had peak concentrations between 0.1 and 0.2. Therefore, although bottom spill scenarios with density greater than water tend to move much slower than surface releases, the concentrations may in fact be significantly higher.

For predictions of plume transport and impact at areas of interest not covered in the spill scenarios, the data given in Table 1 can be interpolated spatially or as a function of river conditions. For instance, areas of interest within the prescribed transects can be interpolated simply by distance. Hence, if in the event of a spill near the Marysville, there is an interest in a water intake that lies between two transects, a simple linear interpolation between the nearest upstream and downstream transects will suffice in estimating the plume characteristics. A similar approach can be carried out for spill locations outside of the three chosen releases in the spill reference library.

$$t' \sim t\frac{Q_{ref}}{Q_{obs}} \tag{4}$$

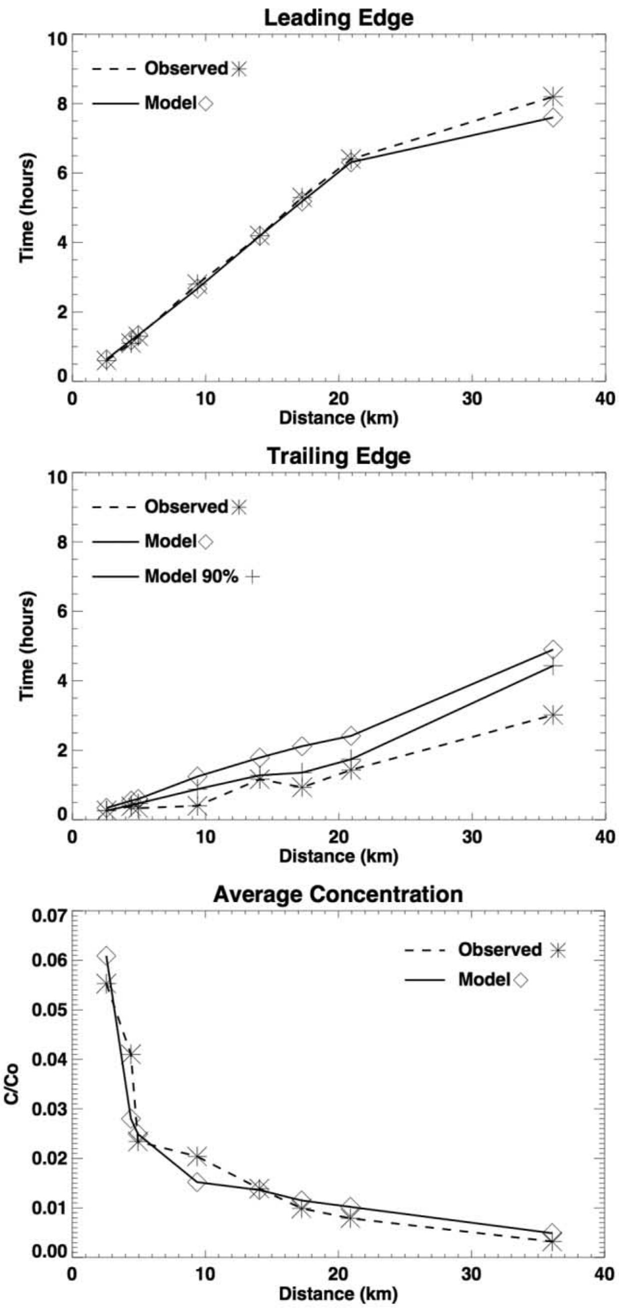
For differences in river flow conditions, a simple scaling relationship can give an approximation of travel time adjustments. Given that travel time is proportional to velocity, where the river flow depends on this velocity and the cross-sectional area of the river, if we assume that changes in water depth are small (<1 m), then the travel time can be scaled by flow changes alone (Eq. 4). Here, Q_{ref} is the reference discharge (5053 m^3/s, Q_{obs} is the observed river discharge (estimated from the HECWFS model, stage-discharge equations, or other means), t' is the scaled travel time, t is the reference table travel time. Justification for this approximation can be taken from recorded water levels along the river. For the period 2001–2010, the maximum recorded water level fluctuation in the St. Clair River was 1.009 m. Considering an average depth of 8.13 m, found at many cross-sections along the river, this yields a potential error of 12% in estimated travel time. Additional spill reference tables are available through the NOAA/GLERL (Anderson & Schwab, 2012).

Discussion

Due to the high current speed in the St. Clair River, travel times between water intakes can be on the order of minutes. In the event of a contaminant spill, in which detection or reporting may already be lagging, the impacts can be felt before action can be taken to mitigate the effects. The ability to estimate the plume arrival time, concentration, and duration is necessary in order to respond in time and protect public health. Our results show that contaminant tracking in the St. Clair River can be accomplished based on knowledge of the flow conditions and the spill location and type. To calibrate the NOAA real-time hydrodynamic model (HECWFS) for spill transport and to provide accurate spill scenario forecasting, dye experiments were carried out in the St. Clair River for 3 days in August 2009. In each release, the dye was found to mix vertically within 3 km downstream of the release point; however, transverse mixing was not found to occur until much further downstream, where specific release location may have a significant role in the amount and rate of diffusion along the river. Other studies have found for instance, that very nearshore releases (less than 50 m from the shore) can take significantly longer to travel downstream due to the velocity shear in the river, where lateral mixing may not extend beyond several meters from shore (Sun et al., 2012). Following the

FIGURE 9

Comparison of leading (top) and trailing edge (middle) arrival times for the center dye release between HECWFS model simulations and the dye observations. “Model 90%” refers to the time taken for 90% of the plume to pass the transect. Trailing edge times are plotted in hours after the leading edge arrival time. (bottom) Peak concentrations for the HECWFS prediction and the dye observation, plotted in normalized averaged concentrations as a function of transect location.



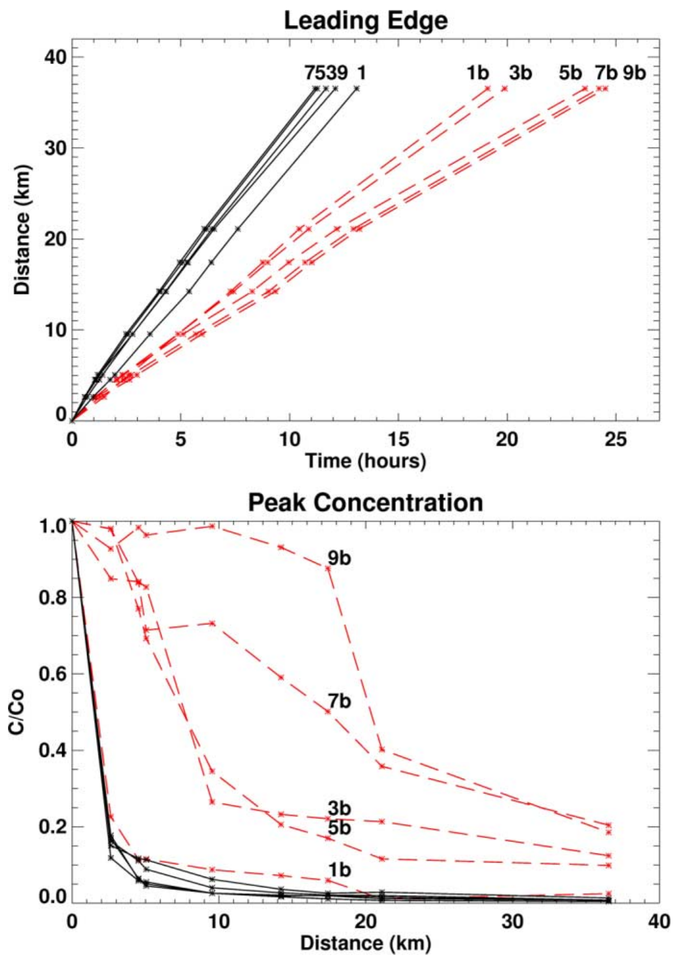
experimental observations and model calibration, simulations were able to recreate the dye movement and concentrations, with model-estimated arrival times within 14 min of the observed plume arrival times and concentrations within 0.005 normalized concentration units of the observed concentrations (which ranged from 0.06 to 0.004).

Certain limitations are inherent in using model simulations, particularly for predefined spill scenarios, as a means to forecast spill transport with limited information about spill conditions and forcing conditions. For instance, in the experimental dye releases, the sampling methods employed may not capture the entire plume or the peak concentration of the plume as it travels downstream. As such, the lateral and longitudinal mixing can only be characterized in an average sense. Hence, multimodal type transport and diffusion, such as that present in rivers with significant surface storage zones, e.g. dead zones caused by small scale recirculations, may not be accurately represented in the data. Therefore, model comparisons and calibration must be done on averaged and interpolated concentrations that are only approximations of the actual plume shape and concentration. Model resolution can also be a limiting factor since subgrid scale processes that may affect diffusion or transport cannot be accounted for, even when parameterization attempts to encompass these phenomena. In addition, environmental and hydrodynamic conditions such as wind and wave effects have not been implemented as part of the spill reference tables. Although wind plays a reduced role in the river as compared to lake transport, during strong storm events, the effect on transport and diffusion, particularly at the surface layer, may be significant.

Predetermined spill reference tables can only provide an estimate of how river conditions and spill type will affect spill transport in the river. Further information is necessary to fully understand contaminant transport in the St. Clair River, specifically during a spill event, in which type of material (oil, etc.), duration, amount, and

FIGURE 10

(top) Spill scenario (spill reference library) results for Marysville release, showing leading edge times for the surface (black solid line) and bottom (red dashed line) releases at each lateral location (marked "1" for surface 10% releases and "1b" for bottom 10% releases). (bottom) Peak concentrations for the Marysville spill scenario (spill reference library). Normalized concentrations are plotted for each lateral location, with surface (black) and bottom (red) releases marked by "1" and "1b," respectively.



location will need to be accounted for to include second-order aspects such as degradation, volatility, wind, etc., that cannot be taken into a generalized approach. However, the spill reference library plays an important role in planning response actions for a spill event.

Overall, the spill-calibrated HECWFS model and spill reference tables provide decision makers and the public with real-time information on river conditions, including currents, water levels, and spill movement. The spill reference library, available through NOAA/GLERL and GLOS, helps fulfill two important steps in spill response and drinking water protection: (1) decision makers are able to obtain generalized and easy to use information on a variety of spill scenarios, which can be used for planning purposes before a spill occurs, and (2) in the event of a spill, between the time of spill detection and modeling or containment response, decision makers can use the spill tables to assess the potential impact, arrival time, duration, and magnitude of a spill for a specific location. This technology and information access allows water intake operators, government agencies, and other stakeholders to effectively protect resources and mitigate impacts due to contaminant spills in the Huron-Erie Corridor.

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