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Transport of municipal wastewater, industrial and tributary discharges in eastern Lake Ontario and upper St. Lawrence River during the ice-free period of 2006

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ABSTRACT

The surface transport of point and non-point source discharges into eastern Lake Ontario and upper St. Lawrence River was modeled as passive tracers using the Estuary and Lake Computer Model (ELCOM) during the ice-free period of 2006. Model hydrodynamics were validated against temperature and current observations and Lagrangian drifter tracks. Root-mean-square (RMS) errors of simulated temperature profiles were comparable to other model applications; however, current RMS errors and Fourier Norms were nominally larger than in open lake applications, and RMS errors for drifter tracks were 0.5–4.0 km (3 day duration). The errors in simulating currents and drifters, relative to temperatures, are likely the result of the difficulty in representing the complex geometry of the region, which is composed of numerous channels and islands. To determine the physical processes responsible for tracer transport, cross-correlation coefficients were calculated when model processes were switched off (e.g., wind forcing, surface thermodynamics, Earth rotation, St. Lawrence River outflow, etc.). Wind was found to be the most dominant process forcing transport of tracers both in the Kingston Basin and the St. Lawrence River, whereas the St. Lawrence River outflow, controlled by the Moses Saunders Dam, was found to influence the transport of tracers along the river. Tracers were transported ~60 km eastward under moderate to strong winds (>5 ms^{-1}), remained nearshore when constrained within channels or by islands and had minimum dilutions of 20% and 39% at the Kingston Central and Kingston West drinking water intakes, respectively. The results suggest that factors such as the proximity between intakes and outfalls and presence of flow constraining topography, should be considered in future source and wastewater planning.

Introduction

Freshwater lakes and rivers, such as Lake Ontario and the St. Lawrence River system, serve as sources for drinking water as well as sinks for municipal wastewater and industrial discharges. Industrial effluents, accidental spills and discharge of sewage to the environment, as combined sewer outflows (CSOs) and/or treated and untreated discharges from municipal wastewater treatment plants (WWTPs), can have negative impacts on human health and on the aquatic ecosystem including: eutrophication, bacterial contamination and toxicity from heavy metals and pharmaceuticals. Management and research studies are needed to minimize discharges, understand their transport pathways and mitigate their effects on public health (Holeton et al., 2011).

To achieve these goals, understanding the hydrodynamics and the processes that affect the transport of tracers is essential. For example, the Kingston Basin and the St. Lawrence River system (Fig. 1) have complicated hydraulic and wind-driven hydrodynamics (Tsanis et al., 1991). The flow in the Kingston Basin is affected by thermal stratification during summer months and is strongly influenced by the presence of numerous islands and complicated topography. The thermal stratification results in a two-layer exchange flow at the open boundary between Lake Ontario and Kingston Basin (Fig. 1). At the boundary, the currents in the epilimnion are riverward and are lakeward in the hypolimnion, against the prevailing winds (southwest) through three deep channels (Tsanis et al., 1991). The mean summer circulation (June–August) showed counterclockwise gyres in the Bay of Quinte region (Paturi et al., 2012; Shore, 2009), north of Amherst Island, north of Wolfe Island and the south region of the Kingston Basin (Paturi et al., 2012). Lake stratification (Shen et al., 1995; Laborde et al., 2010), basin morphology (Morillo et al., 2008) and Earth's rotation (Laborde et al., 2010) modify circulation and dispersion and hence affect pollutant dispersal.

This region provides source drinking water for eight municipal drinking water intakes (Fig. 1a) in the Cataraqui Region Conservation Authority (CRCA) jurisdiction on the Canadian side. Under the Clean Water Act (2006), the threat of contamination to intake water must

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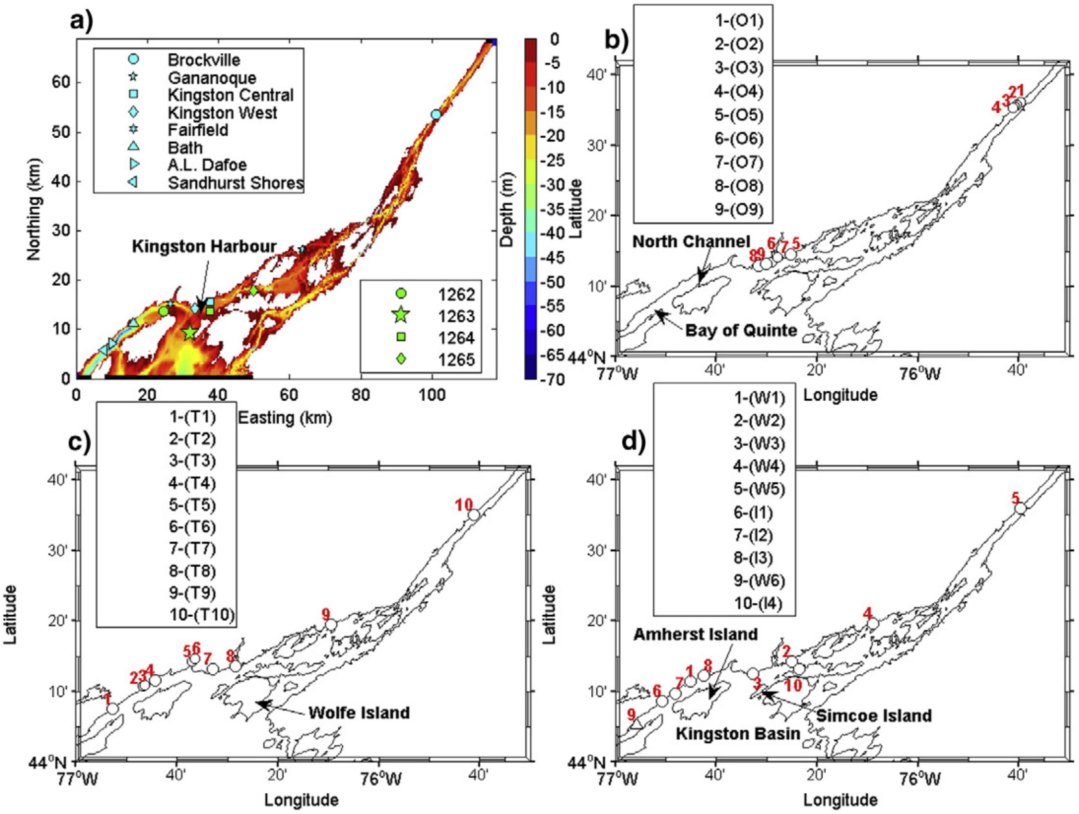

Fig. 1. (a) The bathymetric grid (300 m × 300 m horizontal resolution) along with the locations of the four field observation stations and the eight drinking water intakes (the blue solid lines are the open boundaries in the model), locations of (b) combined sewer outfalls (CSOs), (c) tributary flows and (d) municipal wastewater and industrial discharges. The details of discharges are given in Table 2.

be determined (MOE, 2009). To this end, it was mandated to delineate three Intake Protection Zones (IPZs) around each drinking water intake. The IPZ-1 is a set-area of 1 km radius around each intake. The IPZ-2 is a zone defined around each intake that encompasses a 2-hour travel time (i.e., emergency intake shutdown time) of influent water during a 10-year return period wind event (see Paturi et al., 2012). The IPZ-3 is defined as the area where the water could reasonably travel from a release point to the intake during a potential contaminant spill or discharge over seasonal timescales.

In the present study, the Estuary and Lake Computer Model (ELCOM) is applied to simulate the hydrodynamics and IPZ-3s in the Kingston Basin of eastern Lake Ontario and the upper St. Lawrence River during 2006. ELCOM has been previously applied for lake-wide simulations in Lake Ontario and comprehensively validated against measured data (Hall, 2008; Boegman and Rao, 2010; Huang et al., 2010). Surface forcing boundary condition and tributary flow data were only available in the ice-free season; hence we do not simulate during ice-cover (e.g., Oveisy et al., 2012). The results from the hydrodynamic study were used to (1) delineate the IPZ-3 from a set of threats to the drinking water intakes (29 combined sewer outfalls, tributary, municipal wastewater and industrial discharges) identified by the CRCA, (2) to understand the physical processes that transport tracers toward drinking water intakes and (3) determine whether the tracers would travel to the intakes or not during the ice-free period of 2006.

Methods

Instrument moorings

Moored temperature and current velocities were used to validate the model hydrodynamics. Water temperature data were measured at Stations 1262, 1263, 1264 and 1265 (Fig. 1a) using Onset Tidbit temperature loggers (10 min sampling frequency) moored on thermistor chains during Apr–Nov, 2006. During the same period, vertical profiles of currents were recorded using an upward looking RDI Workhorse acoustic Doppler current profiler (ADCP) with 1 m vertical bins (sampled every 30 min at 1200 kHz) at Stations 1263 (106 days) and 1264 (111 days). For a detailed description of the data, please see Paturi et al. (2012; Table 1 therein).

Drifter deployments

Satellite-reporting ARGOS/GPS drifting buoys (Clearwater Instrumentation) were used to track the surface circulation in eastern Lake Ontario and upper St. Lawrence River and validate modeled advection. The drifters have excellent water tracking capability with very low direct wind- and wave-induced horizontal motion to the drifter (Davis, 1985). The drifter consists of a 1 m long tube that houses the electronics and battery pack. Attached to the housing are four drogue/vanes directed radially outward at 90° intervals with a small surface float attached at the outward end of each vane. The drifter has a center-of-effort at approximately 0.8 m below the water surface. Only GPS data, measured every hour with 10 m accuracy, were used in the analyses because of the higher accuracy relative to ARGOS (150 m). In contrast to typical oceanic applications, all drifters were retrieved, upon entering shoal water, rather than deemed expendable. Nine drifters were deployed during two cruises in 2006 and drogued at 1 m depth. The model predicts drifter movement by determining the wind and inertia forces acting on the drifter motion (Furnans et al., 2008).

Errors in modeled drifter and velocity accumulate with time, causing a divergence in the observed and modeled trajectories (Furnans et al., 2004). To compare the movement of the drifters with the corresponding model results, the drifter tracks were used to calculate the observed drifter U (east–west component) and V (north–south component)-