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A model of the three-dimensional hydrodynamics, transport and flushing in the Bay of Quinte

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ABSTRACT

The Bay of Quinte, Ontario, receives excessive nutrient loads and suffers from poor water quality. The 70 km long z-shaped bay traps the nutrients due to limited flushing with Lake Ontario, leading to increased nutrient residence times. Therefore, it is important to understand the three-dimensional hydrodynamic conditions within the bay, as these drive horizontal transport, dilution of nutrient rich inflows and water exchange to the lake. In this study, the effects of meteorological forcing, river inflows and Lake Ontario exchange on the hydrodynamics and mixing were investigated using a numerical model. The model was validated against temperature time series and profile data, with a maximum root-mean-square deviation < 2.3 °C in comparison to observed temperature profiles. Six methods were applied to estimate flushing from the bay, with three methods (tracer release, drifter paths, bulk residence time) converging to predict the main channel of the bay flushes 5 times a year. Isolated embayments have higher water ages (4–5 months) and may trap nutrients with sufficient time and conditions for algae blooms to occur. Strong advection is modeled in the main channel, with low horizontal transport in the embayments and efficient flushing near the connection with Lake Ontario. This provides insight for watershed management, for example, to design ideal locations for nutrient discharges (e.g. wastewater plumes), to target specific rivers for nutrient load reductions, and to support future coupled hydrodynamic and biogeochemical modeling of the bay.

Introduction

The Bay of Quinte is a significant freshwater source for drinking, recreation and industry. The bay not only is narrow and sheltered, but also receives excessive pollutant and nutrient loads (Minns et al., 1986) leading to persistent toxic and bacteriological contamination, undesirable algae growth, fish toxicity, and taste and odor problems, which are exacerbated near Belleville, Hay Bay and Picton (Fig. 1). In 1986 the Bay of Quinte was classified as an Area of Concern in the Great Lakes basin by the International Joint Commission and a Remedial Action Plan (RAP) was initiated.

The studies conducted under the RAP have been mostly observational and descriptive. The Great Lakes Laboratory for Fisheries and Aquatic Science has been monitoring water temperature and oxygen since 1972 (Minns, 2011), water quality both before and after phosphorus load reductions (Robinson, 1986), and phosphorus loads from municipal sewage treatment plants (STP) between 1965–2005 (Kinstler and Morley, 2005). Recent field monitoring was focused on management of taste, odor and toxins in the framework of the Bay of Quinte Harmful Algal Blooms (BQHABs) initiative (Watson et al., 2009), which is comprised of new fieldwork and analysis of the existing Bay of Quinte dataset. The study of exchange flows between the Bay of Quinte and Lake Ontario using current meter observations has also been undertaken (Freeman and Prinsenberg, 1986).

Hydrodynamic and water quality box models have been applied to the bay. Moin and Thompson (2006) applied a one-dimensional (longitudinal) hydraulic model based on the solution of the St. Venant unsteady flow equations with reasonable success and utilized water temperature data to evaluate the health of fish species in the Bay of Quinte for a 100 year period under different water level scenarios. Minns and Johnson (1986) and Minns et al. (1986) included tributary inputs in a box-model and parameterized the exchange flow with Lake Ontario to study the budgets for phosphorous, nitrogen, and chloride during 1965–81, 1992–2001 and 2002–2031 (Minns and Moore, 2004). Similarly, Razavi (2006) divided the bay into seven segments for mass balance modeling to determine the source and fate of contaminants. They assessed the effects of four metals and thirteen hydrophobic organic chemicals (HOCs) on the food web. Recently Zhang et al. (2013) and Kim et al. (2013) assessed and improved the capability of the Minns box model (Minns and Moore, 2004) to seasonally evaluate the regional nutrient loading to the Bay of Quinte and it's suitability for assessing relevant water quality parameters. They concluded that loading from the Trent River is the most important factor in the total

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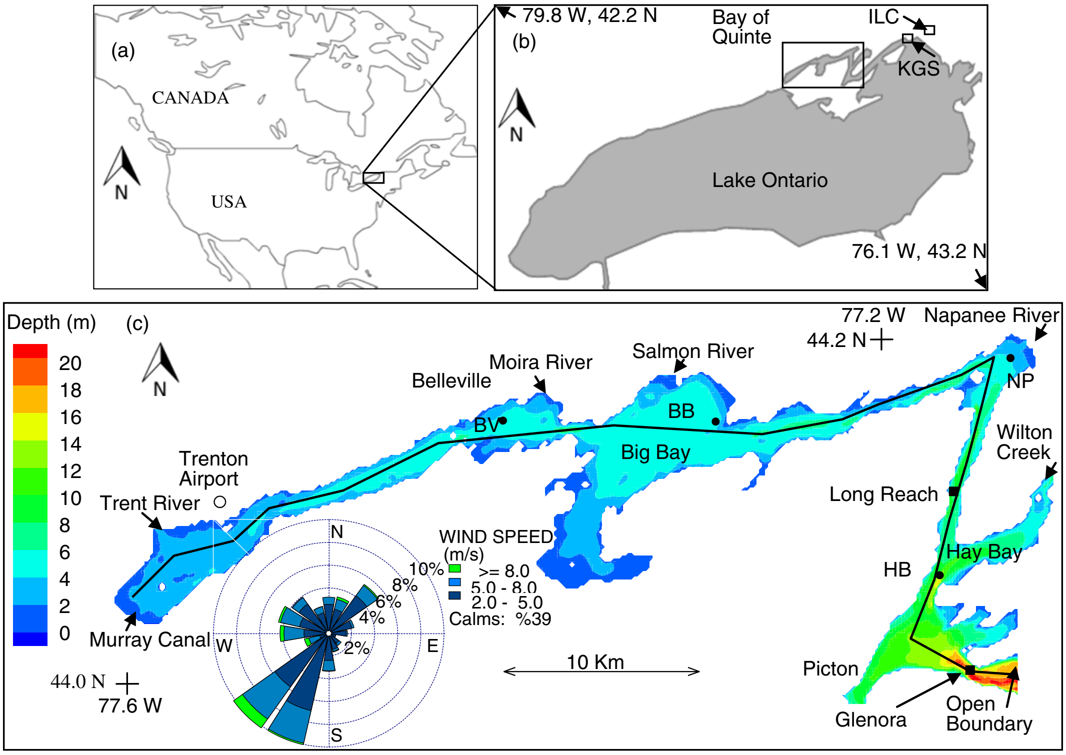

Fig. 1. (a) Location of Lake Ontario in North America, (b) location of the Bay of Quinte in Lake Ontario, indicating Kingston Gauge Station (KGS) and Integrated Learning Center (ILC). (c) Bathymetric map of the 150 m horizontal grid used for the Bay of Quinte model domain showing: locations of tributaries, meteorological station at Trenton Airport (open circle), Trenton Airport wind rose plot for the duration of the simulation (inset), field observation stations (solid circles), the location of the velocity rose plot (solid square), and curtain plot (black line). The Upper Bay is the region from the Murray Canal to the Napanee River and the Middle Bay is the region from the Napanee River to Glenora.

phosphorus in the upper bay. These previous one-dimensional and box model efforts to numerically model the bay have been unable to reproduce the complexity of the flow, including temperature and nutrient gradients between the quiescent embayments and the main channel. Consequently, the objective of the present paper is to investigate the transport and mixing of nutrient laden inflows to the Bay of Quinte and determine their subsequent residence time and flushing with Lake Ontario using a contemporary three-dimensional hydrodynamic model.

Towards this objective we apply the three-dimensional (3D) hydrodynamic model ELCOM (Estuary and Lake Computer Model; Hodges et al., 2000) to the Bay of Quinte (Fig. 1). The model is validated against observed temperature data and applied to determine metrics that quantify the age, retention, mixing, dilution and flushing of riverine inputs. This will allow identification of high-risk areas for nutrient enrichment and poor water quality to guide future management efforts. In the present work, conservative passive tracers are used as surrogates for actual nutrient concentrations; however, ongoing work will include simulation of 3D biogeochemistry in the bay by coupling ELCOM to the Computational Aquatic Ecosystem Dynamics Model (CAEDYM).

Methods

Description of field site

Located on the northeastern shore of Lake Ontario (44.15 N, 77.25 W) the Bay of Quinte is z-shaped and 70 km in length with a surface area of 255 km^2 and volume of 2.67 km^3. It includes several shallow embayments of 4–8 m deep. The eastern outlet is connected to the Kingston Basin of Lake Ontario and at the western end the Murray Canal connects the bay to Lake Ontario for navigation; we neglect flow through the Murray Canal, which is shown to have a weak oscillatory flow that has a negligible influence on the overall dynamics (Johnson and Owen, 1971). The long complex z-shape geometry and shallow embayments make the bay difficult to model with simple 1D vertical or longitudinal dynamics alone.

The Upper Bay (from the Murray Canal to the Napanee River, Fig. 1) is supplied by the Trent River, Moira River, and Salmon River and is reported to be the most sensitive region for accumulation of nutrients (Robinson, 1986). The Napanee River and Wilton Creek have watersheds approximately 12 times smaller than Trent River, and they are also closer to the Lake Ontario open boundary; therefore, we expect fewer effects from these rivers on nutrient dynamics. However, high concentrations can persist near the mouths of these rivers, as well as in side bays away from the main channel, where low velocities are expected.

Model description

ELCOM is a hydrostatic Reynolds-averaged Navier–Stokes equation model that solves the scalar transport equations to model mass and temperature distributions in space and time (Hodges and Dallimore, 2006). Eddy-viscosity and mixed-layer models are used for horizontal and vertical turbulence closure, respectively. Heat exchange through the water surface is governed by standard bulk transfer models as found in the literature (e.g. Hodges et al., 2000). The fundamental numerical scheme is adapted from the TRIM approach of Casulli and Cheng (1992) with modifications for accuracy, scalar conservation, and numerical diffusion. We have chosen the ELCOM model because it has been applied extensively to study lake processes from the basin-scale (Hodges et al., 2000) to the large eddy scale (Botelho and Imberger, 2007) and will be coupled with the CAEDYM (Computational Aquatic Ecosystem Dynamics Model) module (e.g. Rao et al., 2009; Leon et al., 2011; Oveisy et al., 2014) for future biogeochemical and management studies on the Bay of Quinte.