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*We present an overview of physical processes that drive water circulation within the extended system of coastal embayments in the Toronto Harbour. The different water circulation patterns occur at various spatial and temporal scales, and our article provides context for the various efforts to improve water quality by the Toronto and Region Remedial Action Plan. Velocity profiles and water level measurements showed that the harbour's Helmholtz pumping mode drives a 1-h period oscillation, which can influence flushing of the shallow embayments. This process likely persists year-round and would lead to flushing time-scales of between 1–11 days for these shallow embayments. If this ubiquitous pumping is combined with solar heat fluxes, it partially explains the persistent temperature gradients amongst the shallow embayments. In the larger and deeper (∼10 m) Inner Harbour, the prevailing westerly winds drive most of the mean circulation, with a current entering through the Western Gap and leaving through the Eastern Gap. This wind driven circulation leads to a residence time of water in the Inner Harbour between 7–14 days. In addition, periodic strong and sustained westerly winds can induce frequent upwelling events in Lake Ontario (between 4 to 10 times during the stratified season) that mildly increase the exchange flow and help maintain good water quality by exchange nearshore waters with cleaner hypolimentic waters. The intrusion of cold water into the harbour can also lead to highly variable temperature regimes with sudden drops in temperature that could have negative effects on aquatic organisms.*

*Keywords:* exchange flow, temperature, water quality, upwelling

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# Introduction

The water exchange between Toronto Harbour and Lake Ontario, exerts an important physical control on the health of the ecosystem, and influences thermal regimes and the chemistry of the water within the harbour (Howell et al., 2018). There are several main mechanisms that drive the water exchange between a semi-enclosed bay with the adjacent body of water; specifically, (1) upwelling events, (2) spatial temperature differences due to differential heating (Wells and Sherman, 2001, Lawrence et al., 2004), (3) wind forcing (Razmi et al., 2014) and (4) water level oscillations, especially for confined bays when Helmholtz resonance occurs as a response to lake seiche forcing and induce Helmholtz pumping (Hlevca et al., 2015b; Fischer et al., 2013; Wells and Sealock, 2009). In addition to these four mechanisms (Figure 1), tributary flows can be important after storms or severe rain events in driving circulation in Toronto Harbour, but these episodic events will not be discussed in this article. The flushing induced by these mechanisms varies with season, topography and the relative position of the embayment along the lakeshore to prevailing winds. As Toronto Harbour consists of multiple embayments of variable depth and area, different processes will dominate different regions of the harbour. Therefore, no single mechanism dominates the overall water exchange everywhere. This paper will describe these main flows that are all relevant to Toronto and Region Remedial Action Plan's goals of improving water quality.

Toronto Harbour (hereafter TH) is a large and complex embayment system ($18\,km^2$) located on the northern shore of Lake Ontario at 43° 38' N, 79° 22' W (Figure 1; Figure A1, available in the online supplementary information [SI]). The harbour has a maximum depth of 11 m and an average depth of 9 m. The harbour has several hydrodynamically distinct zones, namely the Outer Harbour (hereafter OH), the Inner Harbour (hereafter IH), with a commercial port and the channels inside the Toronto Islands, and lastly the sheltered embayments of Tommy Thompson Park (hereafter TTP). The OH is connected directly to Lake Ontario through a wide opening (~1200 m) and it is characterized by steep bathymetric slopes on the northern shore due to a natural occurring ridge and enhanced by the navigation channel. The IH is almost rectangular with a quasi-uniform depth of 10 m, with vertical walls on the northern shore and milder bathymetric slopes along the Toronto Islands (TI). The IH is connected to Lake Ontario through Western Gap (WG) channel (9 m deep and 120 m wide) and to the OH through the Eastern Gap (EG) channel (10 m deep and 230 m wide). TH receives inputs from several combined sewer overflows (CSOs), but the most significant input is Don River (Dewey, 2012; Haffner et al., 1982), which has an average flow of 4 $m^3s^{-1}$, implying a long hydraulic residence of 115 days. We will show that the actual residence time of the IH is much shorter due to wind, upwelling exchange and Helmholtz pumping processes, and hence on average the river is not a significant source of circulation in the harbour. While on average the Don River has little influence on the circulation or the thermal structure within the harbour, after large storms high loadings (e.g. 369.4 $m^3s^{-1}$ for the 25-year return period flow) can be significant contribution to water quality problems (Dewey, 2012; Snodgrass et al., 2018). The last zone in the harbour is composed of the shallower artificial embayments of TTP and the channels inside the TI, which are characterized by slower currents and finer sand and mud substrates, and macrophytes (Hlevca et al., 2015a). One notable feature of the topography of the harbour immediately outside the 10–12 m deep OH and within 600 m of the end of TTP, is the presence of a steep underwater escarpment that drops off to 75 m depth, making the harbour particularly sensitive to upwelling of hypolimnetic waters (Figure 1a). Due to the water quality problems, mostly related to the IH and Humber Bay area (west of the WG), Toronto Waterfront was designated as an Area of Concern by the International Joint Commission and a remedial action plan (RAP) has been initiated in 1987 to guide efforts to improve water quality in the area with a target of delisting by 2020.

The objective of this article is to discuss the dominant exchange processes at different scales in the harbour in order to provide context for efforts of the Toronto and Region Remedial Action Plan to remove various Beneficial Use Impairments that relate to water quality. We will start with a review of previous studies of physical processes in TH. We will then introduce our

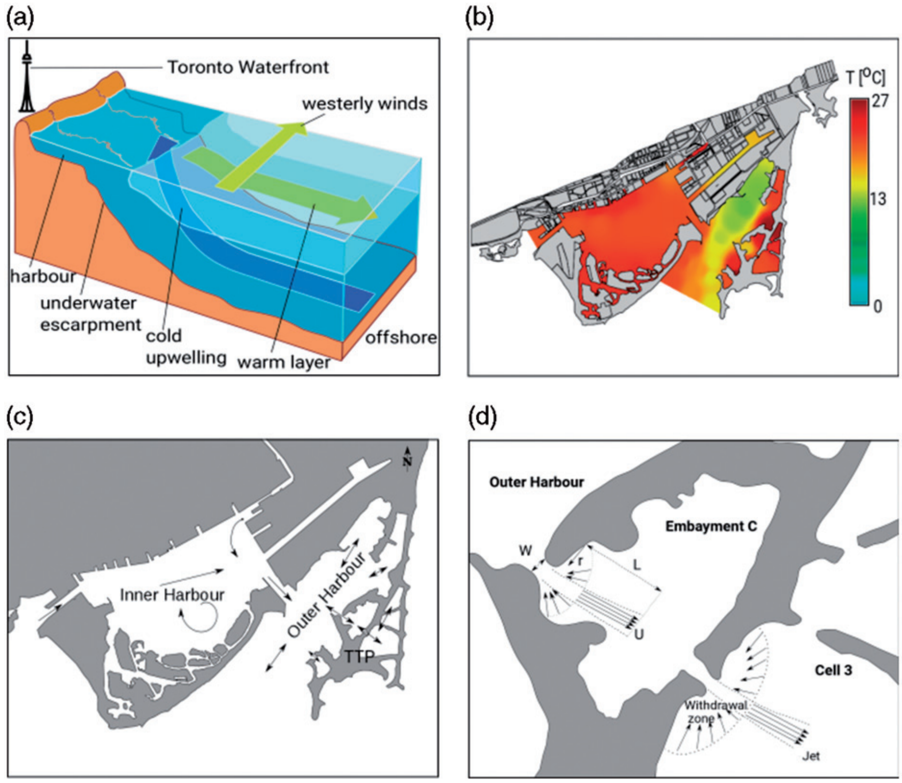


**Figure 1.** Main mechanisms that drive the water exchange between a semi-enclosed bay with the adjacent body of water. (a) Upwelling event formation on the northern shore of Lake Ontario. (b) Map of spatial mean temperature in Toronto Harbour during the 2013 stratified season (June–September), interpolated from field data (Figure A1). (c) Predominantly wind induced circulation patterns (Hlevca et al., 2015a). (d) Seiche flow leaving a sharp forming a jet. When the seiche changes phase, the flow leaving the embayment will have the form of a sink, therefore, part of the incoming flow is not drawn back through the channel, resulting in a net exchange of water masses (Stommel and Farmer, 1952).

recent observations and models of the residence time and the thermal habitat of TH, which are determined by four main factors: (1) upwelling events, (2) spatial temperature differences, (3) meteorological events (wind) and (4) amplified response to water level oscillations (Figures 1a–d).

## Previous studies on dominant hydrodynamic processes

There have been only a limited number of previous studies that have looked at the hydrodynamic processes in the harbour, mainly targeting the IH. These studies have shown that at least four processes could be important in the harbour. Firstly, there are frequent upwellings in Lake Ontario that propagate into harbour multiple times each summer (Hlevca et al., 2015a). Secondly, there are the horizontal temperature gradients within the harbour, which Murphy et al. (2011, 2012) have suggested that these might have a role in driving the exchange between TTP with Lake Ontario. Thirdly, Haffner et al. (1982) and Dewey (2012) have shown that currents in TH, and specifically the IH, are mainly wind-driven. Finally, Freeman et al. (1974) suggested that a one-hour water level oscillation could drive significant barotropic water exchange within TH.

Very few studies have addressed the thermal regimes in TH, especially in the relatively new artificial embayments of TTP. Murphy et al. (2011, 2012) have shown in their studies that the embayments in TTP are generally much warmer than the surrounding waters in TH and Lake Ontario, due to their limited flushing. They used a statistical approach to classify the fish thermal habitat of the embayments in “cold,” “intermediate” and “warm,” based on comparison with inland lakes of similar sizes. However, they did not directly measure the water currents that would have driven the flushing; therefore, they speculated that the entire exchange flows between the shallow embayments in TH with Lake Ontario were driven by horizontal temperature gradients. Their conclusion was that a combination of distance from the lake and geometry of their connection to the lake are the main determinants of thermal regimes, but importantly, as they did not measure the water currents, they left open the question as to what actually drives the exchange in the many biologically important shallow embayments of TH.

Recently, Hlevca et al. (2015a) showed that there is a large variety of thermal habitat due to the complex bathymetry of the harbour. They analyzed the data from a large array of temperature loggers, pressure loggers and acoustic Doppler profilers and showed that deep (>8 m) benthic zones have a cold habitat, but relatively low temperature variability, including those directly exposed to lake water exchanges. Conversely, the shallow zones of the harbour (<3 m) had highly variable temperature regimes, and surprisingly, even in some the sheltered embayments that had changes temperature with a rate up to 4 °C $h^{-1}$. Their conclusion was that the most important factors in regulating the thermal regimes in TH are the relatively frequent and pervasive cold-water intrusions induced by thermocline upwellings.

The mean daily exchange rate between Lake Ontario and TH was estimated by Haffner et al. (1982) to be 97 $m^3s^{-1}$ based upon measurements made in 1977. They have calculated that the IH (the volume of which is approximately 40 x $10^6$ $m^3$) has an average a residence time of approximately 10 days, with the predominant flow entering through the WG. Also, they observed that the water depth in the harbour is too shallow and the exchange with the lake too efficient to allow extended thermal stratification to develop. This rapid flushing also means there are few problems with anoxia in the harbour. The estimates given by Haffner (1982) were later confirmed by Dewey (2012) who based his results on field measurements with ADCP units and hydrodynamic modelling. The estimates of Dewey (2012) for the residence time of the IH range between 7 to 12 days, and corroborate Haffner's idea that wind driven flows are dominant in flushing the IH. Furthermore, he showed that water circulation is directly related to water quality and beach closures, by presenting tabulated control options for the assessment of effectiveness in improving the *E. coli* levels in the IH for the swimming season (1 June to 31 August).

Water level oscillations in lakes are small, but analogous to oceanic tides, which are well known as an important mechanism for flushing water in and out of harbours. The magnitude of the response of the harbour depends in detail upon the Helmholtz resonance in the specific harbour (e.g. Seelig and Sorensen, 1977; Miles and Lee, 1975). The Helmholtz response in TH has been only briefly studied by Freeman et al. (1974). In their paper, they used data records from the International Field Year for the Great Lakes study and analytical and numerical model to understand the effect of seiches in several harbours around the Great Lakes. They analyzed the Helmholtz mode, which has a longer period than the natural frequency of the harbour, and which represents the balance between the kinetic energy of the water flowing through the narrow connecting channel and the potential energy from the rise of the water in the harbour. They found a Helmholtz oscillation period $T = 62$ to 65 min for the IH, which compared favourably with limited water level data from a 2–week record from 1971. They also showed that the Helmholtz oscillations have amplitudes considerably larger in harbours of small surface area such as TH and are relatively unimportant in larger harbours, like Hamilton Harbour. Consequently, they assumed that the Helmholtz mode could lead to significant flushing in TH.

Furthermore, many non-peer reviewed documents and technical reports from City of Toronto, Toronto and Region Conservation Authority and Toronto Port Authority have analyzed various scenarios related to water quality and shore stability management during floods, but are limited to a small area of interest, mainly flooding near the Don River mouth, located within the IH.

In the current study, we will also present new material from a combination of our field observations, analytical and numerical hydrodynamic modelling (Delft3D-FM) to study the depth averaged circulation within the harbour that is driven by water level fluctuations. These results will be presented in the next sections.

# Field observations, analysis and numerical modelling

To study lake-embayment exchange and circulation patterns in TH, a series of observations were conducted in 2013 and 2015. Water levels, water column temperature and velocity profiles were measured to trace water motions and spatio-temporal distribution of temperatures.

## Meteorological observations

The wind is the principal source of energy for horizontal circulation and vertical mixing in the harbour. The atmospheric weather patterns have much larger scales than the size of TH, therefore, we assumed that the wind field is rather uniform over the harbour. Accordingly, we analyzed meteorological data from one Environment Canada weather station (Station 6158359; 43° 37' 39" N, 79° 23' 46" W; TI-WS, Figure A1). The air temperature, wind speed and direction (Figure A2) and relative humidity were measured at 10 m above lake level. During the studied period winds were moderate (average speed ~3.7 m $s^{-1}$).

## Water levels fluctuations

There is considerable variation in water levels in Toronto Harbour on both seasonal scales, and on very short time-scales of hours (Figure 2a). Long-term water level variations follow closely those of the neighbouring Lake Ontario, and show a seasonal cycle with variations of up to 0.5 m over the course of the year. In contrast, short term water levels changes of 5–10 cm are induced by wind set-ups that are followed by upwelling events, and to a lesser extent, by inflows, outflows, precipitation and evaporation. When a steady wind blows along the lake, it increases the elevation along the downwind end of the lake, which is balanced by a depression at the upwind of the lake. After wind cessation, surface seiches are formed as an oscillatory response to lake surface displacement. The pumping action of the seiches can have a significant impact on the circulation in the harbour especially if there is a resonant response of the harbour. We used Onset U20-001-04 (range 0–4 m; accuracy 0.3 cm) water level loggers sampling every 10 min, which were deployed in all the embayments in TTP, OH and IH (Figure A1). The spectral analysis of the water level time-series determined significant peaks for water level oscillations with periods $T = 0.56$, 1.03, 2.2, 3.3, 5.06, 12.4 and 24 h present at all the monitored locations (Figure A4). The prominent peaks at $T = 5.6$, 3.3, and 2.2 h match the signatures of previously detected Lake Ontario 1, 2 and 3 seiche modes, and the oscillations with periods $T = 12.4$ and 24 h match the semi-diurnal and diurnal tide respectively (Hamblin, 1982). The water level oscillation with the period $T = 0.56$ h has never been reported in TH, and the oscillation with period $T = 1.06$ h has been reported by Hamblin (1982) as a possible theoretical mode 9 Lake Ontario seiche and calculated theoretically by Freeman et al. (1974) as a Helmholtz oscillation of the IH. Analytically, this one-hour period can be calculated for Lake Ontario with the well-known Merian formula for rectangular basins (Merian, 1828; Kämpf, 2009), $T_n = 2L/(n\sqrt{gH})$, where $n$ is the mode, $L$ is the length of the basin, $g$ is the gravitational acceleration and $H$ is the average depth of the basin. The prominent peak of the oscillation with period $T = 1.06$ h (Figure A4) suggests that there is a strong resonant Helmholtz mode amplification in the harbour, which could lead to significant flushing in TH (Figure 1d) through the pumping action mode and will be discussed in the next section.

## Circulation in the Inner Harbour, Outer Harbour and Tommy Thompson Park

Our measurements made in 2013 and 2015 confirmed many of the predominant circulation patterns described by Haffner (1982). In addition to the mean wind driven flows, we also found that in the OH (Figure A1, ADCP A-1) the currents were relatively moderate (0.1–0.2 m $s^{-1}$) and were oscillatory, with a one hour period, changing direction every 30 min along the longitudinal axis of the harbour and over the full depth, suggesting a Helmholtz pumping induced flow. The surface circulation was slightly stronger in the direction of the prevailing wind direction (Figure A3a and b). In contrast, a new finding was our measurement of the alternating currents in the narrower TTP channels (Figure 2b),

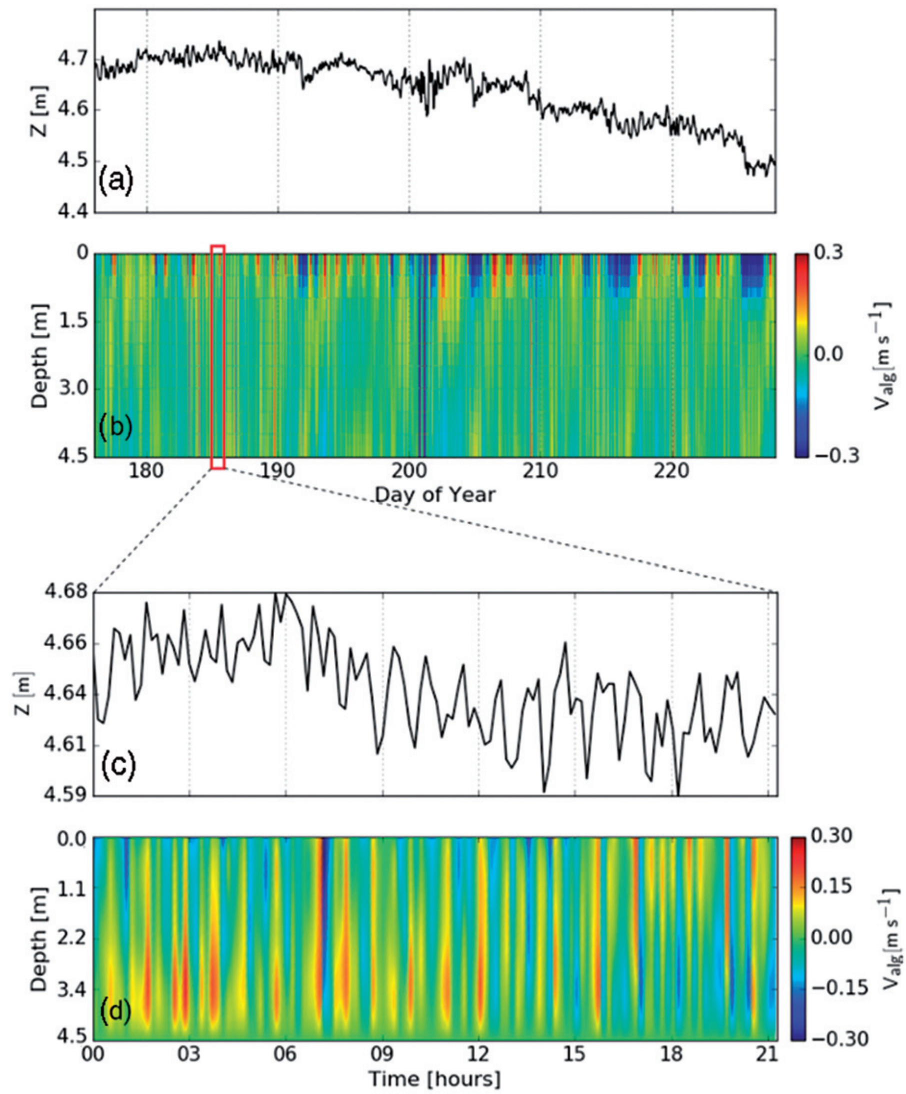


**Figure 2.** Water level (water depth) oscillations and velocities in the channel between Embayment C and Cell 3. (a) Water level oscillations with one hour moving average (WL-EC). (b) Velocity profiles in the channel between Embayment C and Cell 3 (A-3). Northwestern direction has positive values. (c) Zoomed in water level oscillations for a 24-h interval. (d) Zoomed in velocity profiles for a 24-h interval.

which had much higher average velocity values (0.3–0.4 m s$^{-1}$) and with peaks of up to 0.9 m s$^{-1}$.

In order to better understand how frequent water level fluctuations might influence circulation within the harbour, we ran a process study using the Delft3D Flexible Mesh in depth-averaged mode for an unstratified period. These runs were forced by measured winds, tributary flows and water level fluctuations at the lake open boundaries. As this process study is focused on seiche driven pumping, these runs do not explicitly model other processes such as extreme flooding or upwelling events. The model was able to reproduce our field data from ADCP deployments (in terms of velocity magnitudes and circulation patterns) in the harbour (Figure 3a and b; Figure A5). In addition, the general features are the same as in previous observations (Haffner et al., 1982; Dewey, 2012). Most importantly, the model accurately determined the dominant 1 h oscillation, which matches our new field observations (Figure A8b).

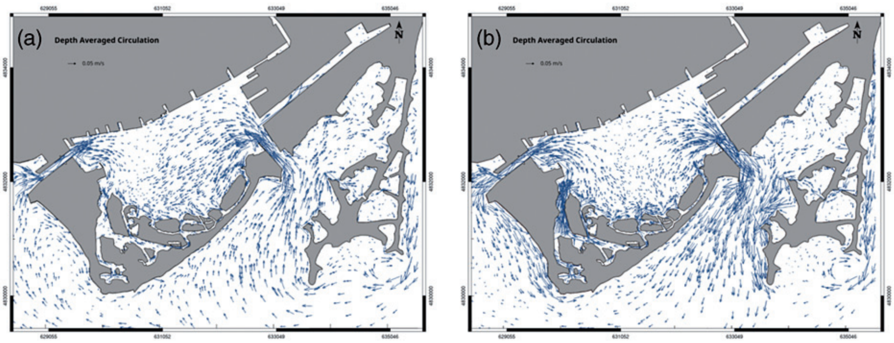


**Figure 3.** Depth-averaged mean circulation obtained by a Delft3D-FM model run that emphasize the flows driven by the 1-h seiche. (a) A snapshot of the circulation when the water level in the Inner Harbour was at its minimum. (b) Half an hour later when the level in the Inner Harbour was at its maximum.

These one-hour water level oscillations lead to periodic tide-like movements through the inlets and can produce water exchange due to flow asymmetries between inflows and outflows at an inlet (Figure 1d). The asymmetry is in the form of a jet on the flood phase and sink-flow on the ebb phase, as explained by Stommel and Farmer (1952) in their classic model of tidal flushing of an estuary. The explanation for the tidal flushing is that part of the outgoing jet is not drawn back through the channel during the ebb phase. We can estimate the flushing ratio of the water in the jet that remains in the bay to the total amount of water passing through the channel, considering a zero velocity mean current as shown in Wells and van Heijst (2003); if the channel has a width $W$ and current with a constant velocity $U$, then the length of the jet is $L = UT/2$ after half a tidal period $T/2$ (Figure 1d). If the same volume of water will be drawn back during the ebb phase by the sink shown as a radius (Figure 1d), then fluid within the half circle of radius $r = \sqrt{LW(2/\pi)}$ is returned. Assuming a constant depth, Wells and van Heijst (2003) showed that the exchange ratio of the fluid that remains in the bay after each oscillation cycle, to the total volume transported through the channel, can be estimated as

$$exchange\ ratio \geq 1 - \sqrt{\frac{4}{\pi}\frac{W}{UT}}. \qquad (1)$$

The ratio $W/UT$ is known as the Strouhal number (Nicolau del Roure et al., 2009), and determines the extent of fluid flushing through an oscillating channel. Small Strouhal numbers ($W/UT \ll 1$) imply that the length of the jet is much greater than the width of channel and hence that flushing is efficient, which was shown experimentally and through numerical simulations (Delft3D) by Wells and van Heijst (2003, 2004). In TTP, where the channels have widths $W = 50$ m, an average velocity $U = 0.4\,\mathrm{ms}^{-1}$ and a period $T = 1\,\mathrm{h}$, so the Strouhal number is small with $W/UT = 0.035$. Using (1) the flushing ratio would be at least 70.1%, implying a very efficient exchange in these shallow embayments. In contrast, in the wide and long channel of Hamilton Harbour, both Hamblin and He (2003) and Yerubandi et al (2016) have found that the Helmholtz mode was not an important mechanism for flushing, as generally the jet failed to penetrate any great distance into the harbour. In Hamilton Harbour the Strouhal number would be large as $W$ is much larger and $U$ much smaller. This difference underscores the importance of the different geometry of TH, and the different physical processes at work.

Although in the OH we found that the frequent upwelling events are associated with smaller velocities (~0.2 m s$^{-1}$) (Hlevca et al., 2015a) when compared with seiche induced currents (~0.4 m s$^{-1}$) measured by the ADCP, the longer excursions associated with upwelling events make them a more efficient flushing mechanism than seiches in the larger IH and OH.

# Differences of the thermal structure within the harbour resulting from water circulation patterns

The thermal structure in TH depends on the specific location and it is generally influenced by

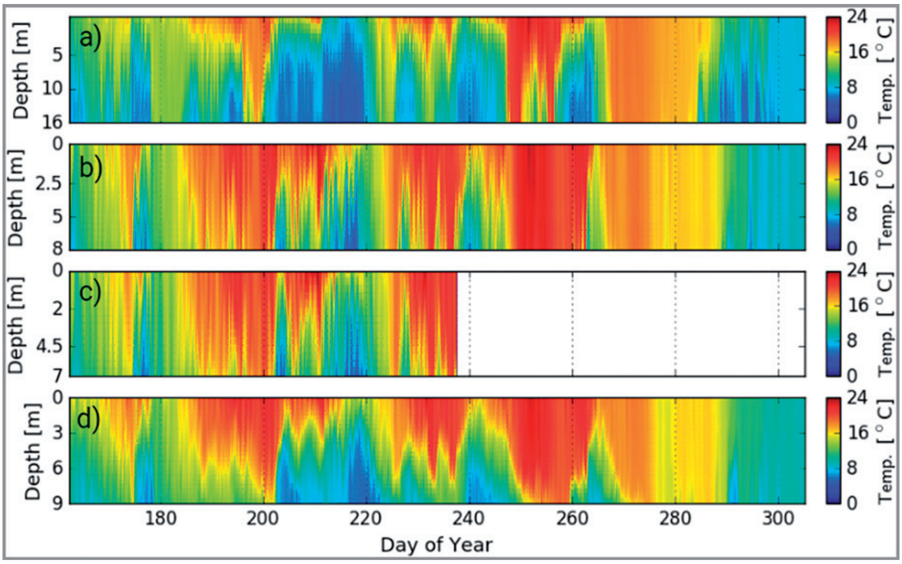


**Figure 4.** Temperature profiles in deep regions in and around Toronto Harbour during the 2015 stratified season. Plots are arranged from top to bottom stating from Lake Ontario to locations in Habour that are farthest from the lake. (a) Lake Ontario station at Loboviz2. (b) Outer Harbour at chain T4. (c) Eastern Gap (the missing data was caused by the temperature chain displacement) and (d) Jarvis Dock. For the exact location of the temperature chains see Figure A1.

the depth of the thermocline in Lake Ontario. We have measured the temperature of the water column in Lake Ontario and at several locations in TH during the ice-free season for several years and we present results for 2013 and 2015. The location of the thermistor chains in TH is marked with red bullets for 2013 (Figure A1) and with blue diamonds for 2015. The location of the thermistor chain deployed in Lake Ontario in 2013 is marked in the map inset (Figure A1), while for the temperature profile in Lake Ontario for 2015 we used data from Ontario Ministry of Environment and Climate Change, Loboviz 2 station located in Humber Bay (http://ontario2.loboviz.com).

In Lake Ontario stratification starts in May and by the beginning of June, a thermocline establishes at depths between 10 to 20 m and lasts until September. In TH, in contrast, the relatively rapid exchange with Lake Ontario and its relatively shallow mean depth (10 m) do not allow extended periods of stratification. The polymictic nature of IH and OH is enhanced by the frequent (9-12 per year) upwelling events and storm events (Figures 1a and 4, e.g. DOY 220 and DOY 255) that occur on the northern shore of Lake Ontario due to the prevailing westerly winds (Figure A1) and enhanced by the steep underwater escarpment. The measured temperature profiles in Lake Ontario show that the quasi-regular upwelling events have average amplitudes of 11 m (Figure 4), which propagate mostly unobstructed in the harbour, with average velocities of 0.1–0.2 m $s^{-1}$ (Hlevca et al., 2015a). In the shallow areas, such as those in the TTP embayments the temporary stratification formed by differential heating (Murphy et al., 2011) is quickly weakened through mixing (Hlevca et al., 2015a) that is produced by wind entrainment and by the strong alternating velocities in the entire water column induced by the Helmholtz pumping.

# Implications of hydraulic residence time on water quality

The timescale at which water is flushed out of different parts of the harbour is a strong determinant of the water chemistry and temperature. One measure of this flushing rate is the hydraulic residence time, which is defined as the average amount of time spent in a region by the water. The residence time is an important water quality indicator that is solely dependent on hydrodynamic processes that determine the exchange between an embayment-lake system, which in turn are highly dependent on the meteorological events and local topography, as shown in the Laurentian Great Lakes by Hlevca et al. (2015b) and in Lake Geneva, Switzerland by Razmi et al. (2014).

Our field observations and modelling efforts were directed toward the entire system of embayments inside TH and we found that the flushing times for these embayments ranged from 1.2 days in Cell 2 to 11 days in Cell 1. Our estimates for the flushing times were 7 days for the IH, 4 days for the OH, 8 days for Cell 3 and 3 days for Embayment C. However, these estimates assume a continuous stirred reactor tank, while in reality, the volume of water involved in the exchange is lower due to a phenomenon known as *short-circuiting* (Andradóttir and Nepf, 2000) that makes that only some water in the harbour to effectively participate in the exchange. This reduction in exchange efficiency can be especially pronounced in exchange flows driven by low amplitude, high frequency tidal forcing (Wells and van Heijst, 2003) and can lead to zones of poor water quality. In TH, as shown previously in our field observations and modelling results, there are strong Helmholtz mode induced water level oscillations that create strong alternating flows (Figure A5) significantly contributing to the flushing of all the shallow embayments in the harbour system, but it is unclear if the short water excursions relative to the length of the larger bodies of water such as the IH and OH have an important effect on their residence time and water quality.

The rapid flushing times in Toronto Harbour will, to some extent, ameliorate the influences of nutrient and contaminant loading, which make it easier to address the various Beneficial Use Impairments described in RAP (1989a,b). For instance, Toronto Harbour generally does not experience hypoxia, as the residence time of water is shorter than the oxygen decay time, unlike in Hamilton Harbour that takes months to flush (Yerubandi et al., 2016). Similarly, Dewey (2012) and Snodgrass et al. (2018) have showed that the residence time in the harbour was a key factor in determining the rapid reduction in *E. coli* levels after storm events.

# Conclusions

This article reviews all the published work related to physical processes in Toronto Waterfront, summarizes some of our findings from previous physical limnology investigations in the system of embayments of Toronto Harbour along with those from our on-going research. The currents, mostly in the IH and OH, are mainly wind-induced during the periods when the predominantly westerly winds blow for periods longer than three days (Haffner et al., 1982). However, the 1-h Lake Ontario seiche mode 9 is strongly amplified in the IH due to resonance, and determines constant oscillating exchange flows between Lake Ontario and all the embayments within the harbour system. The field observations and modelling results presented in this article show that resonant seiche induced flushing is a strong and dominant mechanism for water exchange, especially in the shallow embayments.

The water quality and thermal habitat of TH is significantly influenced by the circulation patterns, which in turn impact the various Beneficial Use Impairments (BUI) in the harbour. Specifically, the Toronto Harbour has the following BUIs that are clearly impacted by water circulation–namely "*Eutrophication or undesirable algae,*" "*Beach closings,*" "*loss of fish and wildlife habitat*" and "*Degradation of phytoplankton and zooplankton communities*" (RAP, 1989a,b). For instance, the rapid circulation in the harbour could be linked with lack of diversity in the zooplankton species. After sewerage overflows, the decay of *E. coli* level in Toronto Harbour is also strongly controlled by water circulation patterns (Snodgrass et al., 2018). Howell et al. (2018) have also clearly shown that the nearshore water quality parameters along the central Toronto waterfront are influenced by water circulation. Fish habitat in Toronto Harbour is also influenced by the frequent upwelling events, which reach all but the most isolated of these comparatively protected regions, and influences the extent of viable fish habitat within the harbour (Veilleux et al., 2018).

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## Supplemental material

Supplemental data for this article can be accessed on the publisher's website.

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