

Article

Characteristics of the Exchange Flow of the Bay of Quinte and Its Sheltered Embayments with Lake Ontario

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Abstract: The nature of the exchange flow between the Bay of Quinte and Lake Ontario has been studied to illustrate the effects of the seasonal onset of stratification on the flushing and transport of material within the bay. Flushing is an important physical process in bays used as drinking water sources because it affects phosphorous loads and water quality. A 2-d analytical model and a 3-dimensional numerical coastal model (FVCOM) were used together with in situ observations of temperature and water speed to illustrate the two-layer nature of the late summer exchange flow between the Bay of Quinte and Lake Ontario. Observations and model simulations were performed for spring and summer of 2018 and showed a cool wedge of bottom water in late summer extending from Lake Ontario and moving into Hay Bay at approximately 3 cm/s. Observed and modelled water speeds were used to calculate monthly averaged fluxes out of the Bay of Quinte. After the thermocline developed, Lake Ontario water backflowed into the Bay of Quinte at a rate approximately equal to the surface outflow decreasing the flushing rate. Over approximately 18.5 days of July 2018, the winds were insufficiently strong to break down the stratification, indicating that deeper waters of the bay are not well mixed. Particle tracking was used to illustrate how Hay Bay provides a habitat for algae growth within the bay.



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Keywords: Bay of Quinte; drifter observations; exchange flow; Hay Bay; isolated bays

1. Introduction

Freshwater runoff during heavy rain events and the spring melt naturally flushes bays and lakes but this flushing can often bypass sheltered embayments. These flushing events typically bring cooler, more oxygenated water and phosphorus attached to suspended sediment, which results in hydrographic changes and potential algae and bacterial growth due the phosphorus. Regular algae blooms are a common occurrence in the Bay of Quinte, a small bay on Lake Ontario [1–3]. These blooms are supplied with phosphorus primarily coming from upstream rivers and they occur during the months of May to October, impairing the bay's use as a drinking water supply [1,4]. Because studies of algae growth and total phosphorous (TP) use flushing rates to determine nutrient budgets, it is important to obtain accurate measurements of these rates for the main channel and off-channel segments of the bay.

The middle part of the Bay of Quinte serves as the main flushing conduit between the bay and Lake Ontario and it is generally assumed to be well mixed in budget models. Middle bay is generally defined as the region from Longreach through the Glenora Gap and also connects to two isolated embayments, Picton Bay and Hay Bay (Figure 1). Previous observations of the hydrography in middle bay showed that during the summer months when there is a thermocline above the sill in the Glenora Gap, the surface flow is outward through the Gap toward Lake Ontario and there is a backflow at the bottom [5]. As a result, models of TP budgets developed for the Bay of Quinte generally assume a two-layer model at the mouth of the bay east of the Glenora Gap while assuming that middle bay, which is shallower, is only one layer and is well mixed [3,6]. These models perform well at

reproducing the seasonal and spatial variations in TP in the bay, but [6] note that the well mixed assumption can lead to an underprediction of TP in middle bay in the summer when this assumption is at odds with the observed stratification likely due to a misrepresentation of fluxes at depth in middle bay.

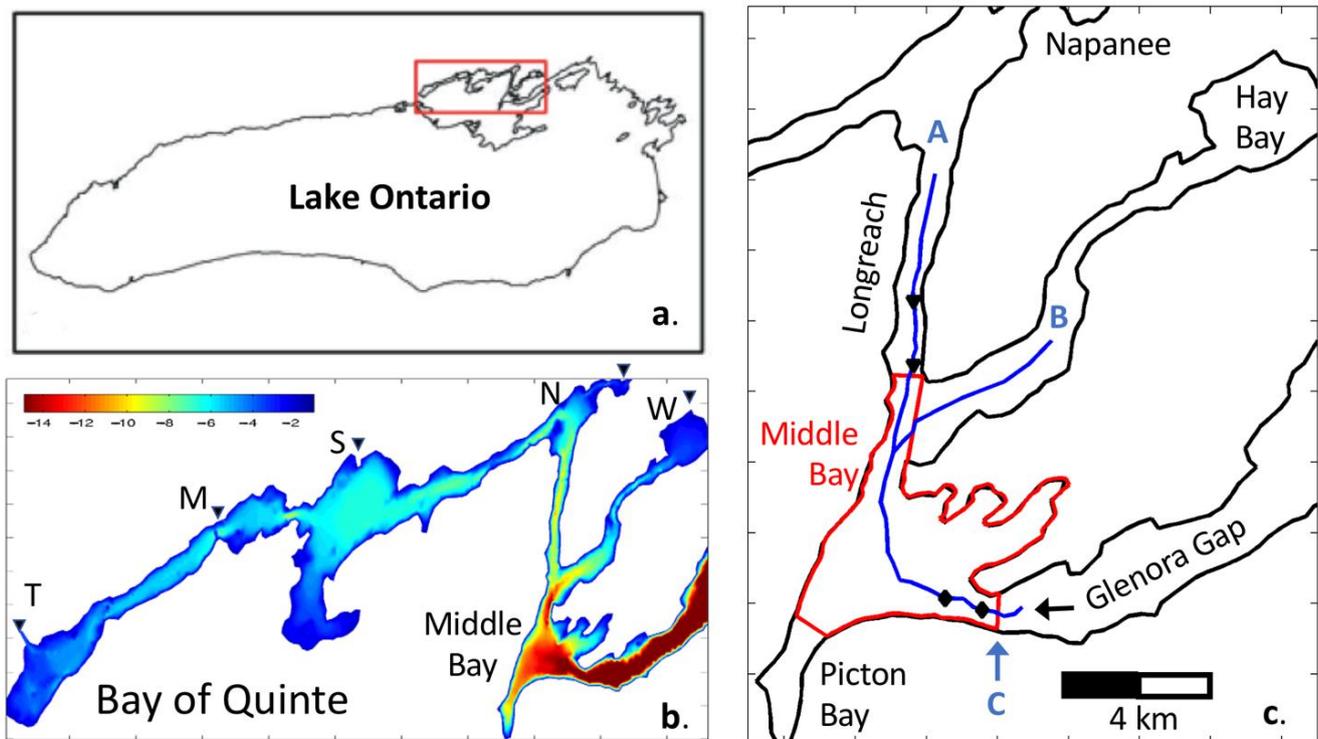


Figure 1. (a) Lake Ontario with Bay of Quinte (red box). (b) Bathymetry (m) of the Bay of Quinte with locations of five tributaries marked with triangles: Trent River (T), Moira River (M), Salmon River (S), Napanee River (N) and Wilton river (W). (c) Middle bay (red outline) between Longreach and the Glenora Gap and its two isolated embayments: Hay Bay and Picton Bay. Transect lines A and B marked in blue; transect line C crosses the Glenora Gap. Ends of the in situ temperature transects for Longreach and the Glenora Gap are marked with triangles and diamonds, respectively.

The flow structure in middle bay controls the hydrography and flushing in its two connected sheltered embayments. Middle bay is subjected to upwelling and downwelling events driven by Lake Ontario water levels [5,7,8]. Previous studies that focus on TP and Chl a concentrations assume that middle bay is controlled more by upstream tributary inputs (such as the Trent River) than by water inflows from Lake Ontario [3,9]. As the waters in middle bay become stratified, the surface outflow through the Glenora Gap can be strengthened by sufficiently strong winds or large tributary inflows. This in turn increases the return flow of Lake Ontario water at the bottom into middle bay. Therefore, it is essential for numerical models to have the correct wind forcing, river inflow and water level specified at the boundary between the bay and Lake Ontario to accurately simulate this region. The bottom inflow is known to affect the seasonal patterns in TP in middle bay as well as vertical entrainment and mixing [10]. These patterns, however, are not repeated in the two sheltered bays connected to middle bay and they experience infrequent flushing. Studies of TP loads in Hay Bay and Picton Bay indicate that the lack of flushing results in sediment reflux being a significant contributor to local TP loading [10]. The local response of the small embayments to this forcing from Lake Ontario has not been examined. This is important because with less flushing, the sheltered embayments can have significantly higher algae growth which feed back into the bay.

Oxygen records illustrate differences between middle bay and its sheltered embayments. Hypolimnetic (below the thermocline) oxygen depletion occurs in the bay during

the summer months when algae is present as oxygen is used during algae growth. However, water temperature also has a significant role with warmer temperatures creating a demand for oxygen. A relationship between warmer bottom water and lowered oxygen was observed for waters in the deep part of middle bay that was not evident in the adjacent shallow embayment in Hay Bay [8]. Hay Bay experiences some of the largest amounts of algae growth [11] and is generally warmer than water in the main channel and thus would be expected to have higher oxygen depletion rates. However, [8] suggested that down-mixing of oxygenated water slowed the depletion rate. The dynamics of Hay Bay and its isolation from the main channel allow it to act as a refuge for algae, where it can grow without being flushed.

Flushing events impact the hydrography, nutrient supply and algae growth within the bay. Over the course of the summer and fall stratified period, the bay flushes at least 1.5 times. This flushing is relatively restricted to the main channel while embayments adjacent to the main channel are not flushed. Studies of the bay have quantified and used the flow rates to determine nutrient budgets, but relatively few studies have focussed on the smaller, more sheltered embayments (e.g., [3,4,7,12]). These sheltered embayments retain material during flushing events but it is not clear how algae is transported from these protected areas back into the main channel and whether this poses a hinderance to the beneficial use of the bay as a source of drinking water.

This paper will investigate the nature of the flow in middle bay using a two-layer flow model and a 3-dimensional hydrographic model. These models will be used to identify the mechanisms that control the exchange flow through middle bay, the effects of wind on transport and mixing within middle bay, and the flushing patterns in middle bay and its sheltered embayments. In situ observations of flow speeds and temperature profiles in 2018 are used with the integrated conservation of momentum equations to describe the flow structure in middle bay. In addition, the summer 2018 hydrography of the Bay of Quinte is modelled using a high-resolution numerical model, the Finite Volume Community Ocean Model (FVCOM) to show the nature of the flow through middle bay and its stability and mixing. This study builds upon previous modelling efforts that used the FVCOM model for the spring of 2016–2019 by employing the same high-resolution mesh and surface forcing data sources [13]. The previous study focussed on calibrating and validating the large spring inflow from the dominant upstream river source, the Trent River, and the subsequent flushing and particle transport within the upper bay. The current study focusses on the summer-time stratified nature of middle bay and the smaller, off-channel embayments to illustrate the exchange flow with Lake Ontario during periods of strong stratification. The model has been shown to estimate the bay's hydrography reasonably well but in this study we further investigate by validating the stratified water column and flow regime against in situ measurements during the relevant summer-time period. Model results are used to quantify fluxes in and out of middle bay and to illustrate particle transport pathways that link Hay Bay, middle bay and Lake Ontario. In doing so, other studies that estimate TP loading in middle bay may be more accurate which is fundamental to algae growth predictions.

2. Materials and Methods

In situ temperatures were used to observe the layered structure of the summer time flow in middle bay. We collected temperature profiles in Longreach and at the Glenora Gap and used the profiles to identify the depth of the thermocline. We then deployed Lagrangian drifters at depths above and below the thermocline to collect concurrent water speeds. Results were then compared to a simple two-layer flow model.

2.1. Two-Layer Model

A simple two-layer model is used to illustrate the fundamental physical forces that control the slope of the thermocline through middle bay. It can be used to quantify

the relative importance of the wind and interface shears and vertical velocity shear in Longreach compared to the Glenora Gap.

To derive equations that represent the steady flow of a fluid with two vertical layers of different constant densities, the momentum balance equations are vertically integrated. By assuming a wind stress, τ_w , imposed on the upper surface layer and a frictional shear stress, τ_i , between the two layers, the 1-dimensional momentum equation for each layer becomes:

$$g \frac{\partial \eta_1}{\partial x} = \frac{\tau_w - \tau_i}{\rho_1 h_1} \quad (1)$$

$$g' \frac{\partial \eta_2}{\partial x} = -g \frac{\partial \eta_1}{\partial x} + \frac{\tau_i}{\rho_2 h_2} \quad (2)$$

where the upper and lower layer variables are subscripted with 1 and 2, thus η_1 is the free surface and η_2 is the interface. In addition, g is gravity and g' is reduced gravity with ρ and h the layer density and thickness.

Substitution of Equation (1) into (2) and assuming that all stresses have a quadratic form (e.g., [14]), results in an algebraic formulation for the interface slope, m_i ,

$$m_i \approx \frac{\partial \eta_2}{\partial x} = \frac{1}{g'} \left(k_i \left(\frac{h_1 + h_2}{h_1 h_2} \right) u_d |u_d| - \frac{\rho_a k_w}{\rho_1 h_1} U_{10} |U_{10}| \right) \quad (3)$$

where k_w , and k_i are the friction coefficients for the wind and interface stresses, respectively, $\rho_a = 1.22 \text{ kg/m}^3$ is the assumed air density, U_{10} , is the 10-m wind speed in the x-direction, and u_d is the difference between the upper and lower layer speeds. We use values for k_w and k_i , and of 0.0013, 0.0014 which were successfully used with Glenora Gap data previously [5]. Therefore, by using observations of the speeds and thicknesses of the upper and lower layers, an estimated interface slope from Equation (3) can be compared to the observed slope from the temperature profiles to determine whether the observed state is consistent with the predictions of a two-layer model.

2.2. Observations

Temperatures and velocities were collected for two transects in middle bay upstream and downstream of the entrance of Hay Bay to compare to the two-layer model. Observations were collected in 3 h time spans in the late summer of 2018 after the waters became stratified: on 2 August 2018 in Longreach and on 17 July 2018 in the Glenora Gap (Figure 1). Temperature profiles were collected using a tethered thermocouple with data collected from the surface down to the bottom at 0.3 m intervals. Surface temperature data were also sampled with a thermometer. During the collection, the observed thermocline depth was used to determine the depth at which to sample the upper and lower layer speeds. By assuming that the thermocline depth was the depth of the interface, average temperatures (and therefore densities) could be derived for each layer. Flow speeds were then collected using lagrangian drifters above and below the thermocline at the ends of the transects. Temperatures and flow speeds were assumed steady over these short 3 h periods. These drifters have been used previously in the Bay of Quinte and have a tethered drogue with four vertical panels [15,16]. The drogue was tethered to a waterproof capsule containing a GPS unit that broadcast its position every minute. The tether length was adjusted to place the drogue at the required measurement depth approximately in the middle of either layer. The data were analysed with a 3-point centered difference scheme to provide a velocity. Hourly wind speeds were taken from the Environment Climate Change Canada (ECCC) Kingston A station located in Kingston, Ontario. The upper and lower layer boundaries were defined by the thermocline giving their thicknesses and then the velocities and densities of these layers could be used in Equation (3) to estimate an interface slope along the transect.

2.3. FVCOM Model Simulations

The FVCOM model was used to simulate the 3-d hydrodynamics of the Bay of Quinte from 15 April to 2 Aug 2018 when there is in situ temperature data to evaluate the model output. Models were initiated on 15 April because the bay is known to be generally ice-free and of uniform temperature at this time [7,8]. The FVCOM model prognostically solves the 3-d primitive equations on an unstructured mesh and conserves mass and momentum on control volumes [17]. It has previously been used to effectively simulate many parts of the Great Lakes freshwater system including the Bay of Quinte (e.g., [12,18,19]).

Model forcing used for the internal heat flux calculations included daily values of air temperature, relative humidity, air pressure, solar and longwave radiation and wind. These forcing data were provided by the High-Resolution Deterministic Prediction System (HRDPS) for the 2018 surface data which have a 2.5 km spatial resolution [20]. River inputs for the main freshwater sources, the Trent, Moira, Salmon Napanee and Wilton rivers, were included (Figure 1). Discharges for all but the Trent River were imposed by the observed discharges from the continuously monitored ECCC river stations whereas the Trent River discharge was estimated based on the ECCC observed Crowe River discharge [13]. River temperatures were set to be a 3-day running average of observed ECCC air temperatures [7]. The bay has depths ranging from 2 m at the head to approximately 35 m at the Glenora Gap and the model used 11 uniformly spaced vertical sigma layers (the average depth in the bay is 6.1 m with a standard deviation of 8.2 m). Water levels at the outflow boundary were set equal to the observed hourly water levels at Kingston (Portsmouth Station 13988 as monitored by Fisheries and Oceans Canada). This study builds on previous studies of the spring time upper Bay of Quinte but it is focussed on middle bay during the stratified late summer period of 2018. These simulations are an improvement over the previous simulations for the years prior to 2006 with higher spatial resolution, higher resolution of surface forcings, improved estimates of river inflow values and use observed water levels at the downstream boundary [12,13].

3. Results

3.1. Two-Layer Observations and Model

The two-layer model predicts that for a stratified flow, the thermocline tilt along a vertical transect is sustained by a vertical velocity shear and wind shear. To determine how well the two-layer model captures the real-world flow in middle bay in the late summer, temperature profiles were first collected along two transects to define the interface slope. On 17 July 2018, temperature profiles were collected at four locations along a transect that bisected the Glenora Gap (Figure 1). Bottom temperatures were observed to be approximately 7 degrees cooler than at the surface and the westernmost profile showed a significant 5 °C temperature drop from 25 to 20 °C at approximately 6.5 m depth (Figure 2). The 22.8 °C temperature contour (shown in black) easily identifies the two distinct layers.

Temperature profiles were collected 2 weeks later along a transect upstream of the mouth of Hay Bay to determine if this two-layer structure extended past the entrance to this sheltered bay (Figure 1). On 2 August 2018, four temperature profiles were collected in Longreach along a transect that runs north–south. Depths here are much shallower and, as a result, temperatures are much warmer than at the gap. The warm upper layer is uniformly approximately 25.8 °C down to approximately 6 m and there is a thin 3 m in thickness layer of cooler water at the bottom with the coldest temperature approximately 23.3 °C (Figure 2). The 25.6 °C contour generally defines the change from warm layer to cold layer.

The observed thermocline slopes in the temperature profiles can be compared to the estimated interface slope from Equation (3) by using concurrent wind and water speed observations. To estimate the velocity shear, Lagrangian drifters were deployed to collect speeds in the layers above and below the observed thermocline at the ends of both transects. At Glenora Gap drogues were tethered at 4.2 and 10.7 m. The observed difference in the averaged speeds between the upper and lower layer was approximately 18.5 cm/s in the

Glenora Gap (Table 1). At that time, the wind speed to the east from the closest ECC station at Kingston was approximately 3.9 m/s. Assuming the thickness of the upper and lower layers to be 6.5 and 8.5 m, the estimated interface slope from Equation (3) is 0.99 m over 1 km. A line of slope 0.00099 is shown overlying the 22.8 °C thermocline of the observed temperatures. The strong agreement between the estimated interface slope and the thermocline shows that the two-layer model is capturing the real-world flow at that time. In Longreach, the estimated velocity difference between the upper and lower speeds was 3 times smaller than at the Glenora Gap (Table 1). Drogues were tethered at 2.7 and 5.6 m. Using the observed winds to the south at Kingston (2.7 m/s), the interface slope was estimated from Equation (3) to be approximately 0.93 m/km (a line with this slope is shown overlying the 25.6 °C contour). The results show that there is an upward trend of the temperature contours to the south from Longreach through middle bay and then to the east through the Glenora Gap. In both locations, the interface slopes predicted by Equation (3) align well with the thermocline tilts showing that the simple two-layer mathematical model well reproduces the rise in the temperature contours. Wind directions on 17 July and 2 August varied by less than 30 degrees during collection of the temperature profiles, which would result in uncertainties in the interface slope of less than 1%.

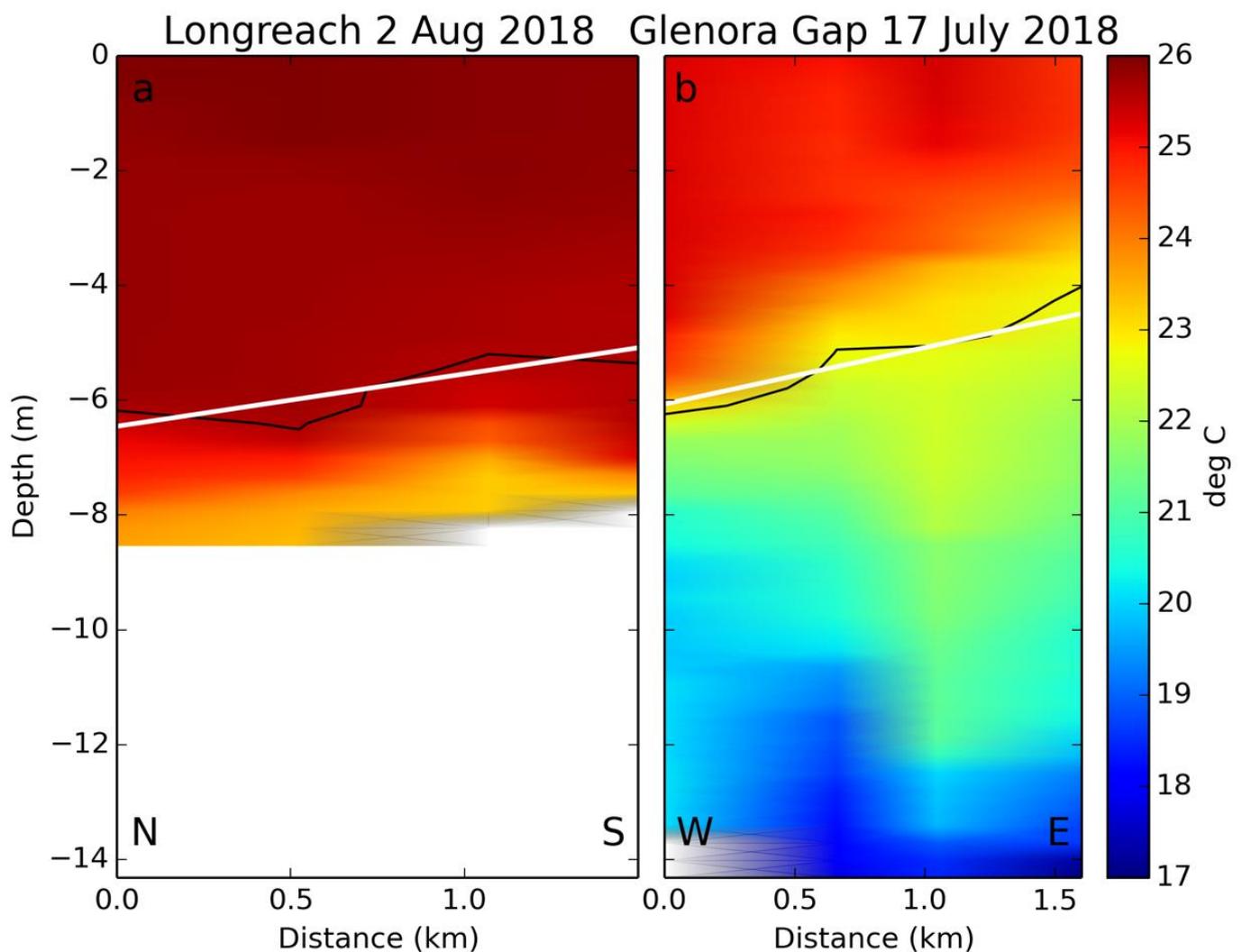


Figure 2. Observed temperature transects in (a) Longreach on 2 August 2018 and (b) Glenora on 17 July 2018. Temperature contours for 25.6 and 22.8 °C in Longreach and Glenora, respectively, are shown in black. Estimated interface slopes from Equation (3) are shown in white.

Table 1. Estimated and modelled layer parameters for 17 July and 2 August 2018.

Location	h(m)		T (°C)		U ₁₀ (m/s)	Observed u _d (cm/s)	Model u _d (cm/s)
	Upper	Lower	Upper	Lower			
Longreach 2 August 2018	6	3	25.8	24.5	2.7	5.5 ± 4.0	4.8 ± 1.5
Glenora Gap 17 July 2018	6.5	8.6	24.5	20.4	3.9	18.5 ± 5.5	9.7 ± 3.3

Equation (3) can be used to quantify the relative importance of wind and velocity shear. The primary controlling factors for the hydrography throughout the Bay of Quinte are tributary inflow, wind-driven flow and differential responses to heating in the shallow versus the deepest parts (e.g., [7,12,21]). In middle bay, in late summer, when the two-layer flow structure is in place, the relative sizes of the two terms on the right-hand side of Equation (3) determine the relative importance of the velocity shear and wind stress in maintaining the two-layer structure. In Longreach, these two terms are approximately the same size, indicating that the wind is equally important to the shear at this location. In the Glenora Gap, however, the ratio of the shear term to the wind stress term is approximately 9:1, indicating that other factors that are driving the water speeds there are likely important in controlling the hydrography there. This is consistent with previous modelling efforts which showed that anomalies in the eastward (i.e., to the east) current through the gap are correlated with the eastward wind but that the mean current was not [12].

3.2. Three-Dimensional Model Results

We used the FVCOM model to fill in the spatial temperature field between the observations collected in middle bay. The model simulated the 3-d hydrodynamics of the Bay of Quinte from 15 April to 2 August 2018 under daily wind and solar forcing and with inputs from five tributaries. Surface forcing was created from HRDPS atmospheric data products with a 2.5 km resolution. A temperature transect on 2 August 2018 along a line that bisects middle bay shows the layer structure replicated in the model (Figures 1 and 3). This transect shows a wedge of cooler bottom water that is thick at the Glenora Gap and thins toward Longreach (Figure 3a). Triangle markers indicate the sites where observations were collected in Longreach and Glenora and the estimated interface slopes from Figure 2 are re-shown as white lines here. The model thermocline tilts are very similar to the estimated slopes illustrating that the model also replicates the observed temperatures well. The average RMSE temperature error between the model and the in situ temperatures profiles collected on 17 July and 2 August was 3.4 °C similar to other model results [7,12]. Figure 3 highlights the benefit of using a numerical model as the results provide a bigger picture of the temperature field. The cooler bottom waters observed at the Glenora Gap are part of a system which extends along the bottom up into middle bay past the entrance to Hay Bay illustrating the continuity in the two-layer structure throughout middle bay.

In nutrient budget models, all parts of the Bay of Quinte except east of the Glenora Gap are assumed to be well mixed, which is true except in middle bay during this period of stratification, as seen in the observations. Interestingly, it appears that Hay Bay is also stratified to some extent as model results show that the two-layer structure extends into Hay Bay (Figure 3b). The wedge of cooler bottom water extends approximately 4 km along the bottom up into this sheltered embayment and there is approximately an 8 °C temperature difference from the surface to the bottom. Examination of the model velocities shows the cooler water is moving into Hay Bay at approximately 2.5 cm/s and the warmer water is moving outward at approximately 2.8 cm/s similar in structure to classical estuarine circulation.

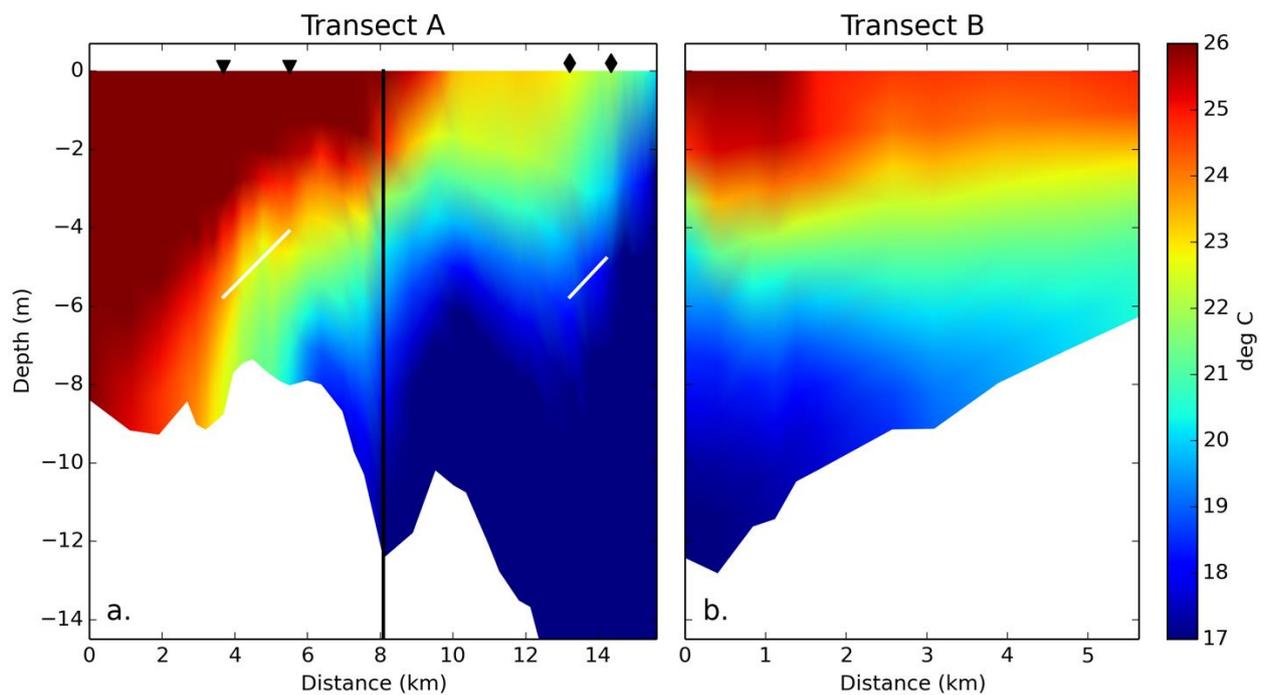


Figure 3. Model temperature along transect lines (a) A and (b) B (shown in Figure 1) on 2 August 2018. Triangle and diamond markers denote the transects along which temperature observations were collected and the estimated interface slopes from Figure 2 are reproduced here. The black line indicates the point at which transect B intersects with transect A.

Model velocities were compared to drifter observations taken during 2018. At Longreach, the averaged speed differences between the two observed layers for the model were very similar, approximately 4.8 cm/s compared to 5.5 cm/s (Table 1). The observed velocities had a high variability as the drifters responded to local accelerations that occurred over the course of the measurement whereas the model was forced with daily average values. These observations are also similar to the modelled flow in Hay Bay, where the overall speed difference was 5.3 cm/s. At the Glenora Gap, the model underpredicted the difference with the largest speed differences in the model comparable to the smallest observed differences. Direct comparisons of speeds were made for observations collected in the Napanee River (Figure 1). Surface drifters were released in the Napanee river at 3 times over the summer of 2018 and the model speeds match reasonably well there over 3 months, with the model estimates falling within range of the drifter speeds (Table 2). In general, the FVCOM model reasonably reproduces the temperature and velocity fields observed in 2018.

Table 2. Comparison of observed drifter speeds in the Napanee River to model speeds.

Napanee River Speeds	24 May 2018	10 June 2018	25 July 2018
Observations (cm/s)	8.0 ± 3.0	11.2 ± 6.0	5.1 ± 2.0
Model (cm/s)	4.5 ± 1.0	7.1 ± 1.5	5.2 ± 1.2

The model temperature transects indicate a potential transport pathway between Lake Ontario waters and Hay Bay when middle bay is stratified. The stratification allows inflow of cool bottom water to flow through the gap up through middle bay and into both Hay Bay and Longreach. To illustrate, we show surface and bottom model velocities after the spring freshet when the Bay of Quinte is newly flushed and the temperature profile is still fairly uniform (April 30) compared to a typical stratified summer flow pattern (June 9) (Figure 4). We chose these two periods because they are significantly different. In April the river inflows into the bay are at their annual maximum due to snow melt and large spring precipitation events (called the spring flush). At this time, the water temperature in the

bay is almost uniformly constant, approximately 4 °C [7,8], and the flow is uniformly out of the bay from top to bottom. In contrast, in June, there is significantly less river inflow and surface solar heating has created a stratified water column which permits a reversal of the flow along the bottom. It is during this stratified period when TP in Middle Bay is underpredicted [6]. On April 30 at the end of the spring flush, both surface and bottom velocities in Longreach are south towards Glenora Gap as expected. At this time, middle bay is weakly stratified and the flux of water is out of middle bay toward Lake Ontario. Winds are to the southwest and flows in Hay Bay and Picton Bay are very weak illustrating their isolation from the main channel and their lack of flushing. In contrast, on June 9, the stratified flow has a strong vertical velocity shear in the main channel. Surface flows are southward from Longreach and out through the Glenora Gap. Surface waters in Hay Bay are to the south west and would tend to transport material at the head of Hay Bay back into middle bay. There is a counter-clockwise recirculation set up in middle bay. With stratification, bottom waters are into the bay through the Glenora Gap and northward through middle bay. The bottom flow diverges and moves northward through Longreach and also northeast into Hay Bay, again, replicating a classic estuarine circulation. These patterns show that in fall, Hay Bay can seed material into middle bay and that there is a potential pathway for Lake Ontario bottom waters into Hay Bay.

When water is stratified, the strength of that stratification determines whether the water column can be mixed. Mixing can be initiated by sufficiently strong winds, or weakening of the stratification by cooling or advection of water into or out of the system. The Schmidt stability index, S_t , can be used to both identify when the water column is stratified and quantify the energy required to result in mixing [22,23]. Comparing the Schmidt stability index to the wind shear energy at the surface can then be used to identify times when the when the wind is strong enough to initiate mixing. We computed the Schmidt stability index for middle bay according to:

$$S_t = \frac{g}{A_0} \int_0^H (z - z^*) (\rho_z - \rho^*) A_z \partial z \quad (4)$$

where g is the acceleration due to gravity, A_0 , is the surface area, H is the maximum depth, ρ_z is the density at depth z , ρ^* is the mean density, A_z is the cross-sectional area at depth z , and z^* is the depth of the mean density [24,25]. The initiation of stratification can be identified in spring when this index becomes greater than 30 J/m² [26]. The Lake Number, LN , is the ratio of the Schmidt stability index to the wind shear energy [25]:

$$LN = \frac{S_t(z_e + z_h)}{2\rho_a C_d U_{10}^2 A_0^{1/2} z_v} \quad (5)$$

where z_e and z_h are the depths to the top and bottom of the metalimnion, respectively, ρ_a is the surface air density, C_d is the drag coefficient, U_{10} is the wind speed at 10 m height, and z_v is the depth to the center of volume of middle bay. It was originally developed to link mixing to the vertical flux of dissolved oxygen, and $LN < 1$ indicates that internal mixing can be induced by wind forcing [23]. The Schmidt stability index and Lake Number for middle bay show that, as expected, stratification develops over the first month of the model simulation and it remains stratified through to August (Figure 5). Daily wind speeds from the ECCC station at Kingston were used in Equation (5) to determine the Lake Number. There are regular periods when the wind is generally too weak to overcome the stratification in middle bay when $LN > 1$. In particular there are 18.5 days in July where the wind is insufficient to cause mixing and these periods last on average approximately 3.6 days (maximum 7 days long). These indices suggest that middle bay is often not well mixed in the summer.

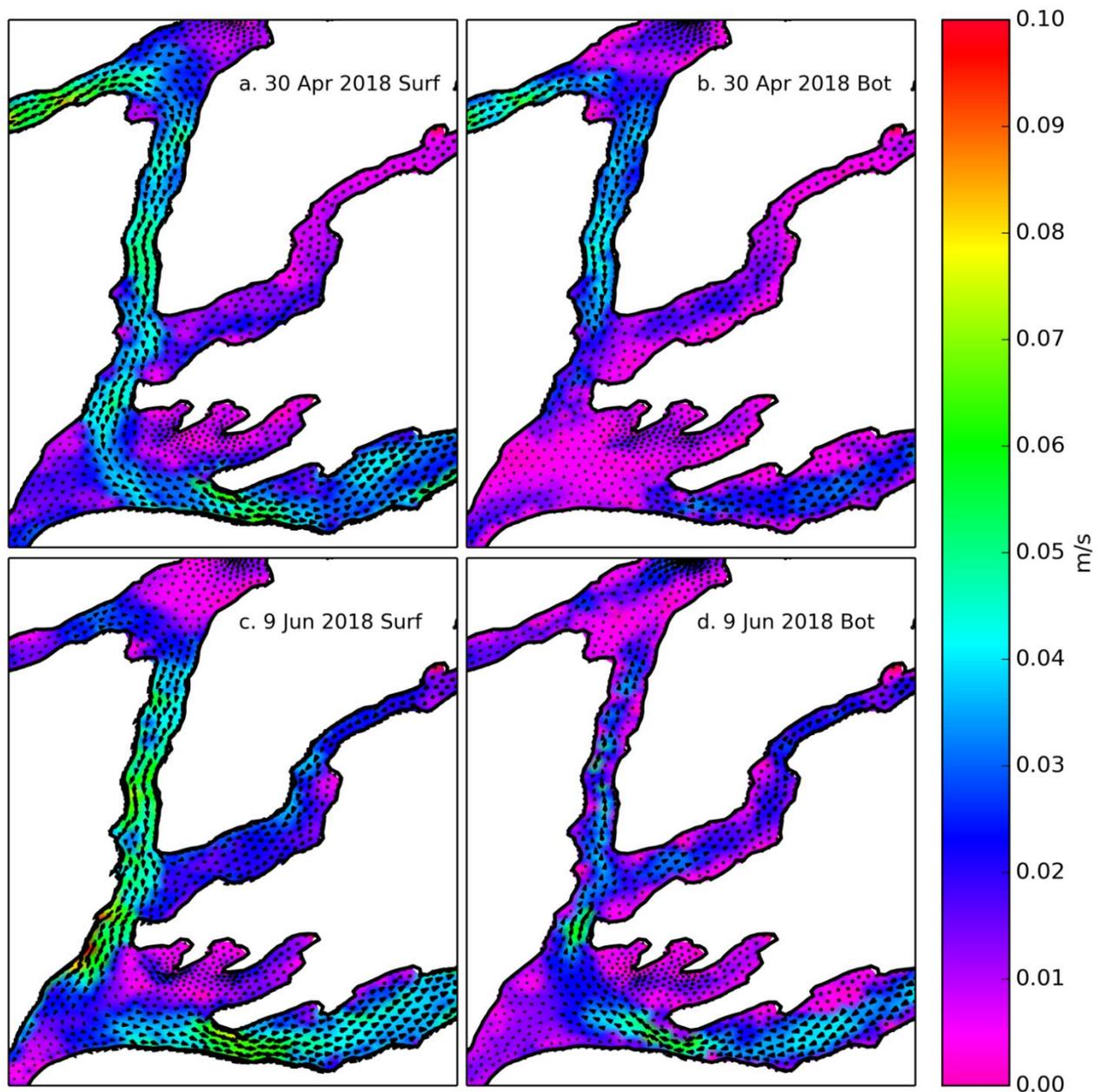


Figure 4. Middle bay flow fields at the (a) surface on 30 April 2018 and the (b) bottom on 30 April 2018 and at the (c) surface on 9 June 2018 and the (d) bottom on 9 June 2018. Directional arrow heads on top of magnitude in m/s.

We used the density field to estimate fluxes assuming middle bay can be divided into two-layers and determined the monthly average fluxes between middle bay and the Glenora Gap (transect C; Figure 1). Flows above and below the depth of the mean density field, z^* , were used to calculate fluxes out of the bay (defined as the upper layer above z^*) and into the bay (defined as the lower layer below z^*) and averaged over each month (Table 3). In April, the water column remains mostly well mixed with an S_t less than 30 J/m^2 and the flux is out of the bay in both layers (the bottom inflow is negative). Capturing only the last 15 days of April and missing the peak of the summer runoff, these values are not representative of the full month. In May, stratification has initiated and there is a significant flux out at the surface with some inflow in the lower layer. The net flux in May suggests that the total volume of middle bay (0.19 km^3) would flush approximately once in this month. June and July show that there are nearly equal fluxes of the surface layer flowing out of middle bay toward Lake Ontario and of lower layer water flowing in. This

suggests a very low flushing rate in later summer except by strong episodic precipitation or wind events. Average vertical velocities can be estimated by vertically integrating the incompressibility equation from the seabed up to the thermocline. On average from May to July, the model estimates a vertical flow across the metalimnion of approximately 25 mm/s in middle bay, consistent with observations from other stratified lakes [27,28]. If Lake Ontario acts as a source of TP, then current budget models could account for this extra TP load into middle bay in the fall using these model estimated fluxes.

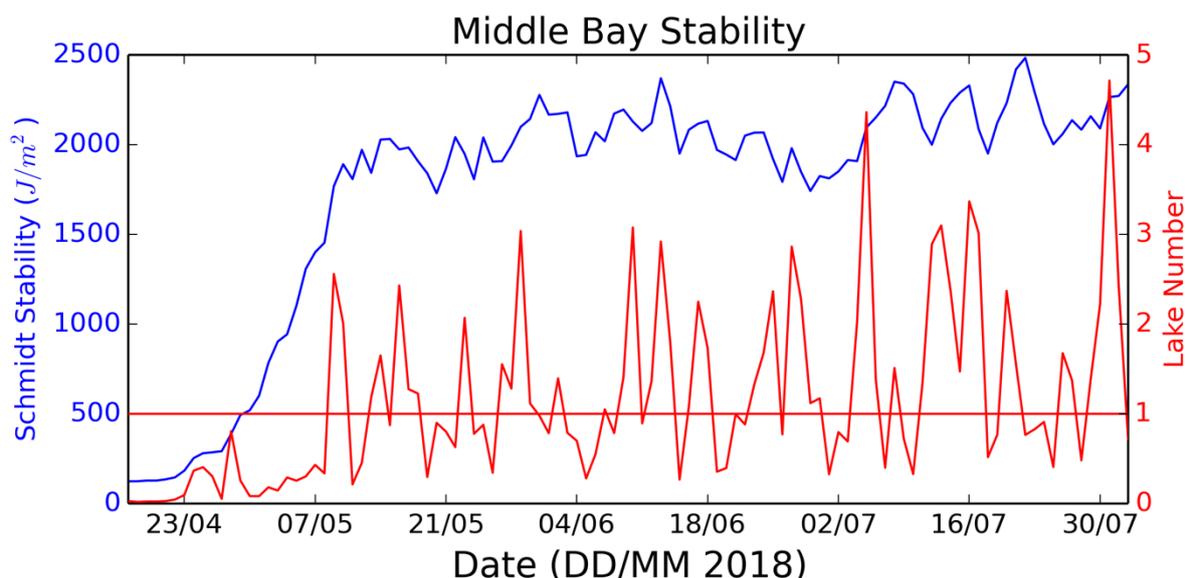


Figure 5. Schmidt Stability index and Lake Number for the area of middle bay estimated from FVCOM model results for 15 April to 2 August 2018.

Table 3. Fluxes (m^3/s) above and below the depth of the average density out of middle bay into the Glenora Gap for April to July, 2018. Surface outflows are positive to the east and bottom inflows are positive to the west across transect C in Figure 1.

Monthly Middle Bay Fluxes	Surface Outflow (m^3/s)	Bottom Inflow (m^3/s)
April 15–30	93	−5
May	258	190
June	236	240
July	236	249

The two-layer structure in middle bay suggests that nutrients and particles are introduced into the deeper waters of middle bay from Lake Ontario and it is important to determine how far into the bay that they spread. Transport pathways between middle bay and the isolated embayments connected to it can be studied with modelled particle movement. The pathways of non-sticky particles were simulated in the stratified period of May to June, 2018, in the top and bottom layers (particles were constrained to either the top or bottom sigma layer and did not settle) (Figure 6). Colours are assigned based on initial locations and subsequent daily positions are sequentially overlaid (most recent positions appear on top) to produce maps of particle movements. As expected, the surface flow moves particles in the main channel from Longreach through middle bay and out via the Glenora Gap (blue and purple particles moved south) (Figure 6b). Surface particles in Picton Bay (green) tended to remain there. Particles from Hay Bay (brown) transit south and fully spread throughout middle bay but also transit north into the small head of Hay Bay. Particles within that small head (which are red) rarely left the area. In contrast, bottom particle movement shows a pathway for Lake Ontario water (lime green particles) through Glenora Gap spreading into Picton Bay and up through the main channel into Longreach

(Figure 6c). Bottom waters in middle bay (olive particles) also spread into Longreach and up into Hay Bay. A Landsat image taken on 29 June 2018 shows a large patch of algae in Hay Bay distributed similarly to the cyan particles giving confidence to the model results (Figure 6d). These maps illustrate the sheltered nature of the algae in Hay Bay and show that these algae can re-seed middle bay. The layered nature of the flow in middle bay allows an exchange in waters from Napanee to Lake Ontario.

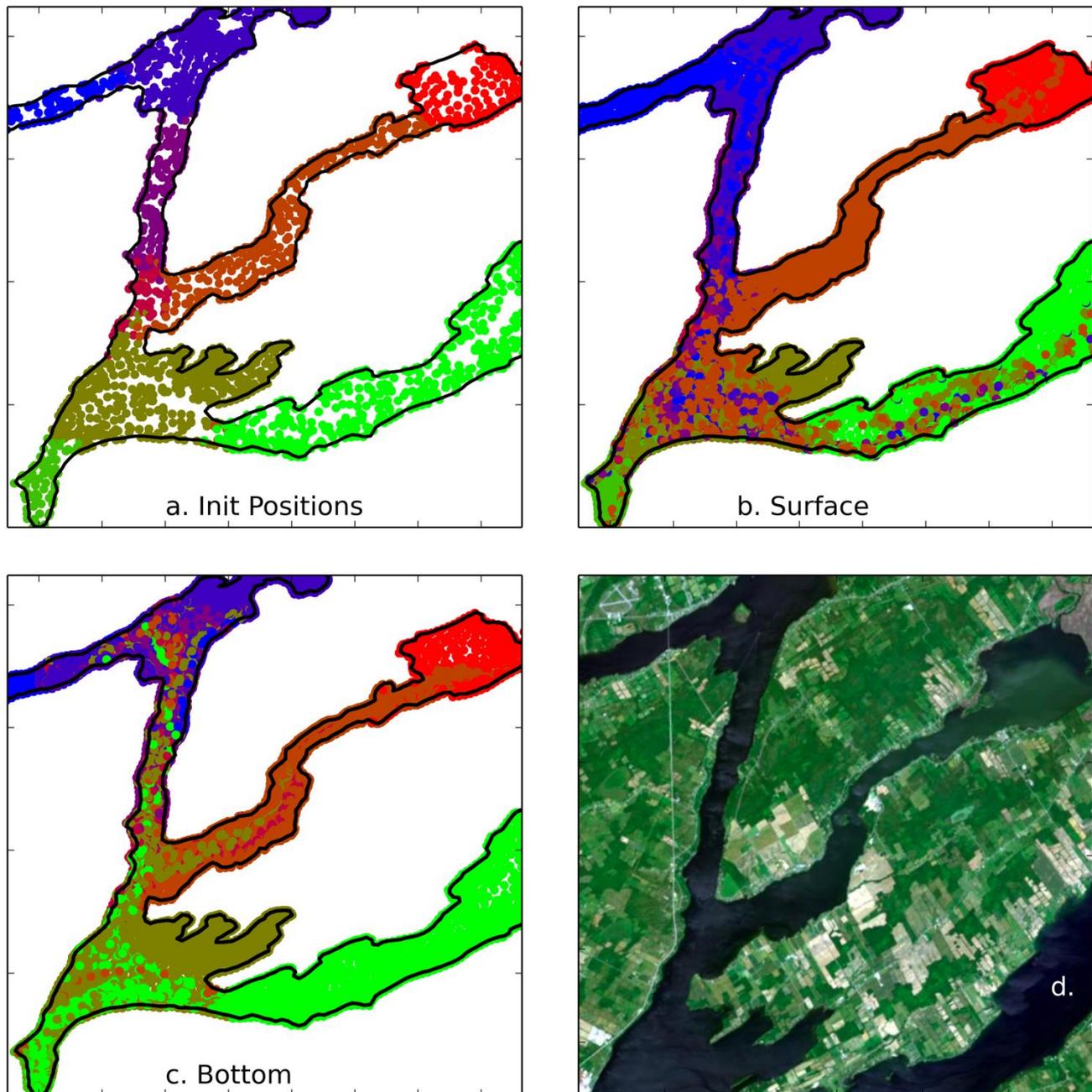


Figure 6. Simulated particle movement from May to June 2018: (a) initial particle positions and designated colours, maps of overlaid particle positions for (b) surface particles and (c) bottom particles, at the end of June 2018. (d) Landsat satellite image of Hay Bay on 29 June 2018 (<https://livingatlas2.arcgis.com/landsatexplorer/> (accessed on 19 April 2020)) (Agricultural Color Image Setting).

4. Discussion

Observations and modelling efforts have been used to show that the nature of the flow in middle bay is generally two-layered in summer, with significant inflow from Lake Ontario at depth. This study used observations of temperature and water speeds together with an analytical model to show that real-world hydrography was reproduced by a simple two-layer model. Because the two-layer model effectively reproduced the thermocline slope, we deduce that the primary forces maintaining the vertical structure were shears. In particular, the analytical model showed that the interface slope between the warm surface layer and cool bottom layer is sustained by a vertical velocity shear and wind stress. These two components are equally important in maintaining the two-layered flow in Longreach, but the wind was much less important in the Glenora Gap.

We used a 3-dimensional numerical model (FVCOM) to simulate the thermal structure of middle bay. Model solutions we used to identify surface and bottom transport pathways through middle bay, the water column stability and horizontal and vertical fluxes. The estimated interface slope computed from in situ observations was well reproduced by the model in late fall and more importantly put the observed temperature profiles in a larger context by showing the transects were part of a wedge of cool bottom water that extended from the Glenora Gap up into both Longreach and Hay Bay. Model velocities showed that in early May before the onset of stratification, flow in the surface and bottom layer would be toward Lake Ontario, increasing the flushing rate for the bay, but that in late summer the cool Lake Ontario water would potentially backflow along the bottom.

Estimates of Schmidt stability index and Lake Number from model output were used to illustrate that middle bay became stratified in May and that the wind was insufficient to cause mixing for more than half of July, re-enforcing the idea that middle bay is not well mixed in later summer. Fluxes for the upper and lower layers were estimated from model velocities which indicated that in June and July there was significant backflow. Current budget models studying TP loading can use these estimates to fine tune their flushing rates for middle bay and potentially account for the influence of Lake Ontario water. These results will also be useful for future studies that look at sediment transport in the bay. TP loading due to sediment reflux may be an important factor in the more sheltered embayment and studies in Lake Superior have shown that the nature of the flow from its embayments to the lake can affect sediment settling rates [29].

Modelled particle movement illustrated the ability of Hay Bay to harbor algae away from the main flushing channel. This may be important because recent sampling for microcystin toxins showed that in 2010 Hay Bay had the highest concentration of these toxins across the Bay of Quinte [30]. Particle-tracking simulations showed that the embayment provided a habitat for algae during the growing months of May through June that was sheltered from the flushing. Because Hay Bay is shallow and warm, it is able to support algae blooms which can seed algae throughout middle bay.

These results extrapolate to all the drinking water source bays around the Great Lakes that are prone to eutrophication events. Flushing and transport within these bays are regulated in part by their connection to lake while isolated embayments may exhibit distinct dynamics.

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