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Determinants of temperature in small coastal embayments of Lake Ontario

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ABSTRACT

Along 25 km of the Lake Ontario shoreline near Toronto, Ontario, small coastal embayments (0.4–32 ha) have been constructed or modified by lake-infilling to restore warmwater fish habitat. The variation in thermal habitat quality for warmwater fishes among these embayments is very high; temperatures range from those found within a small pond to those of much cooler Lake Ontario. Since meteorological conditions and surface heat fluxes are almost identical, the temperature variation among embayments must be caused by differences in bathymetry or exchange with Lake Ontario. However, a previous study on these embayments found paradoxically that temperatures were not strongly associated with channel size or embayment bathymetry. This paper resolves the paradox by showing that flushing times for almost all of the constructed embayments were less than 1 day, and often less than 12 h. With so little time to warm within the embayments, water temperatures of almost all embayments remained very close to the temperatures of the adjacent lake waters. The coldest embayments connected directly to open Lake Ontario and warmer embayments connected to Lake Ontario through other embayments or protected harbors, where the inflowing water from Lake Ontario had already substantially warmed. To allow embayments along the exposed shoreline of Toronto to reach acceptable temperatures for warmwater fish, we use heat budgets to calculate that average summer flushing times must be increased from their current length of 1.5 to 5.5 h to approximately 30 h. Such changes could be achieved through large reductions in the channel cross section.

Introduction

Since 1986 Canada's Fisheries Act has prohibited the harmful alteration or destruction of fish habitat (DFO, 1986). However, when unavoidable, harmful alteration or destruction of fish habitat can be authorized provided replacement habitats are constructed to compensate for the lost productivity. For this reason, small coastal embayments have been, and will likely continue to be constructed in the Great Lakes to replace warmwater fish habitats lost through shoreline urbanization. Unfortunately, cool thermal conditions in existing small coastal embayments appear to limit the growth potential of age-0 warmwater fishes (Murphy et al., 2011); and many small embayments are too cold to produce cohorts of age-0 fish large enough to survive their first winter (Murphy et al., 2012).

The thermal environment in coastal embayments is principally determined by the balance between heating from solar inputs, cooling from evaporation and radiative losses (Monismith et al., 1990; Rodgers and Anderson, 1961), and the exchanges of water with the adjacent lake (Murphy et al., 2011). In the Great Lakes, exchanges between the connected lake and the embayment are driven primarily by horizontal temperature or density gradients and seiche-driven changes in water level (Hamblin and He, 2003; Lawrence et al., 2004; Rueda and Cowen, 2005; Wells and Sealock, 2009). Horizontal temperature gradients establish because shallow embayments and the deeper Great Lakes have large differences in their thermal inertia (Andradóttir and Nepf, 2001; Monismith et al., 1990; Wells and Sherman, 2001). The extent of the thermal gradient varies according to local meteorological and atmospheric conditions and the occurrence of episodic cold water upwelling or warmer downwelling events (Boyce et al., 1989; Csanady, 1977; Haffner et al., 1984; Plattner et al., 2006; Rueda and Cowen, 2005).

Water level fluctuations are ubiquitous in the Great Lakes, and are primarily caused by seiche events and storm surges (Herdendorf, 1990; Trebitz, 2006). The fluctuations are usually on the order of 1 to 10 cm and occur at timescales of several hours (Trebitz, 2006; Wells and Sealock, 2009). The magnitude of exchange from water-level-driven forcing between the embayment and connected lake can be heavily influenced by Helmholtz oscillations. In embayments and harbors, Helmholtz oscillations refer to a phenomenon where, coupled by the water level in the harbor and excited by oscillations of the lake level, the inlet serves as an oscillator for the masses of

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water that flow in and out. The amplitude of the response of an embayment to water level fluctuations in the adjacent lake depends upon how closely the period of the water level fluctuation is to that of the mode of the Helmholtz resonance (Jordon et al., 1980; Miles, 1974; Miles and Lee, 1975). If the periods of the Helmholtz and external water level fluctuations are in or near agreement then a resonance in the channel will amplify the water level fluctuations within the bay, increasing lake–embayment exchange. The converse is also true, if the periods are not in agreement than the Helmholtz oscillation will serve to dampen the exchange across the channel.

The effect of lake–embayment exchange on the thermal regime of an embayment varies according to seasonal heating and cooling cycles. During the heating part of the year, the relatively shallow embayments warm quickly, so exchange with the much larger (and slower warming) Great Lake cools embayments (Rueda and Cowen, 2005). Conversely, during the cooling period of the year, embayments cool faster than the connected lake, so horizontal exchange keeps the embayments warmer than an unconnected pond of similar size (Murphy et al., 2011). In addition, at any time during the stratified summer period, cold hypolimnetic water from the lake can upwell and decrease the surface water temperature of embayments by over 10 °C in just a few hours (Lawrence et al., 2004; Murphy et al., 2011; Rueda and Cowen, 2005). Coastal upwellings are particularly common along the northwest shoreline of Lake Ontario because the predominately westerly winds force relatively frequent cold water upwellings (Rao and Murthy, 2001).

Murphy et al. (2011) found that the temperatures among the small coastal embayments (0.4-32 ha) along the northwest shoreline of Lake Ontario used in this study varied considerably; a few had temperatures that resembled those of a small isolated waterbody but 60% of them closely followed the temperatures along the exposed shoreline of Lake Ontario. Since all the embayments were located within 25 km of each other and therefore experienced similar solar inputs and meteorological conditions, the differences in their temperatures must largely be from differing amounts of water input from Lake Ontario and bathymetrically determined differences in thermal inertia.

If embayments are to create productive warmwater fish habitats then it is critical they be designed so the cooling effects of the connected lake are minimized. Trebitz et al. (2005) found a negative correlation between seiche-induced exchange flow and temperature among and within 10 small Lake Superior wetlands. Persson et al. (1994) found that simple topographical openness (the cross-sectional area of the inlet divided by the surface area of the embayment) was negatively correlated ($r^2 = 0.93$) with surface water flushing time in coastal embayments that spanned a large size range (15–15,000 ha). The findings of Trebitz et al. (2005) and Persson et al. (1994) both suggest that decreasing embayment channel size would increase embayment temperature by limiting exchange flows with the adjacent lake. However, Murphy et al. (2011) compared embayment temperature with channel size, simple topographic openness and other bathymetric variables known to correlated with embayment temperatures, and found that mean depth was the only important predictor of the variation in temperature among the small embayments that were the focus of their study. They proposed that in these small embayments the association between bathymetry and temperature was not higher because the rates of water exchange with Lake Ontario were all too high to allow substantial warming above the temperatures of Lake Ontario.

In the hope of constructing or modifying existing embayments so they create more productive warmwater fish habitats, we re-evaluate the temperature data examined by Murphy et al. (2011). Instead of trying to correlate embayment bathymetry with temperature, we quantitatively examine their hypothesis that the flushing rates of the small embayments along the Toronto shoreline are so rapid that the embayments are prevented from significant build up of solar heat inputs. We then provide suggestions for improving the thermal environments in existing and future embayments by estimating the embayment flushing times necessary to limit the cooling effects of Lake Ontario.

Methods

Study sites

We selected 14 coastal embayments, a Reference Embayment, and three open coastal and one sheltered location in Lake Ontario, along approximately 25 km of the northwest shoreline in Toronto, Ontario for this study (Fig. 1). The 14 embayments we selected are shallow (mean depth: 0.3–6.8 m), but several have been deepened by dredging to provide for boat or ship passage (Table 1). The embayments are not fed by tributaries and have almost no watersheds. The Reference Embayment is centrally located among the 14 embayments and comparable to their size, but has had its connection to Lake Ontario temporarily closed as it undergoes remediation and restoration. We used the Reference Embayment as a way of monitoring the temporal variation in local heating and cooling processes, absent the influence of exchange with Lake Ontario. The open and sheltered locations of coastline are used to establish thermal conditions outside the embayments.

Based on several years of in situ temperature monitoring, the embayments have been assigned to a thermal grouping as defined in Murphy et al. (2011). Briefly, embayments with temperatures similar to that along the exposed shoreline of Lake Ontario are in the Cold embayment group (C), those with temperatures similar to that of the Reference Embayment are in the Warm embayment group (W), and those with temperatures intermediate to the Reference Embayment and the exposed shoreline of Lake Ontario are in the Intermediate embayment group (Int). The embayments within each thermal grouping are identified by ascending numbers from warmest to coolest.

Water temperature data

In 2008, we used submersible temperature loggers with ±0.2 °C accuracy (Optic StowAway or Hobo U22 Water Temp Pro v2 by Onset Computer Corporation) to measure water temperatures in the Reference Embayment, Lake Ontario and the 14 embayments (Fig. 1). Loggers were deployed in early spring and retrieved in late fall. Temperatures were recorded at half-hour intervals at 1 meter from the surface, unless stated otherwise.

We obtained the temperature along the exposed shoreline of Lake Ontario by averaging temperatures from three data loggers (Fig. 1: L1, L2, L3), spanning 25 km of exposed Toronto shoreline. Murphy et al. (2011) showed that there was low spatial variation in surface temperatures along the exposed Lake Ontario shoreline, so that even a single logger deployed along the open coast is a suitable indicator of the surface water temperatures along the entire exposed shoreline of Toronto. However, a number of the coastal embayments in this study are located within sheltered areas, protected by the peninsula of Tommy Thompson Park (Fig. 1: W-1, W-4, Int-1, Int-2, Int-3, C-1) and the Toronto Islands (Fig. 1: W-2, W-3). These sheltered embayments may not be exposed to waters as cool as those along the exposed shoreline of Lake Ontario. To determine the temperature in the area of Lake Ontario sheltered by Tommy Thompson Park, we collected the water temperature at the surface (1 m), middle (5 m), and bottom (9 m) of the water column in Toronto's Outer Harbor (Fig. 1, panel II inset: *a*).

We collected vertical temperatures profiles in C-8 and Int-2 to determine the strength of thermal stratification in embayments. C-8 and Int-2 were instrumented because they were among the only embayments that were deep enough to stratify (Murphy et al., 2011), and thermistor chains could be deployed at or near the