ARTICLE IN PRESS

Marine Pollution Bulletin xxx (2011) xxx–xxx

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

The dilution and dispersion of ballast water discharged into Goderich Harbor

Mathew G. Wells[a,*], Sarah A. Bailey[b,c], Barry Ruddick[d]

[a] Department of Physical and Environmental Sciences, University of Toronto Scarborough, Toronto, Ontario, Canada M1C 1A4
[b] Great Lakes Laboratory for Fisheries and Aquatic Sciences, Fisheries and Oceans Canada, 867 Lakeshore Road, Box 5050, Burlington, Ontario, Canada L7R 4A6
[c] Great Lakes Institute for Environmental Research, University of Windsor, 401 Sunset Avenue, Windsor, Ontario, Canada N9B 3P4
[d] Department of Oceanography, Dalhousie University, Halifax, Nova Scotia, Canada B3H 4J1

ARTICLE INFO

Keywords:
Biological invasions
Great Lakes
Harbors

ABSTRACT

Observations are presented on dilution and dispersion rates of ballast water discharged under normal operational conditions at the semi-enclosed port of Goderich, Ontario. The ballast water was tagged with Rhodamine-WT dye and microscopic magnetically-attractive tracer particles. Maximum concentrations of dye immediately after discharge were diluted to 1–5% of initial ballast tank concentrations, and within 3 days had decreased to less than 0.1% of initial concentrations. Inside the harbor, there was 10–20% of the ballast water still present after 2 days, consistent with a flushing rate of 0.8–1.15 day^{-1}. Magnetic particles were collected up to 7.5 km outside the harbor after one day, consistent with a dilution factor of order 10^5 outside the harbor. The results of this study are discussed in the context of ballast water discharge standards proposed by the International Maritime Organization to minimize the introduction of aquatic nonindigenous species through ships' ballast water and sediments.

1. Introduction

Ballast water carried by commercial ships is presumed responsible for 55–70% of aquatic nonindigenous species' (ANS) introductions to the Great Lakes since 1959 (Holeck et al., 2004; Ricciardi, 2006; NRC, 2008). Beginning in 1989, various voluntary and mandatory ballast water management practices have been introduced to ameliorate the risk of ship-mediated introductions to the Great Lakes (e.g., USCG, 1993, 2004; Government of Canada, 2006). An international convention to regulate ballast water discharges was also adopted to reduce ballast-mediated introductions globally, primarily through the use of physical and/or chemical treatment systems (IMO, 2004; Lloyd's Register, 2010). The international convention, once ratified, will set density-based discharge standards, including a standard applicable to zooplankton (<10 individuals greater than 50 μm in minimum dimension per m^3, summed over all species; IMO, 2004).

The theoretical efficacy of the proposed standard is based on 'propagule pressure theory', wherein establishment success is positively related to characteristics of the propagule supply (i.e., the total number of propagules released and frequency of inoculation events; see Simberloff, 2009). For sexually-reproducing taxa, this relationship can be understood in terms of basic population demographics, such as birth and death rates, immigration events and Allee effects. The expectation is, that if the number of propagules in ballast water can be reduced below some threshold inoculum size, then the population growth rate becomes negative and the probability of successful establishment will be zero (Drake and Lodge, 2006; Bailey et al., 2009). Empirical evaluation of the proposed ballast water discharge standards is extremely difficult because threshold densities for successful establishment are unknown, and are likely species- and perhaps system-specific (see Bailey et al., 2009).

Understanding the spatial dispersion of propagules post-discharge further complicates estimates of establishment probability. After the initial release of ballast water, the growth of introduced populations will depend upon how rapidly the population can increase through reproduction, compared to the rate at which the density decreases due to losses, such as through physical dispersion of aquatic organisms. If a population is dispersed faster than it can reproduce, then the population density will decrease until extinction. Conversely, a population discharged into a habitat that supports a reproduction rate which is greater than the rate of loss can increase in density and establish a local foothold (Reynolds, 1984; Lewis and Kareiva, 1993; Drake et al., 2005; Pringle et al., 2009). Introductions into sheltered areas may increase establishment probabilities of low-density inocula if the inoculum is maintained within a cohesive unit of water (see Reynolds, 1984; Drake et al., 2005). As an example, in the Great Lakes, ballast water is almost exclusively discharged while ships are at port – often sheltered areas with limited rates of water exchange.

This report describes the spatial dispersion of ballast water after discharge into a semi-enclosed port, with a view to improve under-

---

* Corresponding author.
E-mail address: wells@utsc.utoronto.ca (M.G. Wells).

0025-326X/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.marpolbul.2011.03.005

Please cite this article in press as: Wells, M.G., et al. The dilution and dispersion of ballast water discharged into Goderich Harbor. Mar. Pollut. Bull. (2011), doi:10.1016/j.marpolbul.2011.03.005

standing of the dispersal of released propagules. While there have been numerical simulations of the spread of ballast water after release (Larson et al., 2003; Brickman, 2006; Brickman and Smith, 2007) and some technical literature is available on the short-range dilution of ballast water (Reynolds, 2005), this report is the first study to empirically examine dilution and dispersion of ballast water in the context of species' introductions. Results are presented from an experiment in 2008 designed to measure and quantify (a) the dilution rate of ballast water post-discharge; (b) the residence time of ballast water in Goderich Harbor; and (c) the transport of propagules over large distances outside the harbor. Dye and magnetically-attractive particles were used to track discharged ballast water and to estimate residence time of water in Goderich Harbor. The residence time in the harbor is then compared to biological growth rates of zooplankton species, and a discussion is presented of the impact of dilution rates as a potentially important factor in determining the risk of ANS establishment.

2. Approach

The competition between growth and dilution can be expressed mathematically, where the rate of change in the population density (D) of an aquatic species can be written as

$$\frac{\partial D}{\partial t} = -\text{physical dilution rate} + \text{net biological growth rate}. \qquad (1)$$

This equation can also be thought of as a comparison of two timescales; where the physical dilution rate can be expressed in terms of a hydraulic residence timescale and the biological growth rate can be expressed in terms of the doubling timescale of plankton (Reynolds, 1984) or the development period of higher organisms (Banas et al., 2009). If the hydraulic residence timescale is longer than the doubling timescale, then the population density will increase and an introduced species could establish itself. Carr et al. (2004) demonstrated the utility of this model in a study of zebra mussel (*Dreissena polymorpha*) larval retention in an embayment of the tidal Hudson River. The study indicated that zebra mussels could form a local, self-sustaining population since a sufficient percentage of larvae were retained long enough for self-recruitment of the population to occur. Such local populations are important for the spread of an invasive species as they can lead to significant downstream recruitment in rivers (Reynolds, 1994). A related study by Banas et al. (2009) investigated the circulation and flushing patterns of Willapa Bay, Washington, USA, in order to better understand the population dynamics of the invasive European green crab (*Carcinus maenas*). Banas et al. (2009) determined that there were specific locations within the bay where the establishment of a substantial breeding population could result in self-recruitment and long-term persistence of a local population. In order to use Eq. (1) for the purposes of this study, an estimate is required of typical dilution and dispersion rates for ballast water releases in the Great Lakes or elsewhere.

Fig. 1 presents a conceptual diagram of three potential scenarios for the invasion success of an invasive species as a function of the cumulative number of individuals introduced (inoculum density). The transverse dotted line represents the case where there is a linear relationship, so that a 10% reduction in inoculum density leads to a 10% reduction in invasion success. The risk of establishment for most species, however, is unlikely to follow the straight line. For sexual species there will be a rapid reduction in risk if the inoculum density drops below some critical threshold. This relationship is illustrated by the lower exponential curve, for which invasion risk is much lower at vertical line A (below threshold) than vertical line B (above threshold). In contrast, the establishment risk for asexual species may be better represented by the upper curve, whereby there is not a critical threshold where the risk drops dramatically (or the threshold is extremely low). In practice, the relationship likely will vary for different species and systems, taking some intermediate form between the two extremes. Because the invasion process occurs over a length of time, it is not solely the initial inoculum density which determines establishment success, but also physical processes affecting population density after introduction, such as the retention timescale in the recipient environment.

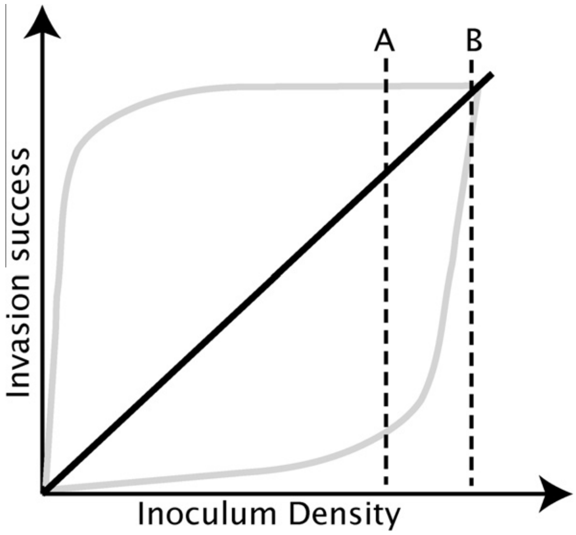

Fig. 1. A conceptual model of the relationship between invasion success and inoculum density (after Lockwood et al., 2005). The straight diagonal line represents a linear relationship whereby a 10% reduction in inoculum density (moving from vertical line B to vertical line A) would equal a 10% reduction in invasion success. In reality, most taxa would fit between the upper (parthenogenetic or asexual species) and lower (sexual species subject to Allee effects) curves. Thus a reduction in concentration of inoculum density from B to A, is expected to have a much greater impact on sexual species (lower line) than asexual species (upper line).

3. Methods

3.1. Field location

Two dye releases were conducted in July 2008 to determine the dilution rate of ballast water released from two commercial vessels at Goderich, Ontario. Goderich Harbor is located at 43°44′42″ N, 81°43′14″ W, on the eastern shore of Lake Huron, and is one of ~120 commercial ports in the Great Lakes – St. Lawrence Seaway (Rup et al., 2010). Goderich represents one of the more extreme (most at risk) cases of interest, being one of the smallest, most enclosed ports in the system; however, there are numerous ports with similar sheltered infrastructure to which these results could be extended (e.g., Kingsville, ON, Calumet Harbor, IL, Cleveland, OH). An aerial photograph of the harbor is shown in Fig. 2. The important features of the harbor are the relatively confined inner harbor of area 200 m by 400 m, that is connected through the narrow channel (60 m wide and 450 m long) to a larger area of water (500 m by 500 m) that is protected from the waves in Lake Huron by two breakwalls. The first ballast release occurred from the Great Lakes bulk carrier M/V Algoway at 15:00 on July 16, 2008. The second ballast release started at 6:00 on July 21, 2008 from the Great Lakes bulk carrier M/V Capt. Henry Jackman.

3.2. Rhodamine-WT dye

Rhodamine-WT dye was used to measure the short-range spread and dilution of the ballast water. Rhodamine-WT dye is a

Please cite this article in press as: Wells, M.G., et al. The dilution and dispersion of ballast water discharged into Goderich Harbor. Mar. Pollut. Bull. (2011), doi:10.1016/j.marpolbul.2011.03.005

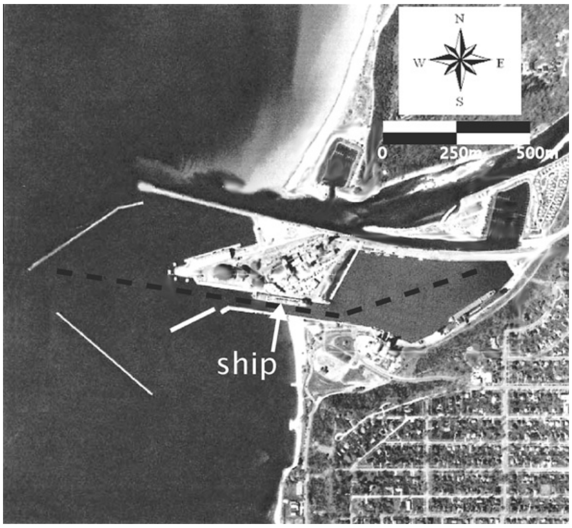

Fig. 2. An aerial photograph of Goderich Harbor. The repeated transects of dye concentration were taken along the dashed path. The ship in the center of the photograph is docked at the same location as the vessels used for this study.

synthetic, non-toxic red dye that has a bright red-orange fluorescence and is commonly used as a tracer within water to measure complex diffusion patterns in large lakes and oceans (e.g., Murthy, 1976; Stevens et al., 2004; Carr et al., 2004). The dye is visible to the naked eye at concentrations as low as 30–40 ppb and below 10 ppb meets US Environmental Protection Agency drinking water intake standards. For each experiment, the dye was introduced into one ballast tank of a large, self-unloading bulk carrier immediately before uptake of ballast water at the port-of-call immediately prior to Goderich. The turbulence associated with loading ballast into the tanks and the movement of the ship underway thoroughly mixed the dye into the ballast water by the time the ship arrived at Goderich.

During the first dye release, 7.1 l of dye was added to a ballast tank having a ballast capacity of 940 m^3, while 10.6 l of dye was added to a 910 m^3 tank for the second dye release. With these volumes, initial Rhodamine concentrations in the tanks were 1563 ppb and 2446 ppb, respectively. In both cases the ballast water was released under standard operational conditions during loading of cargo; the ballast tanks were discharged in pairs through a single discharge pipe, resulting in an immediate dilution factor of 50% before the dyed water left the ship. The exterior discharge outlet of both vessels was below the water surface during both dye releases. The dye concentration was measured in the recipient harbor water using a Seapoint Rhodamine sensor interfaced with an RBR CTD (conductivity, temperature and depth) unit, which also recorded temperature, conductivity, pressure and turbidity. The Seapoint sensor can accurately measure dye concentration over the range of 0.02–150 ppb and can sample every second. Due to weak background fluorescence of water at Goderich, our measurements were limited to concentrations at or above 0.2 ppb. The CTD was interfaced with a global positioning system to record the position of each measurement taken. Towing the sensor at 2 m depth, from the side of a small 5 m long vessel traveling at very slow speeds of 5 km h^{-1}, allowed for repeated transects of the dye concentration over the 1.5 km path shown in Fig. 2. Due to the small vessel size, and very low vessel speed, our measurements made negligible contributions to mixing in the harbor.

The weather was relatively calm during both dye releases, with no rain. Mean winds were from the west with a speed of 3 m s^{-1}, and with a diurnal wind pattern that peaked at speeds of 6–8 m s^{-1} in the afternoons. The mean air temperature was 20 °C, i.e., close to mean surface temperatures of Lake Huron during the summer. Due to the breakwalls there were no waves within the harbor.The main mechanisms for water exchange from a sheltered port in the Great Lakes are due to wind driven currents and thermal gradients (Lawrence et al., 2004; Rueda and Cowen, 2005; Wells and Sealock, 2009). The hydraulic residence time of the water can be estimated by measuring the mean concentration of ballast water in the harbor over time. Such an approach has been used in many estuarine circulation studies, whereby the concentration of a conservative tracer is used to estimate flushing rates of the estuary. For example, Austin (2002) used measurements of the mean concentrations and fluxes of salt and nitrogen to estimate a residence time in Chesapeake Bay. A related study by Wells and Sealock (2009) also used measurements of mean concentration and flux of salt to determine the residence time of water in a shallow embayment connected to Lake Ontario. For a harbor of volume V, having a well-defined mean exchange rate $\bar{Q}$ with the surrounding water, the rate of change of the areal mean concentration of dissolved material in the harbor ($\bar{C}_{\text{harbor}}$) can be written as

$$\frac{d\bar{C}_{\text{harbor}}}{dt} = -\frac{\bar{Q}}{V} \times \left(\bar{C}_{\text{harbor}} - \bar{C}_{\text{lake}}\right) \qquad (2)$$

where the overbar denotes a spatial average. In this equation it is assumed that the concentration of ballast water in the lake is essentially zero due to rapid dispersion in the very large body of water. If we assume that the harbor is close to being well-mixed (due to wind driven currents and possible boat movements) on a timescale faster than the hydraulic residence timescale, and that the exchange rate of water between the harbor and the lake is constant, then the mean concentration in the harbor will decrease exponentially as $\bar{C} = C_o e^{-t/T}$, where C_o is the initial mean concentration and the mean hydraulic residence time is defined as $T = V/\bar{Q}$ (Monsen et al., 2002). Implicit in this solution is that the dye distribution within the harbor is sufficiently well mixed that the concentration near the harbor opening (which determines dye loss) is fairly close to the mean concentration $\bar{C}$. These assumptions are reasonable for the relatively small Goderich Harbor, but may not hold for larger ports in the Great Lakes and elsewhere. The importance of this hydraulic residence timescale is that it is the relevant timescale to compare with biological growth rates in Eq. (1). If the hydraulic residence timescale of the harbor is longer than the e-folding timescale of a potential biological invader and the habitat is suitable, then the harbor is at risk for successful establishment.

3.3. Magnetically-attractive particles

To determine the long-range spread and dilution of ballast water, small (200–400 μm) magnetically-attractive particles (MAPs) were released into the ballast water as it was pumped from the ship. The magnetically-attractive particles combine glass microspheres for flotation with fine magnetite plus a non-toxic binding agent. The microsphere to magnetite ratio was adjusted so that the particles are close to neutrally-buoyant in fresh water and therefore mimic the buoyancy characteristics (slight, but positive, rise-rate) of biological propagules. The novelty of these particles is their ability to be used for long-range dispersion measurements (Ruddick and Taggart, 2006). When the particles drift and disperse in the near-surface of the water column, they can be collected using inexpensive autonomous moored magnetic collectors designed to float near the water surface. The collectors consist of flow-through tubes of 5.5 cm × 5.5 cm cross-section, with rare-earth magnets strategically placed such that any MAPs will be caught and retained with greater than 90% probability in <0.8 m s^{-1} currents. The collectors were moored in place prior to the release of particles and retrieved at the desired time interval after each release. The particle numbers from each collector are analogous to the time integral of concentration multiplied by the

Please cite this article in press as: Wells, M.G., et al. The dilution and dispersion of ballast water discharged into Goderich Harbor. Mar. Pollut. Bull. (2011), doi:10.1016/j.marpolbul.2011.03.005

current speed, with the advantage that particles are more immune to dilution than most dyes and hence can be detected at longer range. In a unidirectional flow, concentration times speed is the particle flux (the most desirable quantity to result from experiments). Knowledge of the flow time history is required to reconcile concentrations and capture in non-steady flow; we use non-coincident ADCP observations for this purpose in Section 4.3.

The MAPs were not introduced to the ballast tanks at the same time as the dye since they are slightly positively buoyant and may have floated to the surface layer of ballast water during the ships' transit. Instead, prior to each experiment, a 1.27 cm (0.5 inch) low density polyethylene tube was installed through the deck vent of the (empty) ballast tank so that a slurry of water and MAPs could be introduced to the ballast water as it was being discharged from the tank; the discharge end of the tube was secured to the bell-mouth of the ballast piping system, such that MAPs injected through the tube would be immediately mixed into the outgoing ballast water.

During each of the two releases, 14 kg ($\sim 10^9$) particles were released into approximately 1000 m^3 of ballast water, so that the initial concentration released from the tank would be $\sim 10^6$ particles m^{-3}. For the first dye release, MAP collectors sampled for 92 h. Collector magnets were changed between releases, with collectors sampling 29 h for the second release. The collectors were deployed at locations up to 7.5 km to the north and south of Goderich as shown in Fig. 3. The collectors were arrayed in two rows parallel to the shore near the 5 m and 7 m isobaths, with roughly logarithmic alongshore spacing.

4. Results and discussion

4.1. Dye observations

Dye concentration along the sampled transect, at different time points after the initial ballast water release, are shown in Fig. 4 as a function of distance. The release location is marked on the x-axis with an arrow in each subplot, and the inner harbor is located between 0 and 600 m. After approximately 8 h the concentration of dye is nearly horizontally uniform within the inner harbor. Vertical profiles (not shown) also determined that the water column was fairly uniform vertically, so that the measurements made in the transects at 2 m depth were representative of the whole water column. The percent dilution of the dye concentration over time is plotted for each dye release with different symbols in Fig. 5, with the error bars displaying the range (minimum and maximum values) of dye concentrations observed. The concentrations of dye are normalized by the initial dye concentration of 1563 ppb and 2446 ppb inside the ballast tanks. The percentage of dyed ballast water observed along each transect is plotted in Fig. 6. There are three main points that can be drawn from the data for both dye releases. Firstly, the peak concentration of dye rapidly decreases with time, indicating dilution of the ballast water. Secondly, a large proportion of the dyed water slowly moved west out of the harbor. Thirdly and most importantly, a significant amount of the dyed ballast water moves into the inner harbor, so that as much as 20% of the ballast water is still present after 2–3 days, as shown in Fig. 6. The concentration of the dye at long timescales is low, so that at 90 h post-release, the maximum concentration is only 0.5 ppb, representing a dilution factor of 4000 from the initial concentration. As the volume of the inner harbor is much larger than the ballast tank, even this low concentration represents a large proportion of the discharged ballast water. Similar observations were seen for the second dye release, where after two days the peak concentration of dye was diluted by a factor of about 1000 from the initial release concentration. In both cases, during the initial phase of the release, there was a rapid dilution in the first 10s of meters from the discharge point due to turbulence of the outflow jet, and the peak concentration dropped by several orders of magnitude compared to that inside the ballast tanks. After this rapid initial mixing, there was a much slower decay in the peak concentration of dye as the ballast water slowly mixed through the rest of the harbor. The data in Fig. 4 shows that the harbor is not completely mixed at any particular time point, as there is a range of observed dye concentrations. Particularly at early time points after the release, the distribution of ballast water in the harbor is somewhat patchy, as is commonly observed during early stages of stirring, but the concentration is close to uniform after one day. The turbulent diffusivity within the harbor can be estimated by calculating the variance σ of dye concentration along each transect, and then estimating the horizontal diffusivity as $K = 1/2\partial\sigma^2/\partial t$ (Murthy, 1976). From data in Fig. 4 we estimate that the diffusivity has a value in the range of $K = 1.2 \pm 0.8\ \mathrm{m}^2\,\mathrm{s}^{-1}$. This value is consistent with other estimates of horizontal diffusivity from other dye release experiments in lakes and the coastal ocean where $K = 0.1 - 1\ \mathrm{m}^2\,\mathrm{s}^{-1}$ for horizontal scales of order 1 km (Murthy, 1976). With a turbulent diffusion approach, the width of the dye patch can be considered to grow as a Gaussian cloud, so that 95% of the dye will be within a length-scale $L = 4\sigma = 5.6\sqrt{Kt}$. Hence with $K = 1\ \mathrm{m}^2\,\mathrm{s}^{-1}$, we can estimate that the time-scale for the dye cloud to spread over the width of the harbor ($L \sim 100$ m) is roughly 5 min and the timescale for diffusion over the length of the harbor ($L \sim 1$ km) is roughly 8 h.

Fig. 3. Location of magnetically-attractive particle collectors relative to the Port of Goderich. The square highlights the region shown in Fig. 2.

4.2. Residence timescale calculations

Based upon the observed change in average dye concentration with time, the average hydraulic residence time of the inner harbor can be estimated from Eq. (2) as $T = -t \times \log(C_o/\bar{C}(t))$. The error bars in Fig. 6 represent upper and lower bounds on the total mass of dye observed based upon the ranges shown in Fig. 5, which in turn leads to the range of estimated hydraulic residence time-

Please cite this article in press as: Wells, M.G., et al. The dilution and dispersion of ballast water discharged into Goderich Harbor. Mar. Pollut. Bull. (2011), doi:10.1016/j.marpolbul.2011.03.005

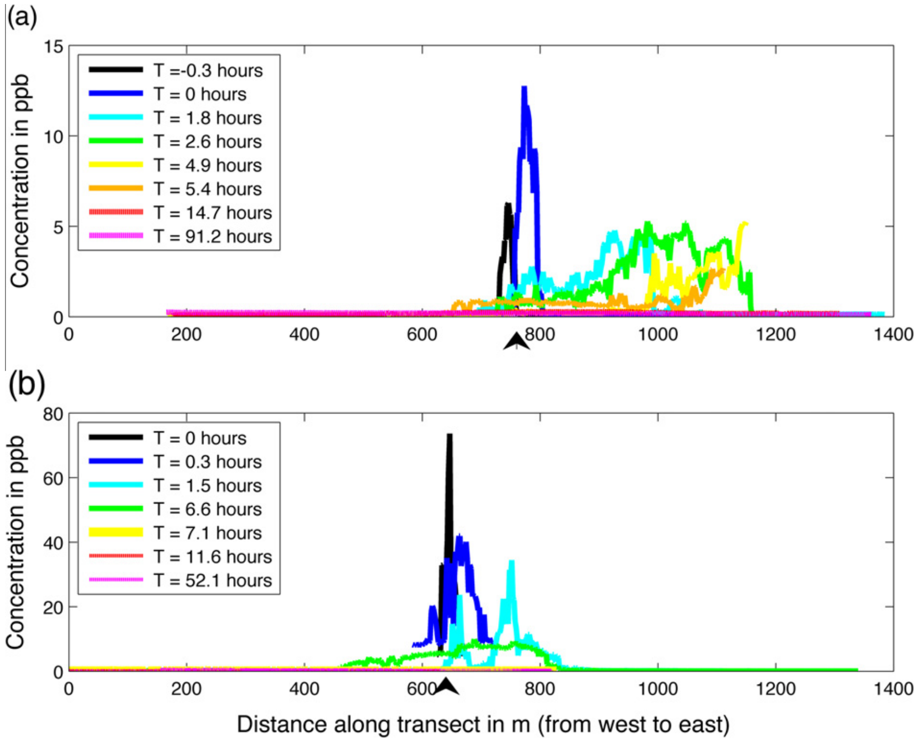

Fig. 4. Concentration of dye, as a function of distance along the transect shown in Fig. 1, for (a) the first dye release starting on July 16 and (b) the second dye release starting on July 21. The transects were made from the inner harbor (east) out to the breakwalls in Lake Huron (west) as shown on Fig. 1. The position of the ships' discharge is marked on the *x*-axis with arrows at *x* = 800 m in (a) and *x* = 650 m in (b).

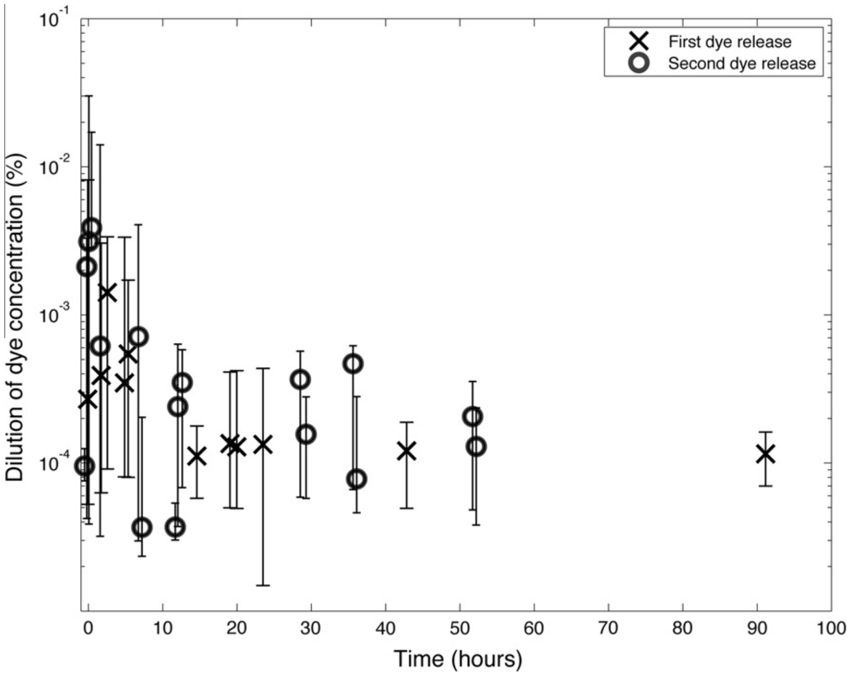

Fig. 5. The observed concentrations of dye are normalized by the predicted value of the undiluted ballast water and are plotted as a function of time after ballast water release from the ship. The symbols represent mean dye concentration and the error bars represent the range of values observed.

scales. We note that due to the patchy distribution of dye within the harbor, it is not until about 8 h after the dye release that we account for almost all of the dye from the dye release. After this time the dye has a fairly uniform distribution throughout the harbor, so that equation 2 is relevant. Using data from Fig. 6, we find that inside the harbor 10–20% of the ballast water was still present after 2 days, consistent with a flushing rate of 0.8–1.15 day^{-1} and a residence timescale of 0.86–1.25 days. Such a residence timescale is comparable to a simple estimate of V/Q based upon an exchange velocity of order 5 cm s^{-1} and the volume of the harbor. The exchange of water between Lake Huron and the protected inner Goderich Harbor is likely to be similar to many other enclosed har-

Please cite this article in press as: Wells, M.G., et al. The dilution and dispersion of ballast water discharged into Goderich Harbor. Mar. Pollut. Bull. (2011), doi:10.1016/j.marpolbul.2011.03.005

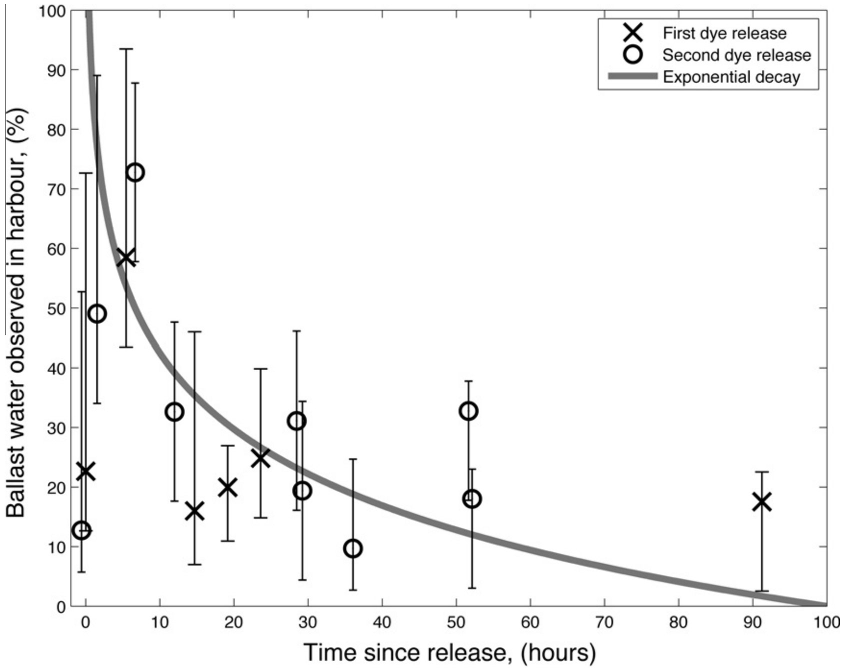

Fig. 6. Percentage of dyed ballast water observed as a function of time for the two experiments. Shortly after the ballast water releases, up to 80% of the dye can be accounted for in our transect observations. Due to flushing of the harbor by exchange of waters with Lake Ontario, only 10–20% of the ballast water is observed after 2–3 days. Note that the total mass of ballast water decreases at a much slower rate than the peak concentrations shown in Fig. 4.

bors or embayments in the Great Lakes where a combination of seiche driven water level fluctuations, horizontal temperature gradients or wind driven currents drive exchange (Lawrence et al., 2004; Rueda and Cowen, 2005; Trebitz, 2006; Wells and Sealock, 2009). Based on concurrent CTD measurements taken along the transects, there was a mean temperature difference of 1.5 °C between the inner harbor (mean temperature 23.5 °C) and Lake Huron (mean temperature 22 °C), which could drive baroclinic exchange flow. The velocity of these exchange flows is of the order $U = 1/4\sqrt{gH\Delta\rho/\rho}$, where g is gravity, H is the channel depth and $\Delta\rho$ is the density difference between the harbor and the lake (Lawrence et al., 2004). With a 1.5 °C temperature difference between the harbor and the lake, water currents of order 5 cm s^{-1} can slowly flush the harbor on a timescale of hours to days. During our study period we believe that baroclinic exchange dominated the flushing. However during other times of the year potentially important mechanisms for mixing and flushing the harbor include shipping traffic, wind driven circulation, surface seiches and cold upwelling events. During our experiments, there was only ever one large freight ship moving into the harbor within a 3 day period, so freight ships and associated tug boats had small impact on long-term flushing but would have been important for mixing dye within the harbor. Wind driven currents may have been important in driving surface circulation comparable in magnitude to the baroclinic circulation. For instance, George (1981) found that a 3 m s^{-1} wind would drive a 4.5 cm s^{-1} current in the top meter of the water column of a lake. If there is a return flow at depth in the 8 m deep channel, then the total exchange flow due to these mean wind speeds would be approximately a quarter of that due to the temperature driven exchange flow. Upwelling events of the thermocline are frequent in some parts of Lake Huron (Wells and Parker 2010), however we saw no strong events during our field experiments in Goderich, so these will not be important in determining the hydraulic residence timescale. Likewise the magnitude of surface seiches in Lake Huron was less than 0.1 m at Goderich Harbor (Canadian Hydrographic Service), so will not be important in driving flushing in the 8 m deep harbor.

4.3. Particle dispersion

The number of particles collected as a function of the north–south distance from the harbor is plotted in Fig. 7. The particle numbers were in the range of $\sim 10^4$ for collectors located within one to two hundred meters of the release site, and of the order of 10^2 for collectors located within 1–3 km from the release site. The first dye release resulted in few particles collected to the south of Goderich Harbor and $\sim 10^2$ particles collected at most sites located to the north, suggesting dominant northward transport by a coastal current exceeding 2 cm s^{-1} (8 km/4 days). In the second dye release the distribution of collected particles was symmetrical, with a horizontal scale of approximately 2 km. A possible explanation for the change in distribution between the two experiments is the known presence of inertial oscillations. The currents in the near-shore region of Lake Huron are dominated by reversing currents (Rao and Schwab, 2007). A shift in the wind from SW to NW between the first and second releases may also have led to the different distribution in the collected particle densities.

Furthermore, the dispersion of MAPs, and ballast water, outside of Goderich Harbor will be influenced by circulation patterns in Lake Huron. The summer circulation in Lake Huron is characterized by a net anti-cyclonic circulation, so that the mean current flows to the north near Goderich with speeds up to 10 cm s^{-1} (Beletsky et al., 1999; Schertzer et al., 2008). A very limited set of three drifter deployments were made during the field experiment in order to estimate current speeds during the 2008 experiments. The surface water currents were oriented parallel to the coast, with peak velocities of order 10 cm s^{-1}. The current direction changed on timescales of order one day, consistent with Rao and Schwab (2007).

The spread of particles observed over one day suggests that the spatial probability of dispersal, the “dispersal kernel” (Cowen et al., 2006), for biological propagules leaving Goderich Harbor is approximately ±2 km from the source in one day. The observation that the scale of observed dispersion after 1 and 4 days are similar may be related to the observation that the long-shore currents are dominantly near-inertial period ($T \sim 17$ h) with amplitude in the range

Please cite this article in press as: Wells, M.G., et al. The dilution and dispersion of ballast water discharged into Goderich Harbor. Mar. Pollut. Bull. (2011), doi:10.1016/j.marpolbul.2011.03.005

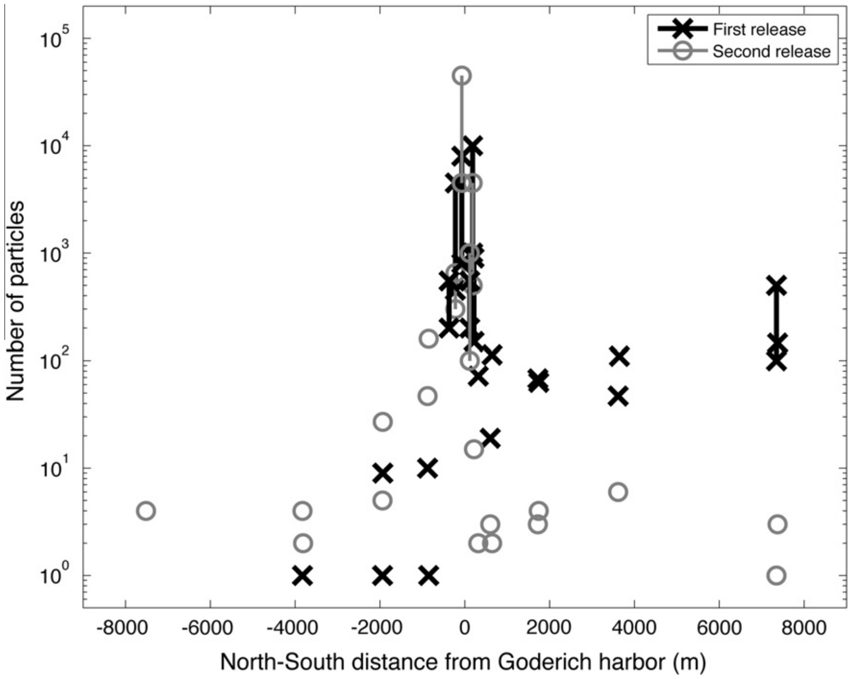

Fig. 7. Distribution of particles in the North–South direction from the ballast water release at Goderich Harbor. After the first dye release the MAP collectors sampled for 92 h and 29 h for the second. Maximum particle numbers were up to 500 at distances of 8 km.

of $U \sim 10$ cm s^{-1} (Rao and Schwab, 2007), an observation supported by ADCP measurements from July 2007 (Todd Howell, Ontario Ministry of Environment, pers. comm., 2008). Such a current can displace water parcels a peak-to-peak distance of $UT/\pi = 2$ km, resulting in rapid apparent dispersal over a few days, but with less rapid dispersal at longer timescales. If the released particles are spread uniformly over a depth of 5 m, then the particle density of 10^9 particles in a volume of (5 m $\times$ 10^7 m^2) = 20 particles m^{-3}, a dilution factor from the equivalent in-tank concentration of 5×10^4. For comparison, the maximum dilution rates measured inside the harbor using dye were an order of magnitude lower and were at the detection limit of the fluorescence sensor. In a current of 5 cm s^{-1}, a collector having an aperture of (5.5 cm)^2 would sweep 15 m^3 day^{-1} of water, and thus capture 300 particles in a day, consistent with observed captures. An alternative calculation assumes that all particles reside within 5 cm of the surface, rather than being spread uniformly over a 5 m depth. Considerations similar to those above result in expected captures of 30,000 particles per day. The observed captures are a factor of 100–300 smaller than this value. There are several possible reasons for this difference, the particles may have been sufficiently neutrally buoyant that the ambient turbulence caused them to be distributed throughout the water column or that the observed onshore winds (SW for release 1, NW for release 2) may have pushed a majority of particles towards shore beyond the collector array. The large number of particles lost to shoreline could serve as an estimate of the number of ANS propagules introduced to nearby shoreline habitat. Thus, nearby shores may be at risk for introductions from the ballast water release itself – in addition to secondary spread of invaders able to successfully establish in the harbor itself. It should also be noted that because the magnetic collector method is new and relatively unproven, there may be unknown subtleties to the technique that may account for the discrepancy.

4.4. Discussion

Peak concentrations of dyed ballast water inside Goderich Harbor (as measured along the transects) were diluted by a factor of order 10^3 after 1 day. Outside the harbor ballast water was diluted by at least a factor of 10^4 from the initial concentration in the ship. This rapid initial dilution rate is expected as high rates of mixing should occur as ballast water exits the ship as a high velocity jet. Comparable observations of high mixing rates were made by Reynolds (2005), who found dilution of dyed ballast water by at least a factor of 44 within the first 15 m from the ship. Most of the mixing of ballast water occurs within a short amount of time as the water leaves the ship, with subsequent dilution (both within and outside the harbor) occurring more slowly since there were no strong currents near Goderich during the period of each release. While the dilution rates observed here are quite high, there was also a long retention timescale for ballast water in the harbor, with 10–20% of the total ballast water still present in the harbor after 3 days. The growth of an introduced ANS population from a potential ballast water release point depends on the relative rates of growth (through reproduction) compared to dilution (due to physical mixing), as described by equation 1. Thus releasing ballast water inside a confined harbor is more risky than releasing in open waters due to the long retention timescales.

It is useful to think about the results of this study in the context of ballast water management, asking what would be the maximum density of propagules if released ballast water contained an initial propagule density near the IMO standard of <10 individuals m^{-3}. The initial dilution of the ballast would immediately drop the peak concentrations to the order of 0.1 individuals m^{-3} and then, after 24 h, maximum densities could be less than 0.001 individuals m^{-3}. The dramatic decrease in population density means that sexually-reproducing planktonic species will be at low risk of establishment due to Allee effects, whereby the population growth rate of sparse populations decreases with decreasing population density (primarily due to a decreased ability to find mates). When severe, Allee effects may generate a critical density below which the population declines until extinction. On the other hand, dilution of population density may not negatively influence parthenogenetic or asexual species. With a low flushing rate of 0.8–1.15 days^{-1}, the population of a parthenogenetic taxon could increase if population growth occurs at rates faster than $\sim$1 days^{-1}. Thus, there is likely to be quite different risks associated with the release of parthenogenetic versus

Please cite this article in press as: Wells, M.G., et al. The dilution and dispersion of ballast water discharged into Goderich Harbor. Mar. Pollut. Bull. (2011), doi:10.1016/j.marpolbul.2011.03.005

sexual species of planktonic organisms into a harbor. The results of our work are most relevant for species that tend to disperse passively, such as most planktonic organisms. We have focused on zooplankton due to their prevalence in ballast water samples and history of negative impact in the Great Lakes, and we acknowledge that other taxa, such as phytoplankton, bacteria and viruses (and to a lesser extent larval fishes and macroinvertebrates), need further consideration of the effect of dispersion on invasion success.

The observed range of dye concentrations shown in Fig. 4 suggests that a potential invasive species will initially have a patchy distribution in a harbor, indicating that a strategic spatial sampling plan is needed to adequately monitor for new ANS in a harbor. Monitoring plans for ANS, if they exist at all, tend to be limited due to expense, so there is a need to incorporate spatial dynamics into monitoring plans (see also Hayes et al., 2005; Harvey et al., 2009). The observation that this harbor is not completely well-mixed could be because there are numerous hydraulic dead-zones that can retain ballast water for lengthy periods and slowly release into the main body of the harbor. Such dead-zones are known to be important for modeling the self-recruitment of plankton in rivers (Reynolds, 1984). The presence of dead-zones in a harbor will result in a distribution of residence timescales and a long-tail for the time decay of ballast water concentration. The hydraulic dead-zones could act as biological incubation zones where ballast water (and any propagules it may contain) could remain at high concentrations for lengthy periods.

There was typically a 1.5–2 °C horizontal temperature difference between the inner harbor and the lake; the resulting exchange flow, with channel depth of 8 m, could result in small exchange velocities of the order of 5 cm s^{-1}, for a total volume flux of $60\ \text{m} \times 8\ \text{m} \times 0.05\ \text{m s}^{-1} = 24\ \text{m}^3\ \text{s}^{-1}$. These velocities in the channel are generally larger than the swimming velocities of plankton reported in Reynolds (1984), supporting the idea that small planktonic organisms will disperse in a manner similar to the dyed ballast water. The total area of Goderich Harbor is of the order 10^6 m^3 so that all the water in the entire harbor would be flushed on a time scale of order several days, consistent with the timescale estimate based upon the evolution of the dye concentrations. The channel where the ships dock to load cargo (salt) has dimensions 60 m wide × 8 m deep × 450 m long so that water is replaced by the exchange flow after approximately 3 h. These simple estimates show that there can be expected to be a distribution of residence timescales within Goderich Harbor. In future experiments we recommend direct measurements of these exchange flows using an acoustic Doppler current profiler, so that an estimate of the hydraulic residence timescale can be made that is independent of the tracer release studies.

The retention timescale of a harbor is also an important factor in determining if there is any risk of ship-to-ship transfer of potential invasive species. Goderich Harbor is a relatively small port that primarily exports cargo, thus there is a low risk of secondary transfer of introduced populations by vessels loading ballast water. However, there is potential for ship-to-ship transfer in large harbors such as Hamilton, ON or Toledo, OH, where multiple ships can berth and both load and unload ballast water in close proximity. If the time between ship visits in a harbor is longer than the harbor's retention timescale then the risk of direct ship-to-ship transfer of ballast water will be very low. This is a potential mechanism of invasive species spread that has not been studied in great detail.

5. Conclusions

The measured dilution rates of the dyed ballast water concentration are relatively high, with an initial rapid decrease in the dye concentration to a value 100 times smaller than the initial concentration, and a subsequent slower reduction to a concentration 1000–10,000 times smaller than the initial ballast water concentration. For sexual zooplankton species released at the densities recommended by the IMO of less than 10 propagules per m^3, such a high dilution rate will likely mean there is very low risk of establishment. However this diluted water remains within the harbor for relatively long timescales, so that between 10–20% of the total ballast water was present in the harbor after 3 days. Such a retention timescale implies a flushing rate of 0.8–1.15 day^{-1}, providing opportunity for establishment of asexual species.

The observed residence time of 0.8–1.15 day^{-1} could potentially be enough to counter-balance the growth of an invasive asexual species, but only if these species reproduce at rates which are longer than the residence time. In general, there is an inverse relationship between plankton size and growth rate, with the smallest and simplest organisms reproducing most rapidly (Reynolds, 1984). The biological growth rates of native cladoceran taxa have been reported as 0.3 day^{-1} (Bailey et al., 2009) or between 0.14 and 0.47 day^{-1} (Flores-Burgos et al., 2003), suggesting that dilution may not be adequate to prevent establishment of any introduced cladoceran species. Many other zooplankton species have similar maximum growth rates to Cladocera. For instance growth rates reported for Rotifera are typically on order of 1 day^{-1} (Allan, 1976) to 0.2–0.7 day^{-1} (Nero and Sprules, 1986). Other zooplankton species, such as Diaphanosoma, Daphnids, Bosminids and Chydorus, have reported maximum growth rates in the range 0.1–0.3 day^{-1} (Nero and Sprules, 1986). All of these quoted growth rates of zooplankton are clearly comparable to the flushing timescale. Thus, while the dilution of ballast water may prevent a sexual species from establishing itself, the relatively long retention timescales mean that dispersal may not be sufficient by itself to prevent the establishment of asexual or parthenogenetic organisms. Thus, there is likely to be quite different risks associated with the release of parthenogenetic versus sexual species of planktonic organisms into a harbor, with much greater risk attributed to parthenogenetic organisms.

Flushing timescales for the Port of Goderich are likely to be comparable to many of the sheltered commercial ports in the Great Lakes – St. Lawrence Seaway so that there will be similar risk of biological growth rates exceeding flushing rates. In contrast, tidally flushed harbors in estuaries or ports along rivers might be expected to have much shorter retention timescales and hence lower risk of establishment. Nevertheless the high dilution rates of ballast that occur within the first 10s of meters from a ship will be similar to those reported in our experiment.

Acknowledgements

Field assistance from Matt Hatcher, Jocelyn Gerlofsma, Harry Zheng, Matthew Deneau and the Canadian Coast Guard is gratefully acknowledged. The co-operation of Seaway Marine Transport, Captains and crew of the vessels Capt. Henry Jackman and Algoway, were crucial to the success of this study. Support and advice from the Goderich Harbor Master, Goderich Port Management Company, Goderich Water Treatment Plant, Sifto Canada Corp. and the Ontario Ministry of the Environment are also appreciated. We gratefully acknowledge funding from the NSERC Canadian Aquatic Invasive Species Network (CAISN), NSERC Discovery Grant, Fisheries and Oceans Canada and Transport Canada.

References

Allan, J.D., 1976. Life history patterns in zooplankton. Am. Nat. 110 (971), 165–180.

Austin, J.A., 2002. Estimating the mean ocean–bay exchange rate of the Chesapeake Bay, J. Geophys. Res., 107, 3192, doi:10.1029/2001JC001246.

Please cite this article in press as: Wells, M.G., et al. The dilution and dispersion of ballast water discharged into Goderich Harbor. Mar. Pollut. Bull. (2011), doi:10.1016/j.marpolbul.2011.03.005

Bailey, S.A., Velez-Espino, L.A., Johannsson, O.E., Koops, M.A., Wiley, C.J., 2009. Estimating establishment probabilities of Cladocera introduced at low density, an evaluation of the proposed ballast water discharge standards. Can. J. Fish. Aquat. Sci. 66 (2), 261–276.

Banas, N.S., McDonald, S.P., Armstrong, D.A., 2009. Green crab larval retention in Willapa Bay, Washington. An intensive Lagrangian modeling approach. Estuaries Coasts 32, 893–905.

Beletsky, D., Saylor, J.H., Schwab, D.J., 1999. Mean circulation in the Great Lakes. J. Great Lakes Res. 25 (1), 78–93.

Brickman, D., 2006. Risk assessment model for dispersion of ballast water organisms in shelf seas. Can. J. Fish. Aquat. Sci. 63 (12), 2748–2759.

Brickman, D., Smith, P.C., 2007. Variability in invasion risk for ballast water exchange on the Scotian Shelf of eastern Canada. Mar. Pollut. Bull. 54, 863–874.

Carr, M.L., Rehmann, C.R., Stoeckel, J.A., Padilla, D.K., Schneider, D.W., 2004. Measurements and consequences of retention in a side embayment in a tidal river. J. Mar. Syst. 49, 41–53.

Cowen, R.K., Paris, C.B., Srinivasan, A., 2006. Scaling of connectivity in marine populations. Science 311 (5760), 522–527.

Drake, J.M., Lodge, D.M., 2006. Allee effects, propagule pressure and the probability of establishment: risk analysis for biological invasions. Biol. Invasions 8, 365–375.

Drake, J.M., Lodge, D.M., Lewis, M., 2005. Theory and preliminary analysis of species invasions from ballast water, controlling discharge volume and location. Am. Midl. Nat. 154, 459–470.

Flores-Burgos, J., Sarma, S.S.S., Nandini, S., 2003. Population growth of zooplankton (Rotifers and cladocerans) fed *Chlorella vulgaris* and *Scenedesmus acutus* in different proportions. Acta Hydrochim. Hydrobiol. 31 (3), 240–248.

George, D.G., 1981. Wind-induced water movements in the South Basin of Windermere. Freshwater Biol. 11 (1), 37–60.

Government of Canada, 2006. Ballast Water Control and Management Regulations. Canada Gazette 140(13), SOR/2006-129.

Harvey, C.T., Qureshi, S.A., MacIsaac, H.J., 2009. Detection of a colonizing, aquatic, non-indigenous species. Diversity Distrib. 15, 429–437.

Hayes, K.R., Cannon, R., Neil, K., Inglis, G., 2005. Sensitivity and cost considerations for the detection and eradication of marine pests in ports. Mar. Pollut. Bull. 50, 823–834.

Holeck, K.T., Mills, E.L., MacIsaac, H.J., Dochoda, M.R., Colautti, R.I., Ricciardi, A., 2004. Bridging troubled waters: biological invasions, transoceanic shipping, and the Laurentian Great Lakes. Bioscience 54, 919–929.

IMO (International Maritime Organization), 2004.The International Convention for the Control and Management of Ships Ballast Water and Sediments (adopted 13.02.04).

Larson, M.R., Foreman, G.G., Levings, C.D., Tarbotton, M.R., 2003. Dispersion of discharged ship ballast water in Vancouver Harbor, Juan De Fuca Strait, and offshore of the Washington Coast. J. Environ. Eng. Sci. 2 (3), 163–176.

Lawrence, G., Pieters, R., Zaremba, L., Tedford, T., Gu, L., Greco, S., Hamblin, P., 2004. Summer exchange between Hamilton Harbor and Lake Ontario. Deep Sea Res. 51, 475–487.

Lewis, M.A., Kareiva, P., 1993. Allee dynamics and the spread of invading organisms. Theor. Popul. Biol. 43, 141–158.

Lloyd's Register, 2010. Ballast Water Treatment Technology, Current Status. Lloyd's Register, London. Available from: www.lr.org/Images/365923_BWTtext_tcm155-175072.pdf (accessed 25.02.10).

Lockwood, J.L., Cassey, P., Blackburn, T., 2005. The role of propagule pressure in explaining species invasions. Trends Ecol. Evol. 20 (5), 223–228.

Monsen, N.E., Cloern, J.E., Lucas, L.V., Monismith, S.G., 2002. The use of flushing time, residence time, and age as transport time scales. Limnol. Oceanogr. 47, 1545–1553.

Murthy, C.R., 1976. Horizontal diffusion characteristics in Lake Ontario. J. Phys. Oceanogr. 6, 76–84.

Nero, R., Sprules, W.G., 1986. Predation by three glacial opportunists on natural zooplankton communities. Can. J. Zool. 64, 57–64.

NRC (National Research Council of the National Academies), 2008. Great Lakes Shipping, Trade, and Aquatic Invasive Species. Transportation Research Board Special Report 291. Washington, DC, USA, p. 226.

Pringle, J.M., Lutscher, F., Glick, E., 2009. Going against the flow: the effects of non-Gaussian dispersal kernels and reproduction over multiple generations. Mar. Ecol. Prog. 377, 13–17.

Rao, Y.R., Schwab, D.J., 2007. Transport and mixing between the coastal and offshore waters in the great lakes: a review. J. Great Lakes Res. 33, 202–218.

Reynolds, C.S., 1984. The Ecology of Freshwater Phytoplankton. Cambridge University Press, p. 384.

Reynolds, C.S., 1994. The long, the short and the stalled: on the attributes of phytoplankton selected by physical mixing in lakes and rivers. Hydrlobiologia 289, 9–21.

Reynolds, K.J., 2005. Ship's Ballast Discharge Dispersion Benchmark Dye Tracer Test. The Glosten Associates, Inc., File No. 03104.

Ricciardi, A., 2006. Patterns of invasion in the Laurentian Great Lakes in relation to changes in vector activity. Diversity Distrib. 12, 425–433.

Ruddick, B.R., Taggart, C.T., 2006. Apparatus, System and Method for Evaluating Fluid Systems. USA and Canada Patent Pending. Appl. No.11/458,287, Filed 07/18/2006. Conf. #8539, with benefit of 60/699,845 filed 07/18/2005.

Rueda, F., Cowen, E., 2005. Exchange between a freshwater embayment and a large lake through a long, shallow channel. Limnol. Oceanogr. 50 (1), 169–183.

Rup, M.P., Bailey, S.A., Wiley, C.J., Minton, M.S., Miller, A.W., Ruiz, G.M., MacIsaac, H.J., 2010. Domestic ballast operations on the Great Lakes: potential importance of Lakers as a vector for introduction and spread of nonindigenous species. Can. J. Fish. Aquat.Sci. 67 (1), 256–268.

Schertzer, W.M., Assel, R.A., Beletsky, D., Croley II., T.E., Lofgren, B.M., Saylor, J.H., Schwab, D.J., 2008. Lake Huron climatology, inter-lake exchange and mean circulation. Aquat. Ecosyst. Health Manage. 11, 144–152.

Simberloff, D., 2009. The role of propagule pressure in biological invasions. Annu. Rev. Ecol. Evol. Syst. 40, 81–102.

Stevens, C.L., Lawrence, G.A., Hamblin, P.F., 2004. Horizontal dispersion in the surface layer of a long narrow lake. J. Environ. Eng. Sci. 3, 413–417.

Trebitz, A., 2006. Characterizing seiche and tide-driven daily water level fluctuations affecting coastal ecosystems of the Great Lakes. J. Great Lakes Res. 32, 102–116.

USCG (United States Coast Guard), 1993. Ballast Water Management for Vessels Entering the Great Lakes. Code of Federal Regulations 33-CFR Part 151.1510.

USCG (United States Coast Guard), 2004. Ballast Water Management for the Control of Aquatic Nuisance Species in the Waters of the United States. Navigation and Vessel Inspection Circular 07-04, CH 1.

Wells, M.G., Parker, P., 2010. The thermal variability of the waters of Fathom Five National Marine Park, Lake Huron. J. Great Lakes Res. 36, 570–576, doi:10.1016/j.jglr.2010.04.009.

Wells, M.G., Sealock, S., 2009. Summer water circulation in Frenchman's Bay, a shallow coastal embayment connected to Lake Ontario. J. Great Lakes Res. 35 (4), 548–559.

Please cite this article in press as: Wells, M.G., et al. The dilution and dispersion of ballast water discharged into Goderich Harbor. Mar. Pollut. Bull. (2011), doi:10.1016/j.marpolbul.2011.03.005