REPORT ON THE BALLAST WATER MANAGEMENT ASSESSMENT PROJECT

PHASE 3

FISCAL YEAR 2008-09

FINAL REPORT

Prepared For:

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March 31, 2009

DISCLAIMER

This report summarizes work completed to date on on-going projects to meet fiscal year-end reporting requirements. **All results are preliminary and must not be distributed without authorization of the authors.**

A. BALLAST WATER MONITORING AND ANALYSIS OF INSPECTION PROGRAM

The introduction of aquatic invasive species (AIS) via deep-sea vessels operating on the Great Lakes is the most important pathway of AIS introductions to the region. Currently, Transport Canada regulations require all incoming vessels to exchange or flush ballast water for open-ocean saltwater. Although these ballast water management practices have generally been considered as a stop-gap measure until more effective treatment technologies can be developed, a recent study conducted by researchers at the University of Windsor suggests that ballast water exchange can be as effective against freshwater taxa as treatment technologies. This study, however, did not give consideration to euryhaline taxa, which have been an important group of invaders via shipping vectors in recent times. It is therefore very important to monitor ballast water of incoming vessels to determine if ballast water exchange/flushing procedures provide sufficient protection against AIS, or whether it will be necessary to implement more stringent regulations for ballast water management.

INTRODUCTION

Invasions by nonindigenous species (NIS) continue to be an issue of global concern. Since the St. Lawrence Seaway opened in 1959, ballast water associated with commercial shipping activities within the Laurentian Great Lakes has been identified as the most important vector for aquatic NIS (Holeck et al. 2004; Ricciardi 2006). Human mediated dispersal of NIS has been in progress for thousands of years, but with technological advances, the signing of free trade agreements and expanding global economies, the number of invaders is steadily on the rise (e.g. Work et al. 2005). NIS are defined as species that have no previous evolutionary history in the Great Lakes and have been introduced since the arrival of European colonists (Ricciardi 2006). Introduction of NIS is becoming increasingly recognized as one of the most important threats to the biodiversity of aquatic ecosystems (Sala et al. 2000; Millennium Ecosystem Assessment 2005; Lawler et al. 2006). In addition to their detrimental ecological and environmental effects, 20-30% of NIS have negative economic impacts (Pimentel et al. 2001).

Ballast is used by vessels without cargo shipments for stabilization, and to permit safe movement between ports by weighing down the ship, and allowing it to travel through the water instead of floating on it (Aquatic Sciences 1996). Before the use of liquid ballast around 1900, ships utilized solid ballast - mainly soil, gravel, or rubble found in proximity to the port. Solid ballast was often contaminated with plants, insects and other organisms (Lindroth 1957; Mills et al. 1993).

Oceanic vessels, or those foreign-flagged vessels known as "salties" traveling from the Atlantic Ocean, through the St. Lawrence Seaway and into the Great Lakes, import approximately 5,000,000 tonnes of ballast water per year (Aquatic Sciences 1996), and are attributed with ~65% of all recorded aquatic invasions since 1959 (Ricciardi 2006). Saltie vessels lacking cargo and carrying full ballast constitute only a small fraction of trade into the Great Lakes (Colautti et al 2003). Far more vessels arrive with cargo in their holds, and thus carry only residual ballast water (Colautti et al 2003).

Voluntary regulations requiring deep ocean ballast water exchange (BWE) were put in place by Transport Canada Marine Safety (TCMS) in 1989 and made mandatory by the United States Coast Guard (USCG) in 1993. BWE is intended to flush organisms from ballast tanks, thus dramatically lowering potential ‘propagule pressure’ (Colautti et al. 2007). Organisms contained within unpumpable ballast following emptying of the tanks would subsequently be killed by emersion in salt water loaded to replace discharged freshwater as extant salinity levels would exceed physiological tolerances of most freshwater species (Ricciardi 2006). This requirement, however, only applied to vessels with ‘declarable water on board,’ also referred to as BOB (Ballast On Board) vessels. Nevertheless, the majority of vessels (~90%) entering the Great Lakes do so with ‘no declarable water on board,’ also referred to as NOBOB (NO Ballast On Board) vessels (Colautti et al. 2003). NOBOB vessels have been identified as an invasion risk (Locke et al. 1993) since they typically carry residual water and sediment that may contain live NIS or their resting stages (Bailey et al. 2003).

A study by MacIsaac et al. (2002) demonstrated that NOBOB vessels may actually pose a greater risk for invasions than BOB vessels having undergone ballast exchange. Many NOBOB vessels load Great Lakes’ ballast water during their inbound transit after discharging cargo, and later discharge the mixed ballast water in the Great Lakes, thereby potentially exposing the system to NIS (Colautti et al. 2003). Recognizing this, in August 2005, the USCG introduced best management practices encouraging vessels in NOBOB status to conduct BWE (USCG 2004). TCMS introduced mandatory regulations in June 2006, requiring all vessels to exchange their BOB or flush their NOBOB tanks with water of a salinity equivalent to ballast water exchange (~30 ppt) before entering Canadian waters (TCMS 2006).

In March 2008, the US and Canadian St. Lawrence Seaway agencies implemented mandatory exchange or flushing of tanks for all ships entering the Great Lakes, regardless of their ballast status. In order to enforce this new policy, the Joint Ballast Water Management Exam Program, comprised of the USCG, TCMS, St. Lawrence Seaway Development Corporation (SLSDC) and the St. Lawrence Seaway Management Corporation (SLSMC) was created to maximize inspections efforts and to ensure compliance. The inspection process begins with a review of ballast water reports, logs, records and ballast water management plans. The crew is then interviewed to assess their understanding of the ship’s Ballast Water Management Plan and on actual practices. Finally, ballast water tanks on both BOB and NOBOB vessels are sampled to ensure a salinity of at least 30 ppt. The overall goal of the joint inspections program is to inspect each ship planning entry into the Great Lakes on every transit and to increase the number of both BOB and NOBOB tanks tested. If a ship is found to have noncompliant tanks they have the option to retain ballast water, however, are issued a Letter of Retention and are inspected again on departure to ensure compliance (BWWG 2008).

Although ballast water is not the only vector associated with cargo vessels, it is of primary concern due to the sheer volume of water being moved as well as the number of potential invaders found within it (Mills et al. 1993; Ricciardi 2001).

METHODS

Analysis of Inspection Program

Information regarding the salinity of ballast water tanks as well as ballast water management practices (e.g. tank flushing practices, location of last ballast uptake, tank volumes/capacities) was obtained from Ballast Water Reporting Forms (BWRFs) and corresponding Ballast Tank Testing Forms (BTTFs). This information was collected mainly by TCMS and the USCG for all vessels entering the Great Lakes during the 2005, 2006 and 2007 shipping seasons. The information was then compiled into an electronic database and analyzed to determine trends in ballast management practices immediately before, during and after the introduction of the voluntary (USCG) and mandatory (TCMS) regulations. Most parameters were inputted directly from the BTTFs into the electronic database. The ballast location, often given as coordinates, and the last port visited were translated into regions (e.g. East-Central Atlantic, West Indian Ocean, Mediterranean Sea) as defined by the FAO geographic map of the oceans

(The Times Atlas of the Oceans, 1983). This allowed for easy comparison of multiple locations. Tanks not in compliance, with salinities less than 30ppt, were highlighted so they could easily be distinguished for later analysis. This data was then examined using both a ship-wise and tank-wise perspective. Furthermore, the tank-wise analysis was subdivided into ‘main’ (double-bottom, wing, deep, holding and trim) and ‘auxiliary’ (forepeak, afterpeak, heel and retention) tanks, as the latter are typically not utilized during standard ballast operations, and so their contents would not be discharged into the Great Lakes-St. Lawrence Seaway (C.J. Wiley, Transport Canada, personal communication).

Tank capacities and estimated tank volumes at time of testing are listed on the 2005 and 2006 BTTFs. The estimated tank volumes, however, are not listed on 2007 BTTFs, therefore, current tank volumes for these forms was determined using the corresponding ballast water reporting forms. Occasionally, there was a discrepancy between the tank type listed on the BTTF compared with that listed on the BWRF. This became problematic when attempting to determine the current tank volume for vessels sampled in 2007, as this value was not given directly on the BTTF. Another problem occurred when the volumes listed on the BTTFs did not clearly identify the vessel as either a BOB or NOBOB vessel. In order to classify a vessel as being either BOB or NOBOB, the following definitions were used: BOB; a. A vessel reporting a minimum total cumulative ballast water volume of 200 metric tons on their BWRF; b. A vessel with at least one main tank filled with ballast containing an estimated volume totaling more than 10% of the tanks capacity (USCG). NOBOB; a. A vessel reporting a total cumulative ballast water volume less than 200 metric tons; b. A vessel not containing a tank with more than 10% of its total ballast water capacity in ballast (this excludes auxiliary tanks that are rarely exchanged and not used in normal ballasting operations).

Ballast Water Monitoring Program

Samples of ballast water from NOBOB and BOB tanks were collected to examine composition and abundance of invertebrates using methodology similar to that used by Duggan et al. (2005) and Bio-environmental Services Ltd. (1981), respectively, allowing for comparison of results before and after the introduction of the respective regulations. Transoceanic or coastal ships were boarded opportunistically at an initial port of call in the Great Lakes (typically Hamilton, Toronto, Sarnia, or Windsor) without regard to the source of ballast water. Nineteen NOBOB tanks, on 15 different vessels, were sampled for residual ballast water via tank entry during November and December in 2005 (n=6) and 2006 (n=8), with an additional sample collected in July 2006. Each water sample (50 L) was collected via grab samples from multiple locations at the aft end of the tank, passed through a 53-µm mesh plankton net, and the retained material preserved in 90% ethanol. In addition, ballast sediment cores were collected from NOBOB tanks using a 5 cm diameter hand-coring device, when possible (n=4 tanks). Three replicate cores were collected from a single location, containing the deepest patch of sediment, within each tank. Cores were capped and kept at 4°C until slicing and preservation, which was completed within 48 hours of collection. Each core was sliced at 1 cm intervals, and the outer layer of sediment (5 mm) was removed using a cookie cutter before preservation in 90% ethanol. Organic material, including soft-bodied invertebrates and diapausing eggs, was subsequently separated from sediment for enumeration using a colloidal silica protocol (Burgess 2001). The vertical distribution of invertebrate taxa and diapausing eggs was examined to determine if density varies with depth.

Ballast water was collected from 24 BOB tanks on 16 different vessels between 26 April and 13 May 2008. Where possible, 1000L samples were collected by conducting multiple plankton net tows (53 um mesh) through opened tank hatches. When tank hatches could not be opened, 25-100L of water was collected via the tank sounding tube using an inertial sampling device (Aquatic Sciences Inc. & Jenkins 1996). As above, water samples were filtered through 53 um mesh prior to preservation in ethanol. Salinity of the ballast water was measured at the time of collection using a hand-held YSI meter, and/or an optical refractometer. Information on ballast water history and tank management practices was collected from ballast water reporting forms, when available.

Invertebrate taxa retained in preserved water samples were enumerated and identified using standard taxonomic methods. Total invertebrate abundance, as well as the abundance of high risk taxa were compared to results obtained prior to regulation (Duggan et al. 2005 for residual water; Bioenvironmental Service, Inc. 1981 for ballast water) to determine if current regulations have had an impact on the biological composition of ballast water. A taxon was defined as high risk if any global population of the taxon was previously recorded from fresh or brackish waters (conservatively defined as salinities of 18 ‰ or less), and included all taxa sampled from ballast tanks containing fresh or brackish water by default. For all analyses, plankton densities were averaged for tanks within ships, since tanks within ships have common ballast histories and cannot be considered independent data (see Bailey et al. 2005).

We explored differences in taxonomic composition of samples collected before and after the introduction of regulations for NOBOB and BOB tanks separately. In addition, analyses of differences in total plankton abundance and abundance of high risk taxa were conducted separately. For residual ballast water, the student's t-test was used to determine if total plankton abundance differed by regulatory period; total invertebrate density was log (x+1) transformed to meet assumptions of normality. All remaining analyses were conducted using the nonparametric Mann Whitney test since the data could not be transformed to meet the assumptions of parametric tests. All statistical comparisons were conducted using JMP 7.0.2 (2007 SAS Institute Inc.).

RESULTS

Information on ballast history, ballast management practices and salinity of ballast water contained in 8808 NOBOB tanks and 2289 BOB tanks of 602 vessels transiting the Great Lakes-St. Lawrence Seaway during the 2005, 2006 and 2007 shipping seasons was compiled for analysis (representing approximately 45% of vessels entering the Great Lakes). Information was primarily obtained from Transport Canada BTTFs (compiled jointly with the USCG), although data was augmented by BWRFs submitted by vessels, when available. An additional four NOBOB tanks of three vessels and 387 BOB tanks of 151 vessels entering the Great Lakes were tested solely by USCG and/or SLSDC Inspectors in 2006 and 2007. TCMS attempted to board and collect information for 100% of vessels on their seasonal transit into the Great Lakes, some ship transits were excluded from this analysis because data provided by TCMS for this analysis was missing or incomplete. A summary of the information collected on a ship-wise basis is presented in Table 1.

For the 2005 shipping season, 146 of the 147 ships inspected by TCMS was included in this analysis. For these 146 ships, Inspectors attempted to sample the salinity of the residual water in 2344 tanks, representing 77.4% of all tanks onboard the vessels. Samples could not be obtained for more than half of the tanks inspected (58.1%); these ballast tanks were considered 'dry' by Inspectors, and documented as compliant tanks. Similar results were obtained in 2006 and 2007, although Inspectors collect samples from a greater proportion of tanks, 93.2% and 95.9%, respectively, resulting in more samples taken for each consecutive year.

With voluntary and mandatory BWE of NOBOB vessels implemented in August 2005 and June 2006, respectively, the ballast water inspection statistics have been divided accordingly (Table 1). This allows for easier comparison of the results considering the transition from voluntary to mandatory ballast water management practices.

The maximum tonnage of ballast on board reported by NOBOB vessels was 962 MT and 1500 MT during the 'voluntary' and 'mandatory' periods, respectively. The percentage of NOBOB ships reporting 0 MT of ballast on board stayed fairly constant over the transition from voluntary to mandatory periods at roughly 14% of vessel transits, with the majority of NOBOB vessels (~70%) reporting between 1-200 MT of ballast on board. The remaining transits for which tonnage was reported was comprised of reports >200 MT of ballast on board (~7% vessels reporting volumes of residual ballast) and vessels failing to report tonnage. Vessels reporting a large volume of residual ballast are those either having at least one auxiliary tank (forepeak, afterpeak, heel, or retention tanks) in ballast or, although large, the main tank volumes are still less than 10% of the total tank capacity. On a tank-wise basis, Inspectors typically estimated depths of 4.5 cm residual ballast water in NOBOB tanks, however, water depths of many metres were recorded in a few cases (largely representing auxiliary tanks in full ballast condition). The median amount of residual ballast estimated by Inspectors was about 1.5 MT per NOBOB tank.

The cumulative tonnage of ballast on board estimated by TCMS Inspectors during voluntary and mandatory periods was 1.75 times greater than that reported by vessels on BWRFs during the NOBOB voluntary period. This is partially due to under-reporting of ballast on board by the majority of vessels (i.e., not reporting residual volumes), although it is primarily due to the fact that information on ballast tonnage generated by Inspectors was available for all ships, whereas reporting forms were available only for a subset of ships. During the mandatory period, the opposite was seen, with 2.1 times the volume reported on BWRFs compared to that on the BTEs. During the mandatory period the cumulative tonnage of ballast estimated by Inspectors was essentially the same as that reported by vessels on the ballast water reporting form.

The maximum tonnage of ballast on board reported by BOB vessels was 1368 MT and 1113 MT during voluntary and mandatory periods, respectively (Table 2). Roughly 25% of BOB vessels reported volumes between 1-200 MT during the voluntary to mandatory period, with the majority reporting volumes >200 MT (~73%). The remainder failed to report tonnage. The vessels reporting smaller quantities (between 1-200 MT) are those containing at least one main (double-bottom, wing tank) tank with a volume greater than 10% of the total tank capacity. Inspectors typically estimated depths of ~14 cm residual ballast water in BOB tanks, with a maximum depth of almost 17 m. The median amount of residual ballast estimated by Inspectors during the voluntary period was 6.5 MT per BOB tank and 88.2 MT (13.6 times greater) during the mandatory period. This large increase is likely due to the greater number of BOB vessels tested, especially in 2007.

Analysis on a tank-specific basis gave more detailed information about ballast management practices (Table 3). From 2005 to June 2006 (the end of the voluntary period), TCMS Inspectors documented 299 NOBOB tanks (86 vessel transits) with residual water salinity less than 30‰ during the voluntary exchange period. Both the number of non-compliant tanks and non-compliant vessel transits decreased during the transition to the mandatory period (187 and 66, respectively). Further breakdown of the non-compliant tanks indicates that about 19% are auxiliary tanks that typically would not be used during ballasting operations, and pose little risk of being discharged into the Great Lakes. Both the absolute number and relative importance of tanks carrying low-salinity residual ballast (< 18‰) decreased from voluntary to mandatory periods. This correlates to the number of NOBOB tanks that had been subjected to 'management' (tanks for which vessels claimed to have flushed or exchanged tanks, or for which geographical coordinates, rather than port locations, are listed as last location of ballast uptake) with an increase from 62.3% to 90.7% over the study period. Similar findings are evident for BOB vessels where Inspectors documented 84 non-compliant tanks (19 vessel transits) with ballast water salinity less than 30‰ during the voluntary exchange period. Again, both the number of non-compliant tanks and vessel transits decreased during transition to the mandatory period (68 and 31, respectively) or from 30.7% to 4.2% of non-compliant tanks. Approximately 7% of the non-compliant voluntary tanks and 22% of the mandatory tanks are classified as auxiliary. The number of compliant tanks increased along with the number of tanks that underwent some form of ballast water management (39.1% to 91.8%) during the study period.

Analysis of the region of last ballast uptake for non-compliant NOBOB tanks indicates that the geographical locations of ballast water uptake changed between voluntary and mandatory periods (Figure 1). The NE Atlantic replaced the North Sea as the primary source of residual ballast for non-compliant tanks. Regions known to be important as sources of established NIS in the Great Lakes region also declined in importance (e.g., Baltic Sea and Black Sea).

Similar findings are noticeable in the analysis of the region of last ballast uptake for non-compliant BOB tanks. Geographical locations of ballast water uptake changed between voluntary and mandatory periods (Figure 2). Once again, the NE Atlantic replaced the most common region of uptake during the voluntary period as the primary source of residual ballast for non-compliant tanks during the mandatory period. A notable difference between NOBOB and BOB vessels is seen for both voluntary and mandatory periods; as well, vessels containing non-compliant BOB tanks had much greater uptake in the Great Lakes region.

Information collected by USCG or SLSDC Inspectors is summarized in Table 4. Only BOB vessels are included in Table 4 as nearly all of the vessels inspected (98%) are classified as BOBs. As well, USCG/SLSDC data only exist for 2006 and 2007, hence the lack of inspection data under the voluntary period. The number of vessels inspected increased 18 to 132 (more than 7 times) over the study period. The number of tanks inspected also increased (over 13 times) during the transition. As BOB vessels were clearly the majority of vessels targeted and inspected, most tanks are in compliance. In such cases where non-compliant tanks were found, the vessel either last conducted BWE in the Quebec region and was permitted entry into the Great Lakes or was given a retention letter forcing the vessel to retain the non-compliant ballast. Although only ~13.5% of available tanks were inspected, an increased effort is evident and must be recognized accordingly. The USCG and SLSDC inspections will be included in the salinity statistics.

Information on the salinity of residual ballast water was analyzed from a temporal perspective to determine if any changes in pattern occurred as a result of the introduction of management regulations for NOBOBs. It is evident from Figure 3, that the number of tanks with residual water salinity less than 30‰ has decreased over time. There appears to be a modest increase in ballast tank salinities after the introduction of voluntary NOBOB management practices in August 2005, with compliance rates varying throughout the 2006 shipping season. Surprisingly, however, there appears to be little change with the introduction of mandatory regulations in June 2006. The number of compliant ballast tanks appears to be slightly more compliant during the 2007 shipping season, yet trends are still similar to those of 2006. It can be considered that the second half of 2006 and the 2007 shipping seasons are transitional learning periods.

Ballast water salinity was also analyzed from a temporal perspective for BOB vessels. As Figure 4 demonstrates, there appears to be no trend in salinity patters over the 2005 and 2006 shipping season. There is, however, a significant increase in compliant tanks throughout the 2007 shipping season; likely a result of increased inspection efforts.

During the 2007 sampling season, the additional testing of 77 vessels not intending on entering the Great Lakes was conducted by TCMS. These vessels, not transiting the St. Lawrence Seaway, comprise only 4.8% of the 1593 vessels entering the area. Of the 1249 tanks inspected, 495 (39.6%) tanks were determined to be non-compliant by some means (94 were less than 30‰ and 491 contained risky mud, were dry, or were 0‰). Retention letters were issued to 32 (41.6%) of the tested vessels for a total of 495 tanks.

Table 1. General inspection statistics collected from BTTFs for Great Lakes vessel transits made between 2005 and 2007. The 2005 statistics and those prior to June 28, 2006 have been classified as ‘voluntary,’ whereas the remaining 2006 and 2007 statistics have been classified as ‘mandatory.’ Numerical values are given for each statistic, followed by percentages, when applicable.

General Inspection Statistics	**Voluntary**		**Mandatory**	
		%		%
No. vessel transits inspected by Transport Canada (or with USCG)	245		381	
No. vessels tested by USCG and/or SLSDC (w/o TCMS)	19		133	
No. vessels entering Great Lakes (through the Snell Lock)				
No. vessel transits included in this analysis	244	99.6	358	93.4
No. NOBOB vessels	211	87.4	248	72.7
No. BOB vessels	33	12.6	110	27.3
No. tanks on inspected vessels	4997		7291	
No. tanks inspected (BOB and NOBOB)	4171	85.1	6926	94.7
No. samples taken	1857	44.9	4208	58.8
No. NOBOB tanks tested	3647	87.4	4802	88.0
No. BOB tanks tested	524	12.6	2124	12.0

Table 2. Summary statistics for NOBOB and BOB vessels during voluntary and mandatory periods. Numerical values are given for each statistic, followed by percentages, when applicable.

	NOBOB		BOB		NOBOB		BOB	
	Voluntary				**Mandatory**			
		%		%		%		%
Maximum ballast on board reported (MT)	961.8		1368.2		1500.0		1113.2	
Cumulative total ballast on board (MT) as reported volume on BWRF (or Laurent)	5250.9		21375.3		48310.8		670042.5	
Cumulative total ballast on board (MT) as estimated by soundings (BTE or BWRF)	9183.2		19926.8		23045.4		167510.4	
No. ships reporting 0 MT ballast on board	30	14.2	0	0.0	35	14.1	0	0.0
No. ships reporting 1-200 MT ballast on board	160	75.8	11	33.3	159	64.1	18	16.4
No. ships reporting >200 MT ballast on board	7	3.3	22	66.7	28	11.3	85	77.3
No. ships with blanks where ballast volume should be reported	14	6.6	0	0.0	26	10.5	7	6.4
Median depth estimated by Inspectors (cm)	4.5		12.5		4.5		15.5	
Max depth estimated by Inspectors (cm)	1440.0		1690.0		1660.0		1680	
Median amount residual ballast water per tank as estimated by Inspectors (MT)	1.4		6.5		1.6		88.2	

Table 3. Tank-specific summary statistics of ballast water salinity, by tank from voluntary to mandatory periods. Numerical values are given for each statistic, followed by percentages.

	NOBOB		BOB		NOBOB		BOB	
	Voluntary				**Mandatory**			
Salinity		%		%		%		%
No. compliant tanks (≥30‰)	1287	81.1	190	69.3	2411	92.3	1566	95.9
No. non-compliant tanks (<30‰)	299	18.9	84	30.7	187	7.2	68	4.2
No. tanks 0 - <5‰ (Fresh + Oligohaline)	19	1.2	12	4.4	30	1.1	18	1.1
No. tanks 5 - <18‰ (Mesohaline)	164	10.3	37	13.5	77	2.9	18	1.1
No. tanks 18 - <30‰ (Polyhaline)	116	7.3	35	12.8	76	2.9	28	1.7
No. tanks >30‰ (Euhaline)	1287	81.1	190	69.3	2411	92.3	1566	95.9
No. non-compliant vessel transits	86	40.8	19	57.6	66	29.6	31	28.2
No. tanks managed	992	62.3	99	36.1	2361	90.7	1497	91.8
No. tanks unmanaged	600	37.7	175	63.9	241	9.3	133	8.2

Table 4. Summary statistics of USCG and SLSDC inspection reports for BOB vessels from voluntary to mandatory periods. Numerical values are given for each statistic, followed by percentages.

	Voluntary		**Mandatory**	
		%		%
No. vessels inspected	18		132	
No. tanks on inspected vessel	197		2670	
No. tanks tested	37	18.8	349	13.1
No. compliant tanks (≥30‰)	37	100.0	317	90.8
No. non-compliant tanks (<30‰)	0	0.0	16	4.6
No. dry tanks	0	0.0	16	4.6

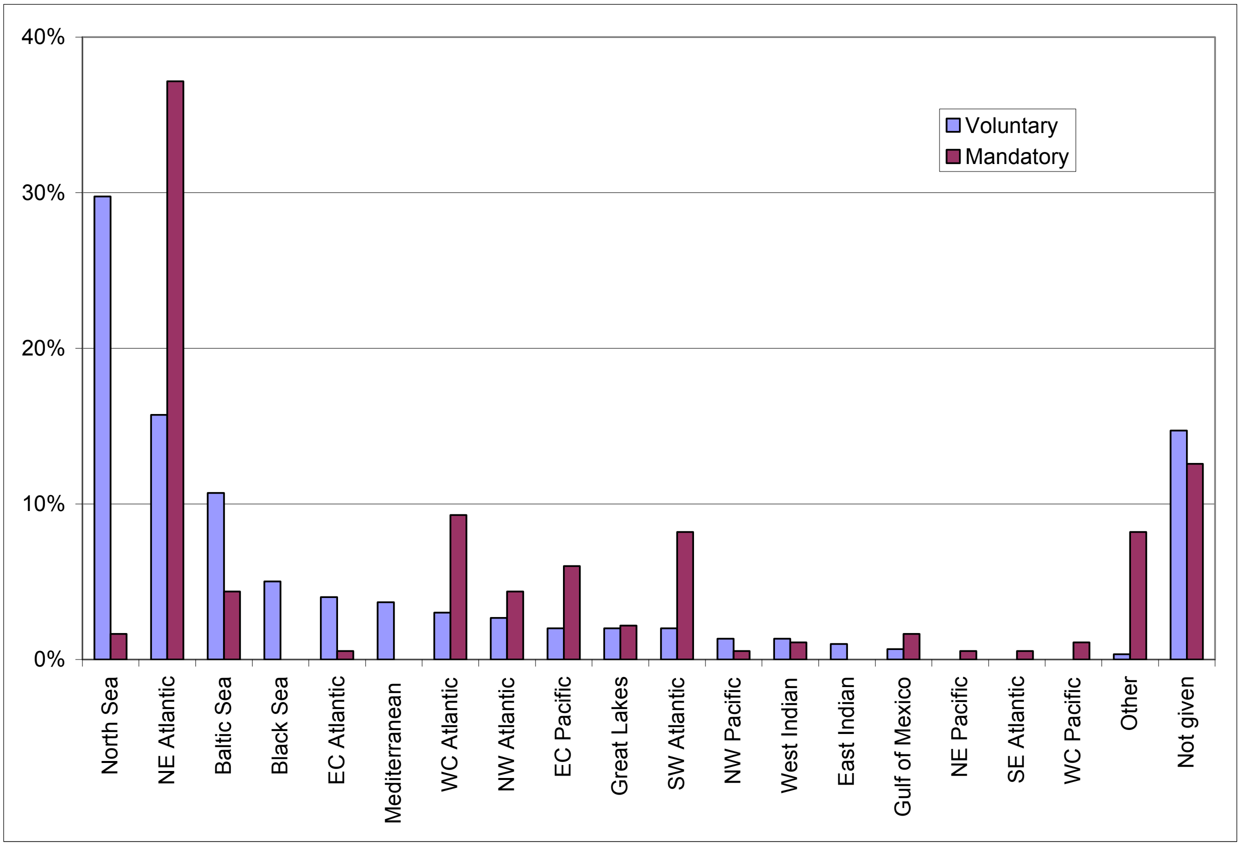
Figure Legend

Figure 1. Region of last ballast uptake for NOBOB tanks with residual ballast salinities of less than 30‰. Regional categories follow the geographical regions outlined by the FAO, with the addition of several major ‘enclosed’ shipping areas (e.g., Great Lakes-St. Lawrence Seaway, North Sea, Baltic Sea and the sub-division of the Mediterranean and Black Seas). ‘Other’ category includes those regions not common for ballast uptake.

Figure 2. Region of last ballast uptake for BOB tanks with residual ballast salinities of less than 30‰.

Figure 3. Percentage of tanks with residual ballast water salinity at each salinity category (0-<5‰, 5-<18‰, 18-<30‰, and ≥30‰) on vessels classified as NOBOBs. Broken line indicates introduction of US voluntary management practices, solid line denotes introduction of Canadian mandatory regulations.

Figure 4. Percentage of tanks with ballast water salinity at each salinity category (0-<5‰, 5-<18‰, 18-<30‰, and ≥30‰) on vessels classified as BOBs. Sample size?


40%
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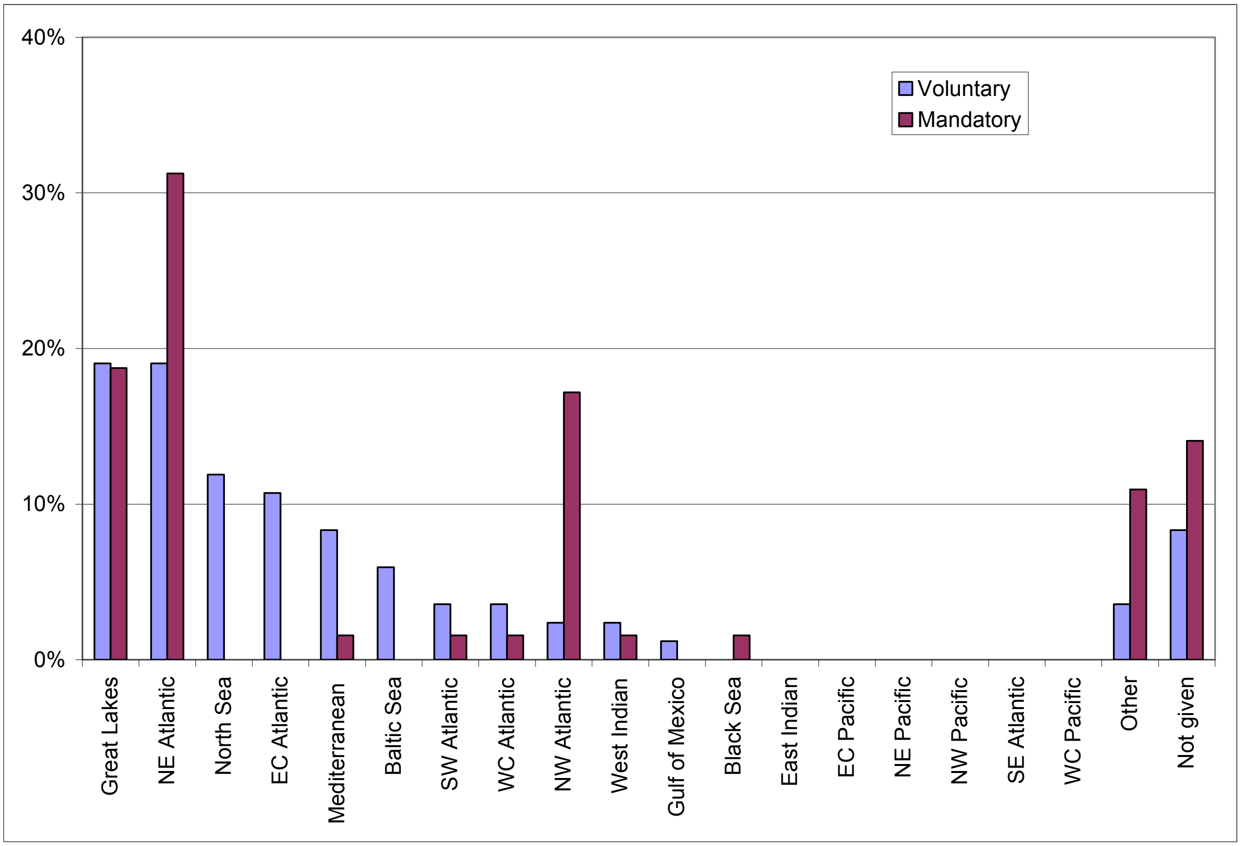
Voluntary
Mandatory
North Sea
NE Atlantic
Baltic Sea
Black Sea
EC Atlantic
Mediterranean
WC Atlantic
NW Atlantic
EC Pacific
Great Lakes
SW Atlantic
NW Pacific
West Indian
East Indian
Gulf of Mexico
NE Pacific
SE Atlantic
WC Pacific
Other
Not given

Figure 1


40%
30%
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Voluntary
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Great Lakes
NE Atlantic
North Sea
EC Atlantic
Mediterranean
Baltic Sea
SW Atlantic
WC Atlantic
NW Atlantic
West Indian
Gulf of Mexico
Black Sea
East Indian
EC Pacific
NE Pacific
NW Pacific
SE Atlantic
WC Pacific
Other
Not given

Figure 2

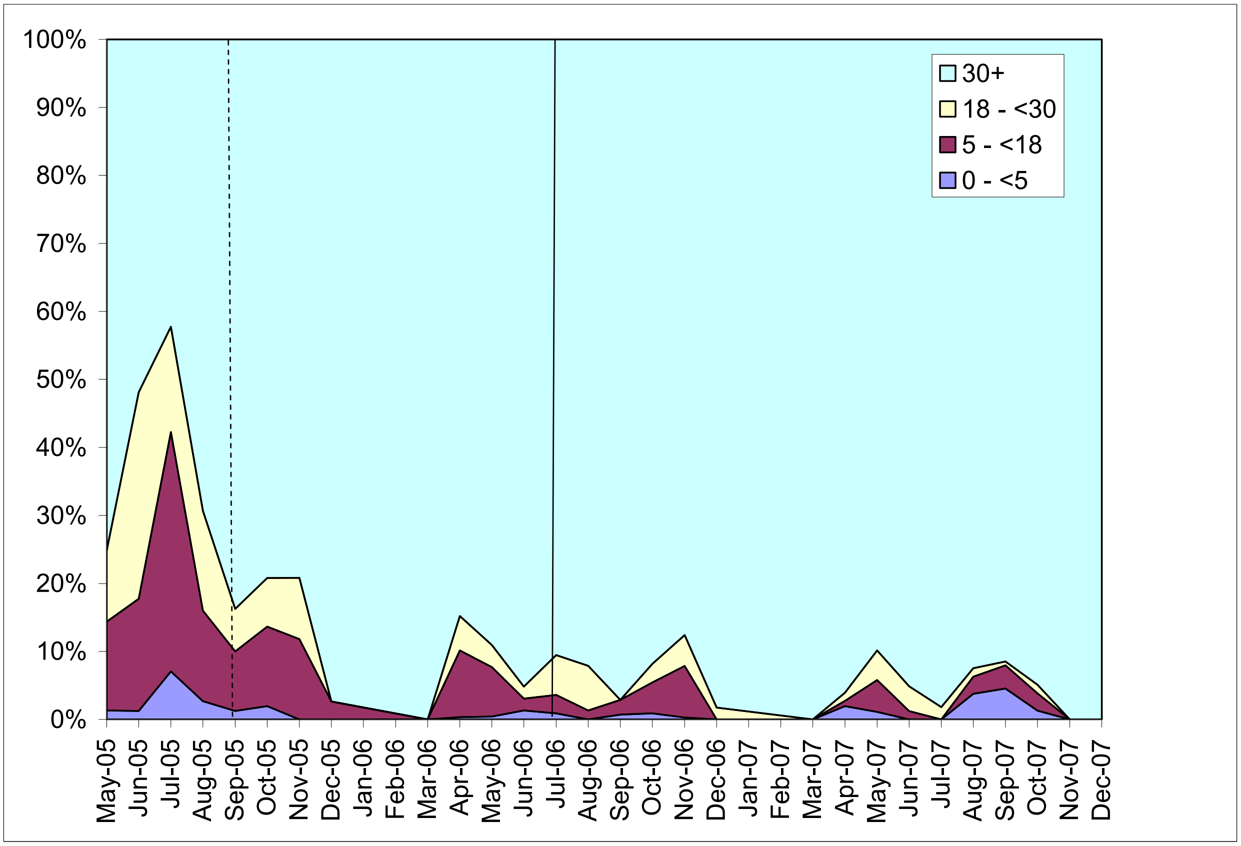
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Figure 3

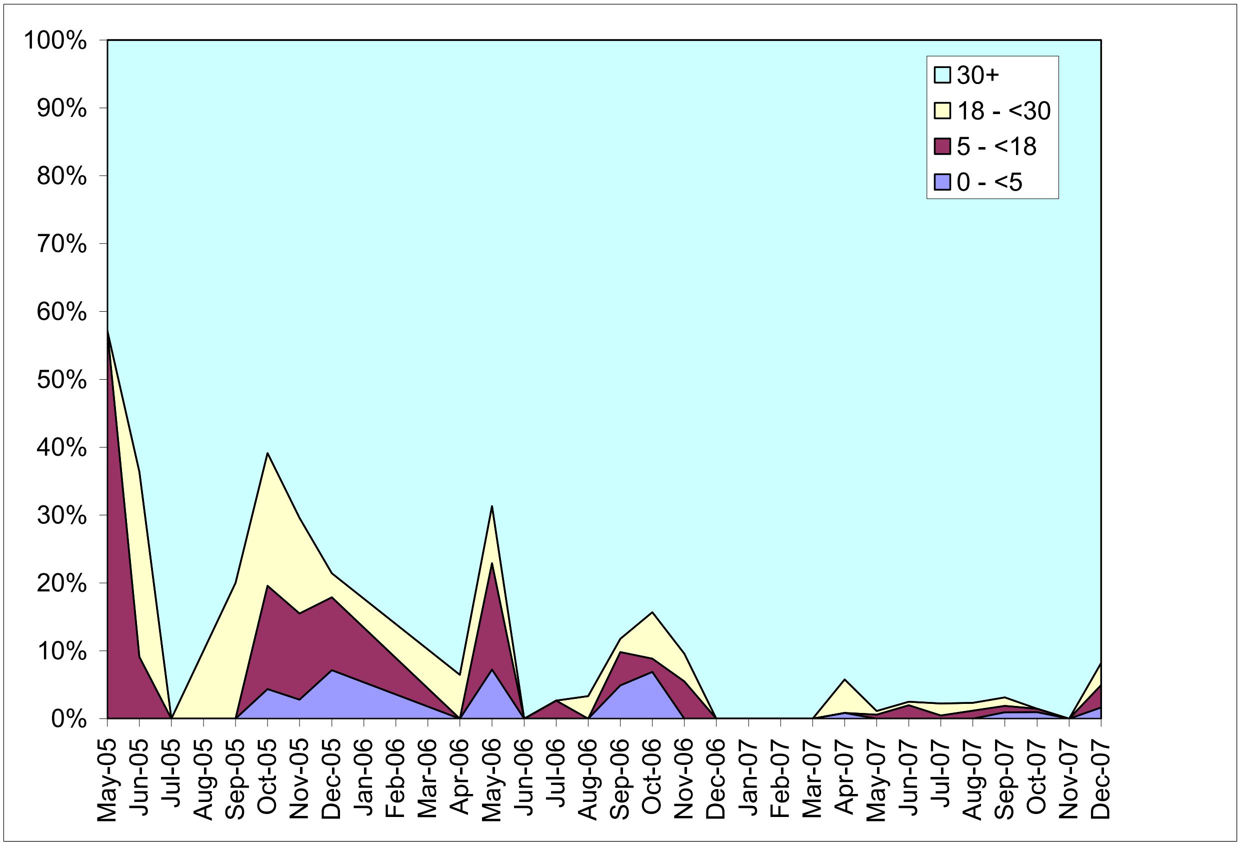


Figure 4

Nine of the fifteen vessels sampled for residual ballast water reported undertaking a ballast water management operation (exchange or flushing) mid-ocean in the North-East (n=6), North-West (n=1), or West-Central Atlantic (n=2). The salinity of the residual ballast collected from these vessels was at or above 30‰ for all but one tank, which measured only 10‰. The remaining vessels did not report the ballast history for the sampled tanks; the salinity for these samples was at or above 30‰ for all but one tank, which measured 20‰. These residual ballast salinities were significantly greater than that measured before 2005 (Mann Whitney test, $p=0.001$; Figure BB). The median total abundance of invertebrates and density of high risk taxa measured from residual ballast were 60.0 ind.m^{-3} and 0.0 ind.m^{-3}, respectively, although variability between ships was high (see Fig. AA); both density values are significantly lower than found in pre-regulation samples (Mann-Whitney test, $p<0.05$).

Samples of residual water from three ships were completely devoid of fauna. The median density of taxa in residual water for all remaining ships sampled was 170.0 ind.•m^{-3} (range 20.0 to 5440.0 ind.•m^{-3}). Harpacticoid and calanoid copepods were the most frequently encountered taxa, recorded in 58.3% and 41.7% of samples, respectively. The taxonomic composition of residual water fauna was diverse, despite the small number of tanks sampled (Appendix 1). Bivalves were the most abundant taxon sampled (35.6% of total abundance), closely followed by polychaetes (32.6%); however, nearly all of the polychaetes were recovered from a single sample. Copepods comprised the next most abundant taxon at 17.9% of total abundance (10.8% nauplii, 9.9% calanoids, 6.3% cyclopoids, and 1.7% harpacticoids). The remaining taxa collectively made up less than 3.5% of total abundance. While there were no predominantly freshwater organisms sampled during the current study, four of the nine taxa identified to the species level are known to have either euryhaline distributions, or have been recorded from brackish waters (*Acartia* nr. *clausi*, *Paracalanus parvus*, *Psuedocalanus minutus* and *Oithona similis*). The salinity of the residual water from which these taxa were sampled was above 30‰ in four of six cases. One of the samples contained only copepod nauplii, while the sample with the lowest salinity (10‰) contained two species of calanoid copepod (*Acartia danae* and *Acartia* spp.). A brief literature search reveals that *Acartia danae* is a marine species that is broadly distributed in the Western Atlantic Ocean, including in the Gulf of St. Lawrence (Owre and Foyo 1967).

Four sets of sediment cores (3 replicates per set) were collected from four vessels during the study period. Depths of cores ranged from 3-17 cm, with the median depth being 7 cm. Over 6800 invertebrate diapausing eggs (and a few active individuals) were enumerated from the cores, including Bryozoan statoblasts, diapausing eggs of rotifers (Asplanchna, Brachionus, and Filinia) and cladocerans (Daphnia, Chydoridae, Moina, Bosmina), as well as harpacticoid copepods, copepod nauplii, polychate worms, Brachionid rotifers and Bosminid and Chydorid cladocerans. The vertical distribution of invertebrate eggs and individuals was patchy, with the maximum abundance recorded in the top 1-2 cm for two sets of cores, while being recorded at 7 and 10 cm depth for the remaining sets (Figure CC).

The ballast history of all but one of the BOB ballast tanks sampled included saltwater exchange in the North-East (n=15), or North-West (n=8) Atlantic. Salinities measured at the time of collection ranged from 25 to 41‰. Ballast water of the single non-compliant tank was marine water from Lobito, Angola with a salinity of 32‰; note that a retention letter was issued by Transport Canada for this tank such that the water was not discharged into the Great Lakes. The salinity of ballast water collected in 2007-08 was significantly greater than that of BOB samples collected prior to ballast water exchange regulation (Mann-Whitney test, $p<0.001$; Figure BB). Comparison of recent samples with historic samples indicates that the density of invertebrates has not decreased significantly. Comparison of recent BOB samples with recent NOBOB samples, indicates that the total density of invertebrates is significantly higher in managed BOB tanks than in managed NOBOB tanks (Mann-Whitney test, $p<0.01$); however, the density of high risk invertebrates in managed tanks does not differ significantly (Mann-Whitney test, $p>0.05$). (Figure AA).

The median density of taxa recorded from BOB tanks was 2672.9 ind.•m^{-3} (range 40.0 to 26220.0 ind.•m^{-3}). Calanoid and cyclopoid copepods were the most frequently encountered taxon, each sampled from 100% of ships; harpacticoid copepods were recorded from 64.3% of ships. Calanoid, cyclopoid and harpacticoid copepods were also the most abundant taxa sampled, comprising 58.9%, 32.4% and 7.2% of total invertebrate abundance. The remaining taxa collectively made up less than 1.5% of total abundance. Five freshwater taxa were recorded infrequently and at very low abundance from two vessels; the single taxon identified to the species level, *Daphnia retrocurva*, is already present in the Great Lakes, although it is unclear if the species is native or introduced (Ricciardi 2006). Five additional species known to inhabit brackish waters (*Acartia tonsa*, *Amphiascus* sp., *Eurytemora hirudinoides*, *Pseudodiaptomus coronatus*, and *Crangon septemspinosa*) were recorded more frequently, although again at very low abundance (see Appendix 1).

List of Figures

Figure AA. Mean (+S.E.) abundance of invertebrates recorded from (a) NOBOB and (b) BOB ships before (black bars) and after (white bars) the introduction of saltwater flushing and ballast water exchange, respectively. Upper panels include data for all taxa; lower panels present data only for high risk taxa known to inhabit fresh- or brackish-water habitats. Data for pre-regulatory period from Duggan et al. (2005) and Bioenvironmental Service, Inc. (1981).

Figure BB. Mean (+S.E.) salinity of ballast water measured from (a) NOBOB and (b) BOB tanks before (black bars) and after (white bars) the introduction of saltwater flushing and ballast water exchange, respectively.

Figure CC. Mean (+S.E.) abundance of invertebrate eggs and taxa by sediment depth, for four vessels (bars). Mean is calculated from 3 replicates for vessel 2 (grey bars) and 2 replicates for all other vessels due to non-uniformity of core depths.

Figure AA.

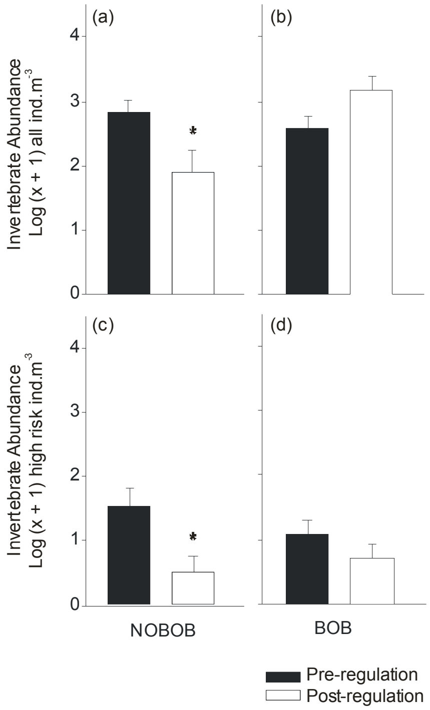


Figure BB.

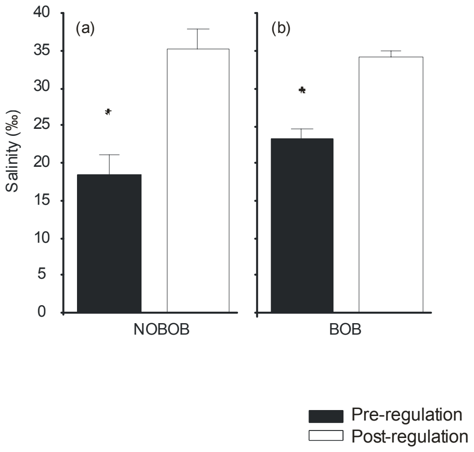
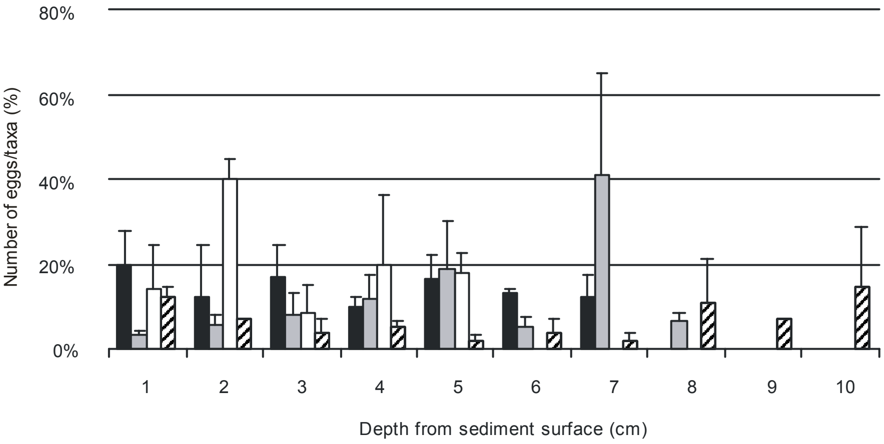


Figure CC.



DISCUSSION

Preliminary analyses indicate that the current joint agency program is very effective. The success of the program appears to be due to the very high level of effort applied by inspectors. Such high levels of inspection will be necessary to ensure any form of ballast water management is effective. Saltwater flushing and ballast water exchange have resulted in ballast water of significantly greater salinity than was observed prior to regulation. Biological samples indicate that the corresponding density of invertebrates has decreased significantly for NOBOB tanks. There appears to be no change in the total density of invertebrates in BOB tanks, although there is a trend towards reduced densities of low-salinity (high risk) taxa.

The lack of significant reduction in invertebrate density for BOB tanks may be due to differences in methodology between the pre- and post-regulation studies. Whereas the pre-regulation study evaluated viability of invertebrates by assessing movement of individuals shortly after collection, we followed the methodology of Duggan et al. (2005), immediately preserving samples in ethanol, considering only severely degraded individuals as being nonviable – we believe the latter methodology is more robust and conservative in terms of evaluating the risk of introduction of NIS, but we acknowledge that densities obtained by this method will likely be much higher than those obtained by the first method.

In addition, the lack of significance for changes in composition of BOB samples may be due to small sample size. Ballast water samples collected from different ships are expected to be highly variable due to differences in ship structure (e.g., depth of water intake, ballast pump capacity) and ballast water history (e.g., locations of source ports and ballast exchange or flushing, length of voyage, time of uptake). Seasonality is also expected to impact plankton composition of ballast water.

Invertebrate density in NOBOB samples collected after 2005 are significantly lower than samples collected before regulation, however, we caution that seasonality may contribute to the decrease since the majority of post-regulation samples were collected in November and December whereas the pre-regulation study was conducted March through December; the limited sample size precluded statistical analysis of seasonality effects for both pre- and post-regulation data.

The biological sampling conducted here indicates that achieving salinity of 30‰ may not completely ensure that only marine taxa will be resident in ballast tanks. This study documented four species recorded from brackish-water habitats or that exhibit euryhaline distributions. These species were present in 6/28 (21.4%) tanks sampled, four of which had residual water salinity greater than 30‰; this indicates that ballast water management practices for NOBOB vessels will not provide complete protection from aquatic NIS. This study suggests that an unquantified level of risk still remains for brackish-water or euryhaline taxa. To be conservative, we must assume that all brackish-water or euryhaline species could survive and reproduce if introduced to the Great Lakes, although the particular individuals present in high salinity tanks might not be able to persist at the lowest salinity inhabited by that taxon globally, especially if the switch from high to low salinity is very abrupt.

We present here the first analysis of the vertical distribution of diapausing eggs in ballast sediment, and though the sample size was very small, the results presented here indicate that the vertical distribution of diapausing eggs in residual sediments is patchy. Hatch rates near 80% are expected for diapausing eggs distributed in the top 2 cm of sediment, with the rate of hatching significantly decreasing below this depth (Marcus 1996, Bailey et al. 2005). Thus, previous estimates of the proportion of diapausing eggs able to hatch from sediments in ballast tanks of ships operating on the Great Lakes (<1%) that were based on an assumption of homogenous vertical distribution (Bailey et al. 2005b) may be underestimates if the patches of eggs occur in the top two cm of sediment. Conversely, as was reported in 50% of the cores studied here, if the eggs are distributed deep in the sediments (perhaps 5 cm or deeper), the eggs may have no opportunity to hatch, and so pose little risk. More work is needed in this area in order to determine if predictive factors correlated with the vertical distribution of eggs in ballast sediments can be isolated, in an effort to develop best management practices to prevent NIS introductions by resting eggs.

B. BALLAST WATER HYDRODYNAMICS STUDY

Ballast water carried by commercial ships is presumably responsible for 65% of aquatic invasive species' (AIS) introductions to the Great Lakes since 1959 (Ricciardi 2006). Numerous technologies to manage ballast water on commercial ships are in various stages of development, and the International Maritime Organization (IMO) has proposed minimum ballast water discharge standards which must be met for any technology to receive approval (IMO 2004). The IMO standard is density based, with set concentration limits for specific groups of taxa that must be met before a technology is granted approval (e.g., 10 individuals·m^{-3} for taxa greater than 50 µm in minimum dimension). 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 Ruiz 2002). AIS discharged at IMO densities are expected to have very low establishment probabilities primarily as a result of density-dependent demographics that will be inhibited as the 'block' of water discharged from a ship is rapidly diluted and dispersed into the receiving water. However, ballast water is almost exclusively discharged in the Great Lakes while ships are at port. Due to infrastructure concerns, port locations are often sheltered areas with limited water flow. Thus, delayed or limited dispersion may increase establishment probabilities of low density inocula if released propagules are maintained in a cohesive unit of water (see Drake et al. 2005). Furthermore, studies have shown that physical factors such as wind and currents or eddies can result in plankton patches that are orders of magnitude greater than median densities in the surrounding area (Pinel-Alloul 1995; Martin & Srokosz 2002; Thackeray 2004). As a result, passive aggregation of plankton due to physical water movements may allow released propagules to accumulate post-discharge, possibly at densities much higher than the discharge density.

This project builds on a 2008 CAISN-funded project (PIs Sarah Bailey, Fisheries and Oceans Canada - Great Lakes Laboratory for Fisheries and Aquatic Science and Mathew Wells U. of Toronto), to trace dilution, retention, and dispersal of ballast water in Goderich Harbour. We augmented this study with an innovative (Ruddick & Taggart 2006) technique that uses small, environmentally friendly and neutrally-buoyant magnetically-attractive drifting particles and an array of moored magnetic collectors. The array-based system directly provides the Lagrangian path of the particles and the time-integrated Eulerian particle concentration in space (locations) for directly estimating the probability of transfer of biological propagules from the ballast water release site to distant locations (1 to 10s km). The synergistic combination of the dye (small-scale) and particle (large-scale) methods will allow us to completely characterize the rates of mixing, dispersion, and transport from scales of a few meters to many tens of kilometers, over timescales of minutes to more than a week. The information allows the physical dispersive processes that affect invasive species establishment and propagation to be completely quantified. Empirical dispersion and transport measures are essential for any model attempting to address invasive species ecology and also have direct application to problems involving prediction and modeling of pollution, toxins, contaminants, suspended particulates, biological propagules and ecosystem connectivity. The objectives of this component of the project are: 1) Directly measure the dispersal/dilution rate of actual ballast water discharged by a vessel in a port to determine if it disperses quickly – intrinsically relevant to the probability of an invader becoming established (the propagules pressure hypothesis). 2) Determine the time/space scales of ballast-water dispersion in the St. Clair River corridor. 3) Use the collector array to secure direct measures of the spatial probability of particle exchange i.e. provided a direct and testable measure of the ballast water dispersion kernel for the Huron – Erie corridor. 4) Determine the dispersion factors that affect transport from a ballast water source to potential sinks. 5) Assess how survey-based dye-dispersal time/space scales and logistics compare with array-based particle-dispersal. 6) Directly compare empirically-derived Lagrangian tracing data with model derived dispersal predictions.

METHODS

During the period 14 through 24 July 2008 scientific staff were on site in Goderich on Lake Huron. Particle collectors were deployed in Goderich harbour (see *fig 2.*) and up and down the coast roughly ten kilometers total in each direction (see *fig 1.*). On July16 roughly one million particles were pumped into the ballast tank near the exit bell-mouth (see *fig 5.*) of the vessel ***MV Algoway*** as it was pumping out its ballast tanks. Particles were dispersed/transported in the harbour, and out, with the ballast water and were collected by the collectors for a period of roughly 4 days. During this time net tows were conducted on the same boat as was towing the fluorometer for dye concentration measurements. On July 20th the collector magnets were collected and replaced with new ones in preparation for a second release. The 21st of July saw a new particle release from the same location but from a new ship, the ***MV Capt. Henry Jackman***. The collectors were left in the water for about 2 days before final retrieval. During this time net tows were conducted.

RESULTS

Results to this point are qualitative. We are currently working on a quantitative analysis of the results. We are working on counting/methods of counting the particles on the collectors. Preliminary results stated below are based mainly on our observations in the field.

Based on qualitative estimates of particles on the collectors (see *Fig 1.* and *Fig 2.* for collector array) we found the inner harbour to be a fairly stagnant environment with a slow turnover time. We presume this is due to the lack of water influx into the system and the very small and narrow opening of the harbour.

The coast around Goderich runs roughly north to south (see *Fig 1.*). When particles leave the inner harbour it appears, based on qualitative counts for both releases, that there are predominately wind-driven long shore currents set up in the north/south directions (see *Fig 3.*) depending on local weather conditions, i.e. a wind blowing from the south creates a northward coastal current. These currents carry matter either northward or southward depending on the local wind conditions. This is tentatively concluded based on qualitative estimates of particle numbers on the collectors for the two separate releases. Wind directions were predominately southerly for first particle release and northerly for the second particle release (see *Fig 3.*).

Qualitatively it was seen that higher dye concentration did seem to yield more particles captured in the net-tows as opposed to areas surveyed with lower dye concentration. To what extend remains to be seen after analysis.

Fig 1. *map showing the locations of the particle collectors for the two releases. North is up.*

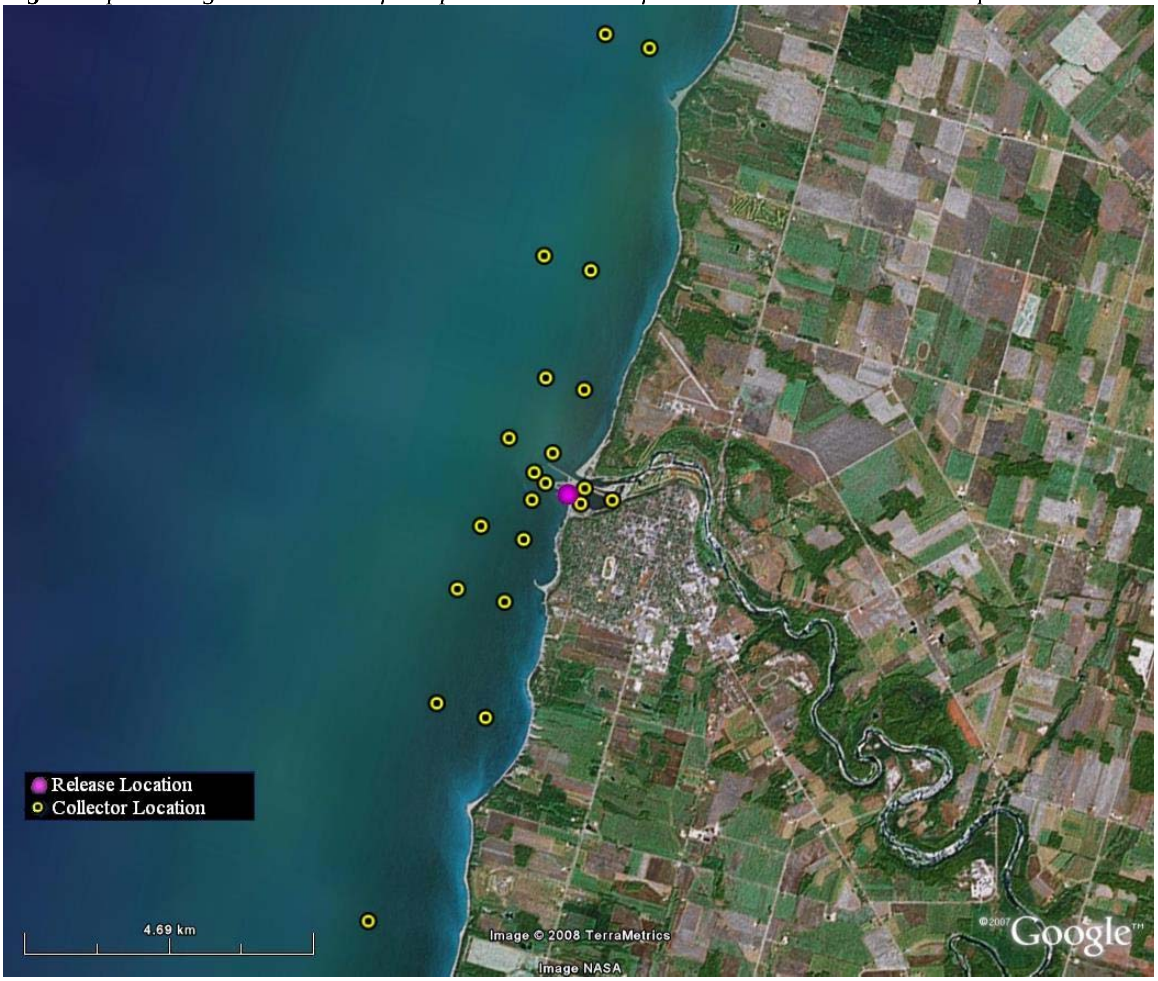


Fig 2. *Map showing details of the Goderich harbour field site. North is up. Tracks shown for net towed surveys are examples only. Complete tracks for all net tow surveys, as well as other positional data, can and will be extracted from the original Garmin database file* Goderich08Fieldwork.gdb *in future analysis*.

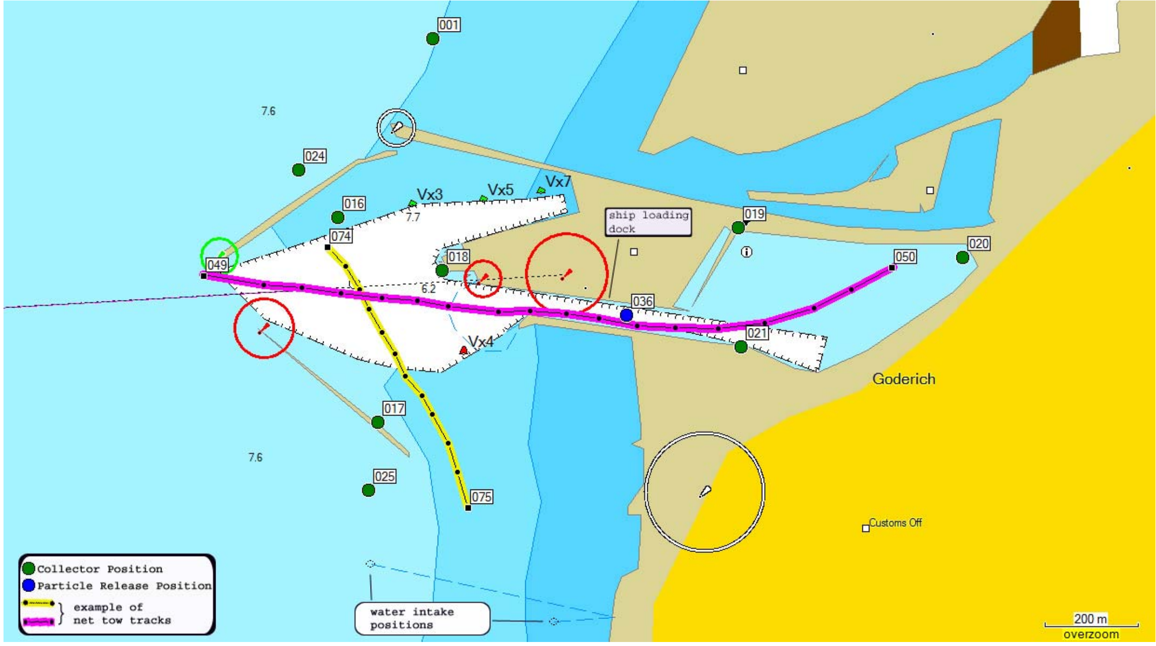


Fig 3. *Wind Data in the northerly direction from Sarnia Airport (larger town about 100 km to the south of Goderich) plotted over the timeframe of the field work. Times of the two releases and capturing periods are highlighted. Notice for the first release that the winds were predominately south and for the second release north, and stronger. Also notice the strong south spike before the first release and the strong north spike before the second release. We couldn't quickly find Meteorological data from Goderich but will find it for future analysis. We believe this wind data to be indicative of winds in Goderich.*

DISCUSSION

Analyses are underway, but preliminary results indicate that current management practices for foreign ballast water have resulted in a lowered risk of invasion. It also appears that artificial augmentation of ballast water salinity may be a viable management strategy to address non-compliant tanks.

ACKNOWLEDGEMENTS

L. Jean and M. Edwards graciously provided information about, and data from, the Canadian and U.S. Great Lakes ballast water inspection programs, respectively. S. Santavy, L. Quiring and C. Wiley assisted with collection of ballast water samples. B. Ruddick and C. Taggart were contracted to conduct magnetically-attractive particle work. J. Gerlofsma and M. Hatcher assisted with Goderich field work. Assistance and cooperation of Seaway Marine Transport, and the Canadian Coast Guard – Goderich base are appreciated. Biologica Environmental Services were contracted for analyses of zooplankton samples.

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Appendix 1

	15 ships		14 ships	
TAXON (NOBOB)	**NOBOB**		**BOB**	
	#/m3	**% Occurrence**	**#/m3**	**% Occurrence**
CNIDARIA				
Cnidaria indet.			0.64	14.29
NEMERTEA				
Nemertea indet.			2.02	7.14
ANNELIDA				
Polychaeta				
Capitellidae indet.	1380.00	8.33		
Hesionidae indet.	1260.00	8.33		
Pectinaridae indet.	180.00	8.33		
Phyllodocidae indet.	1760.00	8.33		
Spionidae indet.	100.00	16.67		
Aphroditidae indet.			10.00	7.14
Phyllodocidae indet.			14.51	7.14
Spionidae indet.			20.27	21.43
Polychaeta indet.			0.67	7.14
MOLLUSCA				
Bivalvia				
Bivalvia indet.	1306.67	33.33	32.80	35.71
Gastropoda				
Gastropoda indet.	123.33	16.67	42.16	35.71
CRUSTACEA				
Crustacea indet.	390.00	33.33	177.59	35.71
Cladocera				
Bosmina (Neobosmina) sp.			6.67	7.14
Bosmina sp.			8.49	7.14
Daphnia retrocurva			4.75	14.29
Daphnia sp.			2.83	7.14
Diaphanosoma sp.			16.67	7.14
Copepoda				
Calanoida				
Calanoida indet.	125.83	33.33	3739.54	100.00
Acartia nr.clausi.	40.00	16.67		
Acartia danae	60.00	16.67		
Acartia tonsa			86.45	50.00
Calanus helgolandicus			181.40	35.71
Centropages abdominalis	40.00	16.67		
Centropages typicus			73.89	28.57
Eurytemora hirudinoides			0.67	7.14
Gaetanus sp.			3.33	7.14
Mecynocera clausi			9.84	7.14
Metridia curticauda			1.68	7.14

Metridia lucens			81.56	14.29
Microcalanus pygmaeus			6.61	21.43
Paracalanus parvus			44.64	85.71
Pseudocalanus elongatus			56.67	64.29
Pseudodiaptomus coronatus			26.93	28.57
Scolecithricella emarginata.	40.00	8.33		
Scolecithricella spp.			10.00	14.29
Paracalanus parvus.	130.00	16.67		
Paracalanus spp.	120.00	16.67		
Pseudocalanus minutus	60.00	16.67		
Cyclopoida				
Cyclopoida indet.	10.00	8.33	20.39	14.29
Corycaeus spp.	10.00	8.33		
Oncaea borealis	50.00	16.67	194.29	50.00
Oncaea spp.	360.00	8.33		
Oithona helgolandicus			1269.18	85.71
Oithona similis	142.22	25.00		
Oithona spp.	64.44	25.00		
Clausidiidae indet.			390.31	7.14
Harpacticoida				
Harpacticoida indet.	34.44	50.00	1.85	7.14
Diosaccidae indet.	40.00	8.33		
Amphiascus sp.			29.09	21.43
Macrosetella gracilis			1.86	7.14
Microsetella rosea			833.64	57.14
Ostracoda				
Ostracoda indet.	20.00	16.67		
Cirripedia				
Cirripedia indet.	80.00	8.33	1.41	7.14
Mysidacea				
Boreomysis sp.			0.94	7.14
Isopoda				
Isopoda indet.			10.00	7.14
Amphipoda				
Parathemisto libellula			5.31	14.29
Parathemisto sp.			16.69	14.29
Euphausiacea				
Euphausiacea indet.			3.08	7.14
Euphausia sp.			3.33	7.14
Hyperiidea				
Parathemisto gracilipes	66.67	8.33		
Decapoda				
Alpheidae indet.			1.81	7.14
Crangon septemspinosa			0.94	7.14
ECHINODERMATA				
Ophiuroidea				
Ophiuroidea indet.			2.02	7.14
Echinoidea				
Echinoidea indet.			0.67	7.14
UROCHORDATA				

Larvacea				
Oikopleuridae indet.	20.00	8.33		
CHAETOGNATHA				
Eukrohnia spp.			1.81	7.14
Sagitta spp.			0.71	7.14