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# Low salinity residual ballast discharge and exotic species introductions to the North American Great Lakes

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**Abstract**

Exotic species introductions to the North American Great Lakes have continued even though ballast water management strategies were implemented in the early 1990s. Overseas vessels that arrive with little or no exchangeable ballast on board have been suspected to be an important source for discharging low salinity ballast containing low salinity tolerant organisms in this region. Residual ballast averaged 18.1 ± 13.4‰ salinity among 62 samples taken primarily from bottom tanks on 26 vessels that entered the Great Lakes in 1999 and 2000. Sampling of 2–4 tanks each on nine vessels indicated all carried at least one tank of residual ballast of $\leqslant$ 5‰ salinity. Many of these transits originated from the northeast Atlantic, Mediterranean and Black Sea regions which have been the probable source for many of the more recent introductions to this region.


*Keywords:* Environmental monitoring; Ballast water; Salinity; Exotic species; Great Lakes

## 1. Introduction

Exotic species have noticeably affected the integrity and stability of the North American Great Lakes ecosystem. This observation is based on the number of species introduced, frequency of introduced species that have become invasive, their effects on lake community structure and function, and economic costs attributed to their effects (Mills et al., 1993; Madenjian, 1995; Dermott and Kerec, 1997; Niimi, 2000a; Pimentel et al., 2000). Introductions have continued since the mid-1800s through intentional and unintentional releases, and range extensions through waterways and channels. The rate of introduction and level of impact increased after 1960, which coincided with the opening of the Great Lakes-St Lawrence Seaway system (GL-SLS) that increased access by overseas vessels to all the lakes. Introductions through ballast water discharge became a major concern because it is one of few means that can account for the taxonomic diversity among introduced species, considerable distances between distribution points, and rapid dispersion among the lakes (Niimi, 2000a). The invasive effects of a ballast-introduced species gained global prominence with the discovery of zebra mussel (*Dreissena polymorpha*) in the Great Lakes in 1988 and its rapid spread in eastern North America to the Gulf of Mexico by 1993 (Hebert et al., 1989; Miller and Payne, 1997).

Canada implemented a voluntary ballast water management plan in 1989 to reduce the risk of exotic species introductions to the Great Lakes (IJC-GLFC, 1990). Overseas vessels destined for this region were requested to conduct an oceanic ballast exchange in waters over 2000 m in depth before passing longitude 64°W. The effectiveness of this action to protect a freshwater ecosystem is based on the removal of fresh, brackish and coastal marine organisms initially retained when the original ballast is exchanged or flushed; enhanced mortality of the remaining low salinity tolerant organisms as seawater is exchanged; and low survival probability for marine organisms released into freshwater. The US passed the *Nonindigenous Aquatic Nuisance Species Act* in 1990 which included a provision that made ballast water exchange mandatory for vessels entering the Great Lakes and Hudson River from outside the economic enforcement zone (EEZ) beginning in 1993. The Federal Register, Title 33 Code of Federal Regulation part 151.1510(a)(1) states a ballast tank

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salinity of 30‰ or higher would be in compliance. This regulation is applicable to all overseas vessels entering the Great Lakes because part of the St Lawrence River navigation channel is under US jurisdiction.

Mandatory exchange has been the key strategy to reduce the risk of introductions, yet five new crustaceans and one ciliate were reported between 1995 and 1999 (Witt et al., 1997; Grigorovich and MacIsaac, 1999; MacIsaac et al., 1999; Grigorovich et al., 2001; Horvath et al., 2001). Continuing introductions could be attributed to the discharge of low salinity ballast containing low salinity tolerant organisms. A probable source for low salinity water is incoming overseas vessels that carry little or no exchangeable ballast. These vessels report their status as no ballast on board (NOBOB) to authorities, and account for over 80% of the overseas vessels that enter the Great Lakes annually (Niimi, 2000a). This study monitored salinity and depth of this residual ballast in NOBOB vessels to estimate the frequency and volume of low salinity ballast carried into the Great Lakes.

## 2. Materials and methods

### 2.1. Sampling point

The GL-SLS is a 3770 km navigable inland waterway that extends from the Atlantic Ocean to Lake Superior. Vessels moving between the St Lawrence River and Great Lakes sections must pass through a series of locks near Montreal, QC. Incoming overseas vessels that reported no exchangeable ballast were identified using the Department of Fisheries and Oceans vessel information database. A request for permission to board was made to the vessel agent, or the Control Office of the St Lawrence Seaway Authority, Montreal, QC in 1999, and the St Lawrence Seaway Management Corporation, Cornwall, ON in 2000. Twenty-one vessels were boarded at the St Lambert-Cote Ste. Catherine locks near Montreal between September and November 1999. An additional 19 vessels were boarded between July and November 2000.

### 2.2. Data collection

A boarding report was completed that included the vessel name, type, gross registered tonnage (GRT), dedicated ballast tank capacity and country of registry. Specific information on each transit included date and port of departure, first Great Lakes port of call and expected date of arrival, and next foreign destination. Information on the history of the ballast included location, date and volume where uptake and discharge occurred, and volume of unpumpable ballast carried into the Great Lakes. This information was generally provided by the Captain or Chief Officer.

A boarding period of approximately 1–2 h usually allowed 1–4 ballast tanks to be accessed on a vessel. Ballast water depth and salinity measurements were taken through the 3–5 cm diameter sounding tube that extended from the deck to the top of each tank. Salinity was measured using a Yellow Springs Instruments 30 SCT meter with a 15.2 m probe in 1999. This method was not always successful because the distance between the deck and water in bottom tanks can exceed the length of the probe. A Vee GeeATC salinity refractometer was also used in 2000 to sample water beyond the length of the probe. A water sample for the refractometer was taken with a $2.5 \times 14$ cm sample tube attached to a cable, a check value on the bottom of the tube allowed depths less than 4 cm to be sampled (Campbell Manufacturing, Bechtelsville, PA). A PVC tape with a plumb bob was first lowered to measure the distance from the deck to the tank bottom, and the water depth. A salinity probe or sample tube was attached to the tape and lowered to the center of the water column for salinity determination. Both instruments were calibrated at irregular intervals using a standard saline solution. Most of the samples were taken from bottom tanks, with some wing, topside, forepeak and aftpeak tanks also sampled. One salinity sample was taken from each tank.

### 2.3. Data screening

Salinity and depth values were excluded if the measurements were questionable. Measurements in water less than 1 cm in depth were often not accepted because of the probe bumping the bottom, or the water sample was turbid. Water depth can be questionable due to vessel list, or not at even keel. Salinities from three transits were not included of because some exchanges occurred in North American coastal waters. Boarding Reports were screened for incomplete information. Ballasting and/or deballasting occurred several times before a vessel arrived at the port of departure on 12 transits. These data were adjusted according to the percentage of total volume exchanged, and days and distance between the points of exchange and the port.

### 2.4. Data evaluation and reporting

Ballast salinity and depth were reported for bulk carriers, tankers and general cargo vessels. Salinities were reported by groups according to the Venice classification system, but modified to include a group of $\geqslant 30$‰ salinity because of its regulatory implication (Perkins, 1974). The groups included <0.5‰ (freshwater), 0.5–5‰ (oligohaline), 5.1–18.0‰ (mesohaline), 18.1–29.9‰ (polyhaline) and $\geqslant 30$‰ salinity (euhaline). Ballast depths in bottom tanks were reported in 5–10 cm increments to examine their frequencies at shallower depths. Ballast volumes recorded as metric tonnes were converted to cubic meters to account for differences in density between sea and freshwater.

History of the ballast included days it was held, and distances between where it was taken and discharged. Geographic regions where these events occurred were based on Food and Agriculture Organization (FAO) major fishing areas (Times Book, 1983). These regions were the Northeast Atlantic (NEA), East Central Atlantic (ECA), Southeast Atlantic (SEA), Northwest Atlantic (NWA), West Central Atlantic (WCA), Southwest Atlantic (SWA), Mediterranean and Black Seas (MBS), Northwest Pacific (NWP), West Central Pacific (WCP), Southwest Pacific (SWP), East Indian Ocean (EIO), and West Indian Ocean (WIO). Distances between transit points were calculated using the "latitude/longitude distance calculation" that was available at http://www.nau.edu/~cvm/latlongdist.html. Coordinates were obtained from a world atlas. Kingston, ON was used as the reference point to calculate distances between vessel transit points and the Great Lakes. Actual route of a transit was longer than the calculated distance which was based on a linear transect.

Residual ballast is described as water that remain after deballast. Tank location and position of the outflow pipe may not allow some tank types to be emptied. It can also include small volumes retained that could be, but are not exchanged. Volume of residual ballast in bottom tanks of a vessel was estimated as tank depth multiplied by 60% of the length × width of a vessel to account for the curvature of the hull. A 50% coefficient may be applied to older vessels and 70% to newer vessels because of their hull design (P.T. Jenkins and Associates Ltd., Font Hill, ON, personal communication). A 218 m by 21 m vessel was used because this is the largest size that can enter the Great Lakes, and represent about 41% of all vessel transits (SLSA, 1996).

Data were reported as mean ± SD and range, or as percentages. Observations on salinities were based on comparisons that focused on the $\leqslant 5‰$, $\leqslant 18‰$ and $\geqslant 30‰$ salinity groups. Statistical comparisons were not applied because salinity and depth measurements were reported in groups, and the number and types of tanks sampled varied among vessels.

### *2.5. Related studies*

Five other studies were reviewed for comparative purposes because of their relevance. These studies reported salinity measurements and biological observations in ballast tanks of overseas vessels that entered the Great Lakes region between 1980 and 1996. The data were screened using the same criteria applied to this study. Enumerations were largely limited to phytoplankton and zooplankton species.

The Bio-Environmental study (1981) reported 55 vessels were boarded at Montreal between August and October, 1980. One salinity value each was reported for 46 vessels, but tank type was not indicated and information on ballast history was limited. There were 24 transits that departed from the NEA region, 14 from MBS, and 8 transits from three other regions. Survival rates were reported for phytoplankton, zooplankton and other taxa.

Locke et al. (1991) reported 97 vessels were boarded at Montreal between April and December, 1990. One salinity value each was reported for 81 vessels, but tank type not indicated. Full exchange was conducted by 38 vessels, and ballast history on 43 vessels ranged from partial exchange to unknown. There were 34 transits from NEA, 18 from NWA, 11 from MBS, 6 from WCA, 6 transits from two other regions, and 6 were unknown. Zooplankton survival rates were reported for 12 taxa.

Locke et al. (1992) also reported 27 vessels were boarded at Montreal between April and May, 1991. One salinity value each was reported for 23 vessels. Full exchange was conducted by 12 vessels, 8 conducted a partial exchange or flush, and 3 were unknown. There were 10 transits from the NEA, 9 from MBS, 3 transits from two other regions, and 1 was unknown. Zooplankton survival was reported on a yes or no basis for 12 taxa.

The Aquatic Sciences study (1996) reported 80 vessels were boarded at the Welland Canal between October and December, 1995. Salinities were reported for 60 samples taken on 30 vessels from four tank types. One tank was sampled on 15 vessels, 2 tanks on 6 vessels, 3 tanks on 6 vessels, 4 tanks on 2 vessels, and 7 tanks on 1 vessel. Ballast history indicated 20 vessels were NOBOBs, and 10 vessels carried exchangeable ballast volumes. There were 13 transits from NEA, 7 from MBS, 8 transits from five other regions, and 3 were unknown. Zooplankton species were identified in tanks, but no survival rates were reported. Volumes of residual ballast discharged by ocean-going vessels at several Great Lakes ports were also reported.

Harvey et al. (1999) examined the biological content in ballast from 88 vessels that entered ports along the Estuary and Gulf of St Lawrence between February 1995 and January 1996. Tanks sampled were not identified, and no salinity values were reported. There were 65 transits from NEA, 11 from MBS, 10 from NWA, and 2 from WCA. The 390 phytoplankton and zooplankton genera or species were reported on a live or dead basis. Zoogeographic distributions were reported by regions for many species.

## 3. Results

### *3.1. Vessel size*

There were 19 bulk carriers and 2 tankers boarded in 1999, and 16 bulk, 2 general cargo vessels and 1 tanker boarded in 2000. One bulk carrier was boarded in both years. The 39 vessels were registered in 19 countries that did not include Canada or the US. GRT among the 34 bulk carriers averaged 17,866 ± 3240 tons (8960–23,306 tons), and dedicated ballast tank capacity 9635 ± 2059 $m^3$ (4306–14,026 $m^3$). GRT ranged from 5207 to 6544 tons, and dedicated ballast tank capacity from 1270 to 3774 $m^3$ for the three tankers, and 5968 to 14,153 tons, and 3390 to 4017 $m^3$ for the two cargo vessels respectively.

### 3.2. Ballast salinity

Salinity averaged 18.1 ± 13.4‰ (0–45‰) among 62 samples taken from 26 vessels (Table 1). Salinity averaged 16.3 ± 12.2‰ for 28 bottom tanks, 13.0 ± 16.9‰ for wing, 29.7 ± 11.1‰ for topside, 26.2 ± 15.6‰ for forepeak, and 27.4 ± 9.4‰ for aftpeak tanks. Salinities below 30‰ were found in 81% of the 42 bottom tanks, compared to 40–62% for the other tank types although the number of tanks sampled was low. Overall, 44 of the 62 tanks sampled had salinities below 30‰.

There were 18 vessels where 2–4 tanks were sampled. Differences among salinity groups were found on 4 of 7 vessels where 2 tanks were monitored, 3 of 4 vessels where three tanks were monitored and all seven vessels when four tanks were monitored. Salinities of ⩾ 30‰ were observed on 12 of the 18 vessels, but 8 also had at least one tank <30‰ salinity. Salinity averaged 19.0‰ (0–45‰) for the 8 vessels where one tank was sampled, that included two values of ⩾ 30‰.

### 3.3. Ballast depth

Depth ranged from 0 to 90 cm among 94 tanks monitored on 34 vessels (Table 2). Depth averaged 6 ± 6 cm for 63 of 72 bottom tanks with measurable volumes. Depths exceeded 10 cm in 10 bottom tanks, some were attributed to broken pipes and related problems. Some of the nine dry bottom tanks were found on vessels equipped with stripping pumps that can remove residual water by aerosol suction. Limited measurements on the other four tank types generally indicated greater mean depths and larger ranges. Residual ballast averaged 50 ± 33 $m^3$ (1–250 $m^3$) among 34 reporting bulk carriers. These volumes represented 0.54% (0.01–1.56%) of the ballast tank capacity. Residual ballast ranged from 10 to 45 $m^3$ for tankers, and 13 to 39 $m^3$ for cargo vessels. Temperatures of the ballast sampled ranged from 8 to 20 °C during 1999, and 4 to 22 °C during the 2000 sampling periods.

Table 2
Depth of water (cm) in 94 ballast tanks on 34 vessels by tank type

| Tank type | *N* | Mean ± SD | Range |
|---|---|---|---|
| Bottom | | | |
| Dry | 9 | – | |
| 1–5 cm | 40 | 2.8 ± 1.3 | 1–5 |
| 6–10 cm | 13 | 8.5 ± 1.3 | 6–10 |
| 11–20 cm | 8 | 13.8 ± 2.8 | 12–20 |
| >21 cm | 2 | 30 | 22–38 |
| Wing | 7 | 8.6 ± 4.9 | 3–15 |
| Topside | 6 | 46.7 ± 28.7 | 24–90 |
| Forepeak | 6 | 13.0 ± 18.5 | 1–50 |
| Aftpeak | 3 | 12.0 ± 4.6 | 4–20 |

### 3.4. Ballast history

Bulk carriers arriving at the port of departure carried ballast that averaged 92% (52–100%) of their dedicated tank capacity. About 98% (66–100%) of this ballast was discharged near the port of departure when cargo was loaded before leaving for the Great Lakes. Ballast was taken on 41 ± 19 days (13–89 days) before a carrier entered the Great Lakes, including 29 ± 15 days (11–69 days) at a residual level after a carrier left the port of departure. Distance between the point of ballast uptake and port of departure averaged 1950 ± 2290 km (0–8650 km). Distance between the port of departure and the Great Lakes averaged 7860 ± 2420 km (5400–15,400 km).

Table 1
Number of measurements in each salinity group, and range, among 62 ballast tanks sampled on 26 vessels by tank type

| Tank type | Salinity group | | | | |
|---|---|---|---|---|---|
| | <0.5‰ | 0.5–5‰ | 5.1–18‰ | 18.1–<30‰ | ⩾ 30‰ |
| Bottom | 4 | 5 | 15 | 10 | 8 |
| ‰ range | 0–0.4 | 1.8–4.8 | 5.5–17.9 | 18.1–26.8 | 30.5–40.4 |
| Wing | 1 | 4 | | | 3 |
| ‰ range | 0.3 | 0.5–1.0 | | | 32.0–34.2 |
| Topside | | | 1 | 1 | 3 |
| ‰ range | | | 11.2 | 27.2 | 36.1–37.3 |
| Forepeak | | | 2 | | 3 |
| ‰ range | | | 6.0–14.6 | | 32.2–45.0 |
| Aftpeak | | | | 1 | 1 |
| ‰ range | | | | 20.8 | 34.0 |
| Total | 5 | 9 | 18 | 12 | 18 |

Tankers arriving at the port of departure carried 89–100% of ballast tank capacity, and all was discharged when cargo was loaded. Ballast was taken up at 17–81 days, and residual ballast was held for 14–54 days before tankers entered the Great Lakes. Cargo vessels took 100% of tank capacity, and discharged all at the port of departure. Ballast was taken up 13–36 days, and any residual ballast held for 11–22 days. Distances between point of ballast uptake and discharge ranged from 80 to 5140 km, and the point of discharge and Great Lakes from 5730 to 13,260 km for tankers, and 670 to 1410 km, and 5400 to 8590 km for cargo vessels respectively.

### 3.5. Transit patterns

Transit information on 38 bulk, tanker and cargo vessels indicated ballast uptake, discharge and port of departure occurred in 10 FAO regions. All three activities occurred in the same region for 25 transits, including 13 in NEA, 6 in NWP, 3 in MBS, and 3 transits in other regions. Eighteen incoming transits listed their first port of call on Lake Ontario, 17 on Lake Erie, 4 on Lake Michigan, and 1 on the upper St Lawrence River. Outgoing patterns were less clear where 16 transits were destined for ports in NEA, 6 for ports in four other regions, and 16 transits noted their next port of call as unknown or did not respond.

## 4. Discussion

### 4.1. Ballast salinity

The high frequency of low salinity residual ballast carried by overseas vessels would provide the means to transport low salinity tolerant organisms to the Great Lakes. This study found 23% of 62 measurements were $\leqslant 5‰$ salinity, and 71% were $\leqslant 18‰$ (Table 3). Among the 26 vessels monitored, 35% carried at least one ballast tank of $\leqslant 5‰$ salinity, and 77% with one tank of $\leqslant 18‰$. Frequencies of low salinity were lower among the other four studies where a single sample was taken on each vessel. Excluding the 50 vessels that conducted a full ballast exchange, 15% of the 160 measurements were $\leqslant 5‰$ salinity, and 27% were $\leqslant 18‰$. Among the 130 vessels that entered the Great Lakes, 16% carried one tank of $\leqslant 5‰$ salinity, and 40% with $\leqslant 18‰$. These lower frequencies may also be due to less bottom tanks sampled because of access difficulties and need for larger water volumes for biological enumerations.

Ballast salinity should exceed 30‰ following a full exchange at sea. This was demonstrated by the 50 vessels in which salinity averaged $35.1 \pm 2.2‰$ (30.8–39‰) after a full exchange (Table 3). Frequencies were lower when exchange was less than full among 76 vessels where 76 of 130 samples were $\geqslant 30‰$ salinity. Lowest frequencies were observed among 46 NOBOB vessels where 28 of 92 samples were $\geqslant 30‰$ salinity.

Differences in salinity among tanks on a vessel would be a concern because this can indicate differences in biological content. Differences were observed on 14 of 18 vessels in this study, and 7 of 16 vessels in the Aquatic Sciences study (1996) when two or more tanks were sampled. A typical six cargo-hold bulk carrier that enters the Great Lakes can have six pairs of bottom tanks, six pairs of either side, wing or topside tanks, and a forepeak and aftpeak tank, for a total of 26 dedicated ballast tanks.

### 4.2. Exotic species introductions

Continuing introductions of exotic species to the Great Lakes are likely due to vessels carrying low salinity ballast from regions where many earlier introductions originated. Studies have noted recent introductions to the Great Lakes likely originated from Northeast Atlantic and Mediterranean and Black Sea waters, and these areas could be the source for future introductions (Mills et al., 1993; Ricciardi and Rasmussen, 1998; MacIsaac and Grigorovich, 1999). Harvey et al. (1999) reported 37 of 70 fresh and brackish water

Table 3
Number of vessels boarded, tanks sampled, measurements in each salinity group, and ballast history of overseas transits entering the Great Lakes between 1980 and 2001 reported by several studies

| Study | No. of vessels | No. of tanks | Salinity group | | | | | Ballast history |
|---|---|---|---|---|---|---|---|---|
| | | | <0.5‰ | 0.5–5‰ | 5.1–18‰ | 18.1–<30‰ | ⩾ 30‰ | |
| Present | 26 | 62 | 5 | 9 | 18 | 12 | 18 | Most tanks with residual water |
| Aquatic Sciences (1996) | 20 | 30 | 2 | 4 | 6 | 8 | 10 | Probably no ballast on board |
| | 10 | 30 | 1 | 4 | 2 | 3 | 20 | Carried 255 to 11,112 $m^3$ ballast |
| Locke et al. (1992) | 12 | 12 | | | | | 12 | Conducted full exchange |
| | 11 | 11 | 0 | 0 | 2 | 3 | 6 | Partial exchange to unknown |
| Locke et al. (1991) | 38 | 38 | | | | | 38 | Conducted full exchange |
| | 43 | 43 | 0 | 7 | 2 | 4 | 30 | Partial exchange to unknown |
| Bio-Environmental (1981) | 46 | 46 | 1 | 5 | 7 | 13 | 20 | Tanks with exchangeable ballast |

species found in ballast were associated with these regions. This study also reported 52% of the 40 transits took their ballast, and 86% of the 88 transits originated from these regions. Four other studies indicated 72% of the 170 transits carried ballast from these regions to the Great Lakes (Bio-Environmental, 1981; Locke et al., 1991, 1992; Aquatic Sciences, 1996).

### *4.3. Regulatory issues*

Ballast uptake and discharge by overseas vessels entering the Great Lakes region are influenced by several US and Canadian regulations. All vessels entering from outside the 200 nautical miles EEZ are required to conduct an exchange to ensure a tank from which ballast is discharged contains a minimum of 30‰ salinity. The *US Merchant Marine Act*, and *Coasting Trade Act of Canada*, further require all cargo moved within their respective borders be carried by vessels registered in their countries. The consequences of these regulations usually result in incoming foreign vessels that unload cargo at one port to take on Great Lakes water for ballast before moving to the next port. This residual ballast and Great Lakes water mixture is discharged at the terminal port when cargo is loaded for export. This study indicated 88% of 40 vessels listed their first port of call on Lakes Ontario and Erie. A previous study reported 66% of 587 incoming vessels visited 2–6 ports on the Great Lakes, and 57% of the terminal ports were located on Lakes Superior, Michigan and Huron (Niimi, 2000a). The Aquatic Sciences study (1996) reported this residual ballast and lake water mixture represented 80% of the total ballast discharged by overseas vessels at larger Great Lakes ports.

About 50 $m^3$ of unpumpable ballast was reportedly carried by 33 vessels in this study. A 5 cm depth of water in the bottom tanks of a 218 m vessel would represent a volume of 14 $m^3$. Based on these volumes, approximately 22,500 $m^3$ of residual ballast, including 6300 $m^3$ in the bottom tanks, could be carried by the 450 overseas vessels that enter the Great Lakes annually (Niimi, 2000b). About 66% of these volumes could be discharged to the Great Lakes by vessels that visit two or more ports. These volumes are small, however differences in salinity, biological contents and origin among the tanks reported in this and the other studies can provide a plausible basis for the continuing introduction of exotic species to the Great Lakes. The risk of ballast water introduced species could remain high until the discharge of low salinity ballast is effectively addressed.

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