Final Report
Executive Summary

Identifying, Verifying, and Establishing Options for Best Management Practices for NOBOB Vessels

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Revisions

October 2007: Page 31, text corrected to remove statement indicating that Enterococci form cysts, which they do not.

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Executive Summary

A "Code of Best Practices for Ballast Water Management" was adopted by the Shipping Federation of Canada and the (U.S.) Lake Carrier's Association in 2000. In 2002 the St. Lawrence Seaway corporations adopted rules making compliance with the Code mandatory for entry into the Seaway. The Code promotes the maintenance of relatively clean ballast tanks through a program of regular inspection and cleaning, combined with a precautionary approach to ballasting with the objective of limiting or avoiding the uptake of ballast under specified conditions. To our knowledge, however, there has never been an assessment of the extent to which commercially operating ships can realistically apply these practices or the effectiveness of the stated practices for reducing the risk of new species introductions. We therefore conducted this scientific study to 1) test and evaluate the effectiveness of the current Best Management Practices (BMPs), focusing on a subset that are specifically applicable to ballast management for reduction of invasion risk associated with empty ballast tanks on ships entering the Great Lakes with no pumpable ballast-on-board (NOBOB), and 2) test a set of enhancements to the existing BMPs, focusing on flushing of tanks with deep ocean water, either when the ship is in NOBOB condition or as an intermediate step in deep ocean exchange. In particular, we wanted to examine whether BMPs are effective at reducing the abundance and viability of live organisms and resting stages.

To complete this objective we conducted detailed biological assessments of microbial, phytoplankton, and invertebrate communities present within both sediment and water ballast residuals for two participating ships during each entry into the lakes and compared results against ballasting history and any BMPs applied. Lastly, we attempted to more thoroughly assess the extent to which salinity toxicity, whether through open-ocean ballast water exchange (BWE) or saltwater flushing, can prevent the transfer of low-salinity species to the Great Lakes.

Constraints on our Experimental Design

Despite substantial effort by the project team, the vagaries of the shipping trade were such that the ships we engaged were unable to assist us as originally proposed. Efforts to overcome these limitations included working with multiple ships instead of the proposed single ship, and conducting two years of field studies instead on the proposed single year. Still, as a consequence of the ships' unexpected altered trading patterns and voyages and their limited ability to consistently apply BMPs, the character of our experimental design (one predicated on sampling "paired-tanks") was altered completely. Instead of sampling "control" and "treatment" tanks, we collected a chronological series of samples as best we could. In response to these limitations, we also modified our sampling approach to incorporate the use of our emergence traps to provide for a direct test of our enhanced saltwater flushing BMP. This modification also provided the opportunity to conduct experiments on the effectiveness of BWE when the ballast originated from a freshwater port.

Task 1: Assess the effectiveness of specific ballast management practices on sediment accumulation and characteristics within ballast tanks.

We used in situ water quality instruments to help define the timing and quantity of ballasting as well as the overall quality of source water. In particular, instrument data provided direct confirmation of when BMPs were applied to the treatment tanks. In addition, adding sensors at various locations and heights throughout the tank provided insight to patterns of sediment accumulation observed during direct tank sampling. The structural complexity within the tank and the nature of the ballast intake and stripping system create a general pattern of thicker sediment accumulation in the forward and outer bilge areas of the tanks. The size of the area of significant resuspension and discharge will be affected by the tank design, deballasting flow rate, and nature of the sediment, all of which can vary widely among ships. Qualitative estimates based on visual observations in a limited number of NOBOB tanks suggest that significant resuspension and removal of sediment occurs during discharge, affecting between 30% and 80% of the bottom area, depending on the previous ballasting and sediment management history of the tank. Again, due to the experimental design limitations and a relatively infrequent application of specific BMPs, we could not quantitatively assess the potential effectiveness of BMPs to reduce sediment accumulation. Instrument data did confirm that saltwater flushing, or 'swish and spit', can resuspend a portion of the resident sediment and increase the likelihood of eliminating this sediment on subsequent discharge. A single ballasting event in highly turbid ports can result in significant addition of sediment that, if not flushed out almost immediately, can quickly settle, coagulate and become difficult to eliminate.

This study also revealed that the consistent implementation of the Code can be problematic, especially for the environmental precautionary actions (Item 6), because application is very much dependent on local conditions – working rules of the dock (24/7 vs. daylight), rainy season vs. dry season, river berth vs. sheltered harbor or deep water harbor. Acceptance and implementation of the Code by the shipping industry must be understood as a commitment to make a "good faith" effort which if regularly and consistently conducted may somewhat lower overall risk of introductions, but will not completely eliminate it. The practical realities and limitations associated with vessel operations makes the existing BMPs inadequate as the lone strategy for reducing the risk of nonindigenous species introductions from NOBOB vessels. The designation and routine use of saltwater flushing as an official BMP would greatly improve the protection framework for the Great Lakes, if aggressively implemented by the shipping industry.

Task 2: Assess the effectiveness of specific ballast management practices to reduce the density and viability of organisms and resting stages.

Microbiology

Given the deviations from our intended experimental design, we cannot state much about the efficacy of BMPs to reduce the quantities and diversity of pathogenic microorganisms. However, summary data for the microbiological analyses certainly would argue for the consistent application of best management practices. In every tank sampled over the course of this study (total of 20 tanks), at least one of the potential pathogens or indicator species for which we assayed was present. In one case there were 8 such taxa present, with most samples containing between 2 and 6. These may be regarded as "model" organisms; had we assayed for more such species, we believe we would have found them in some samples. We reiterate, therefore, a point expressed in our previous NOBOB study that "it seems prudent to regard all NOBOB ships entering the Great Lakes as potential carriers of pathogens".

Phytoplankton

As a part of BMPs for application to the management of NOBOB vessels, the regular use of saltwater flushing can minimize delivery of viable freshwater phytoplankton to the Great Lake. Short-term changes in salinity can cause problems in osmotic regulation for freshwater phytoplankton. Our results showed that switching from freshwater to saltwater conditions reduced phytoplankton community diversity and restricted phytoplankton growth in lakewater media. The effects of the saltwater exposure/exchange were greater on the water samples than sediment samples; flushing muddy sediment out of tanks may be important steps to minimize the risk of phytoplankton via NOBOB operation. Variations in phytoplankton composition and growth occurred in response to BWE and saltwater flushing, however it was not possible to directly relate differences in populations or viability to any given management activity given the alteration of our experimental design.

Invertebrates

Ballasting events changed (increased or decreased) the number of organisms found in association with both water and sediment residuals, whether ballast was with fresh, brackish, or saltwater. However, there was no consistency to the changes, either in the types of organisms present, or the densities at which they were present. Due to the multiple ballast events between each sampling opportunity, we are unable to associate particular changes with specific ballast events or practices.

It is difficult to directly assess the effects of BMP's on fauna living in residual water from this study as water could not be collected on each sampling date and BMPs were not applied in a consistent or controlled manner. Furthermore, high densities of animals were detected in residual water from both fresh- and salt-water sources. However, our salinity toxicity studies and ballast water exchange experiments show that many taxa from low-salinity ports are eradicated from ballast tanks relatively quickly through exposure to full-strength seawater.

Due to the confirmed presence of viable organisms within water and sediment residuals following ballasting events in overseas freshwater ports, it should be recommended that all ships complete a flushing/exchange in the mid-ocean during voyages to the Great Lakes as the potential risk for introducing saltwater animals to the Great Lakes is much lower than those from potential freshwater sources.

Ballast Water Exchange Experiments

Open ocean ballast exchange (BWE) proved to be a highly effective method to reduce the concentration of zooplankton in the ballast tanks studied. Freshwater animals were completely absent from the exchanged ballast tanks of vessels 1 and 4, while low concentrations remained in the exchanged tanks of vessels 2 and 5. Overall, sequential (empty-refill) exchange resulted in a decrease in total zooplankton abundance by >99% for the four ships for which we were able to assess exchange efficiency. The results from our study suggest that the effectiveness of BWE for freshwater organisms is less variable than that for marine organisms. The reduced variability of BWE effectiveness in our study may result from pronounced osmotic shock experienced by freshwater animals remaining in ballast tanks after BWE. Vessels transiting between marine ports must rely on purging and dilution of ballast water to eliminate coastal organisms. Vessels transiting between freshwater ports can expect decreases in zooplankton density due both to purging of organisms and to salinity effects. However, it should be noted that this subset of experiments was performed in upper wing tanks and the efficiency of water exchange in these tanks may be greater owing to their structural design and location.

Benthic Invertebrates

To evaluate the effect of BWE on benthic invertebrates, 30 *Echinogammarus ischnus* amphipods and 30 *Brachiura sowerbyi* oligochaetes collected from the Great Lakes were placed with sediments inside an incubation chamber placed within the control and experimental tanks of vessels 4, 5, and 6. Most oligochaetes in the control tanks survived their intercontinental voyages, with mortalities of 16.6%, 0%, and 20%, for vessels 4, 5, and 6, respectively. However, nearly all individuals perished in the exchanged ballast tanks, with mortalities of 100%, 100%, and 96.6% (one live individual out of 30). The survival of one of the oligochaetes in the hatch-out chambers in the exchanged tank highlights one of the potential problems with BWE. The lone live individual was found at the very bottom of the sediment layer, suggesting that saline water may not have been able to penetrate through the sediment. If individuals can survive below the sediment:water interface then they could represent an invasion risk if sediments are disturbed during subsequent ballasting activities. *Echinogammarus ischnus* mortality in the control tanks was higher than that for the oligochaetes at 40%, 60%, and 53.3% for vessels 4, 5, and 6, respectively. In the treatment tanks that had undergone exchange, 100% of *E. ischnus* individuals were deceased at the end of each experiment. These results suggest that saltwater exposure during BWE is likely to be lethal for many species found above the sediment:water interface.

Invertebrate Resting Eggs

The effect of saltwater exposure on diapausing invertebrate eggs was evaluated both directly in the tank and in follow-up laboratory-based hatching experiments. Ballast sediment (300g) previously collected from vessels operating on the Great Lakes was placed inside each of the chambers. Following incubation within the tank and exposure to BWE, sediments were retrieved from the traps and returned to the laboratory to conduct a follow-up hatching viability experiment. The number of animals recovered from hatch-out chambers in control tanks (mean = 0.5 – 3.25 ind/trap) was significantly higher than that from chambers in the exchanged tanks (mean = 0 - 0.25 ind/trap). Three possible explanations for the lower abundance in exchanged tanks are: 1) saltwater exposure may have killed animals that hatched during the pre-exchange period; 2) the presence of saltwater in the chambers could have prevented further recruitment from diapausing eggs in the sediment since environmental conditions would not cue hatching; or 3) environmental conditions inside the incubation chambers deteriorated to conditions unsuitable for hatching. We conducted experiments in which instrument sondes were embedded inside separate incubation chambers of the same design used here. Results showed that exchange between ambient water and water trapped in the chamber can be limited, depending on ship motion, and hence biochemical oxygen demand from sediment can lead to hypoxic or anoxic conditions inside the chambers. Such conditions would prevent most diapausing eggs from hatching.

In follow-up post-BWE laboratory viability experiments, neither the total abundance of hatched individuals nor the species richness of hatched individuals differed significantly between sediments collected from hatch-out chambers in the exchanged versus control ballast tanks. These results suggest that diapausing invertebrate eggs may be largely resistant to saltwater exposure, and that BWE may not mitigate the threat of species introductions posed by this life stage. Previous experiments by our team on diapausing eggs that were isolated from sediment did report significant differences in viability after exposure to saline water. This difference may suggest that eggs embedded within sediment are less vulnerable to saltwater exposure.

Task 3: Characterize source invertebrate populations and assess salinity toxicity as a barrier to prevent transfers of "high risk" species to the Great Lakes in ballast tanks.

Characterizing Source Populations

The Great Lakes and low salinity ports of the east coast of the U.S. and Canada share an invasion threat from the North Sea and Baltic Sea. Of the 269 species reviewed, the Great Lakes and port systems of the North Sea and Baltic Sea have at least 100 species (37%) in common, with 18 of these considered exotic to the Great Lakes region. At least 5 of these species are considered to have negative impacts on the indigenous fauna (invasive). In particular, commercial ships from ports of the Netherlands, Belgium, Germany, Finland, and Russia may represent the greatest threat of invasive species to the Great Lakes and estuarine ecosystems of the eastern United States. Based on trends of temperature, salinity, and ship traffic, the ports of Rotterdam, Antwerp, Ghent, Brake, Bremen, Klaipeda, Kotka, and St. Petersburg have been classified as high invasion risk donor ports. Based on species diversity and environmental tolerances, the most likely taxonomic groups to invade the Great Lakes are the amphipods, isopods, harpacticoid copepods, cladocerans, mysids, and mollusks. During the last 50 years, several long-term shifts in zooplankton composition and abundance have occurred within the North Sea and may potentially increase the invasion rate of Ponto-Caspian species into adjacent freshwater port systems and hence possibly to the Great Lakes.

Salinity tolerance experiments

Salinity tolerance experiments, designed to mimic both flow-through and empty-refill methods were carried out in several different regions known for high invasion rates and commercial ship traffic. Experiments were conducted in the Chesapeake Bay (Maryland), San Francisco Bay (California), and in the European ports of Curonian Lagoon, Klaipeda, Lithuania, Vistula River (Poland), and Rotterdam (The Netherlands) located within the Baltic Sea and North Sea. Over 70 experiments were conducted using 43 invertebrates identified to the species level, four invertebrates identified to the genus level, and ten experiments that included unidentified species of bivalve veligers, barnacle nauplii, cladocerans, polychaetes, flatworms, and copepods. All of the cladocerans in our experiments were eliminated by either 14 or 24 ppt seawater. There are marine cladocerans that can survive in salinities greater than 24 ppt such as species of *Podon*, *Pseudoevadne*, *Evadne*, *Penilia*, and *Pleopsis*. However, these species are rarely found within freshwater habitats or cannot survive in constant freshwater systems. The majority of copepods in our experiments were not tolerant of full-strength seawater, but considering the ability of some species to recover from short-term exposures to dramatic salinity shifts, exposure duration should be at least a day to assure mortality of all copepod species. The larvae of crabs, shrimps, barnacles, and bivalves as well as adult amphipods, isopods, cumaceans, and mysids were generally tolerant of full-strength seawater (or higher salinities). For these taxa, it is a better discriminator of 'invasion risk' for the Great Lakes region to determine species that are capable of establishing populations within a constant freshwater habitat. However, all of these euryhaline species do pose a significant invasion threat to estuarine systems.

In addition, salinity tolerance experiments were conducted in the Great Lakes by both SERC (western Lake Erie; Grand Traverse Bay, MI) and the University of Windsor. In the SERC experiments the common native cladoceran species; *Bosmina longirostris*, *Leptodora kindtii*, and *Daphnia retrocurva* were all eliminated in the initial exposure to 14 ppt seawater. This was also true for the highly abundant rotifer, *Asplachna priodonta*. Two of the most problematic invasive species in the Great Lakes, the predatory cladocerans *Cercopagis* and *Bythotrephes*, were slightly more tolerant of higher salinities and survived until the 24 ppt treatment. This was also true for the widely distributed cladoceran species of *Polphemus*, *Alona*, and *Eurycercus*. However, late stage juveniles brooded within adults of *Bosmina longirostris* and *Eurycercus lamellatus* survived in some of these short-term salinity treatments when returned to ambient water. The only full-strength salinity tolerant species encountered were the abundant quagga and zebra mussel veligers. However, as a final check of viability we transferred these animals to freshwater at the end of the experiment and left them overnight, and no individuals survived the full-seawater treatment and return to freshwater.

With regard for ballast water exchange methods, the greater risk for the Great Lakes lies with species or particular life stages that can tolerate full-strength seawater for at least two days and also establish viable populations within a constant freshwater system. Clearly, this is not the case for the adult forms of the invasive cladocerans *Cercopagis pengoi* and *Bythotrephes longimanus*. Their may be several reasons for their establishment in the Great Lakes, including that these species were introduced prior to ballast water exchange practices, that ballast water exchange practices had not been followed rigorously, or that their resting stages have more physiological resistance than the adults. Previous experiments designed to test the efficacy of ballast water exchange on the hatching success of resting stages of other species of cladocerans from the Great Lakes yielded mixed results, but suggest that saltwater exposure is unlikely to significantly reduce the risk from this potential source of propagules.

Though not a complete barrier against all exotic species, these experiments clearly show that many taxa that originate from low-salinity ports can be eradicated from ballast tanks relatively quickly through exposure to full-strength seawater (34 ppt). This is especially true for several species of rotifers, cladocerans, and copepods that are more likely to occur in freshwater or oligohaline habitats (0-2 ppt). It is not surprising that our experiments with animals from habitats with higher average salinities (2-5 and 5-10 ppt) exhibit greater resistance to treatments of full-strength seawater. These findings support similar conclusions drawn from previous ballast water exchange experiments conducted in the Chesapeake Bay and San Francisco Bay. Invertebrates from our experiments identified as salinity-tolerant species (34 ppt) include mysid shrimps, amphipods, isopods, harpacticoid copepods, bivalve veligers, and decapod zoea. Members of these taxonomic groups often experience dramatic fluctuations in salinity and temperature as part of their normal life histories and these factors have contributed to their ability to invade estuarine habitats. Of these estuarine animals, only a subset of salinity-tolerant species are capable of surviving and reproducing in a constant freshwater habitat such as the Great Lakes. Identifying species and populations with these characteristics from the port systems of the east coast of the U.S. and Canada, North Sea, and Baltic Sea is paramount for preventing problematic species from invading the Great Lakes region via the operations of commercial ships.

Conclusions

In summary, based on our previous work with NOBOBs and the results of direct salinity experiments conducted both on board ships and in the lab, we strongly support the new Canadian ballast management regulations adopted in 2006 that require, and the policy statement issued by the United States Coast Guard in 2005 that encourages mid-ocean tank flushing. Specifically, we recommend that vessels operating outside of the Great Lakes conduct saltwater flushing of their empty (NOBOB) tanks prior to each entry. Flushing is accomplished by allowing a limited amount of saltwater water to slosh around in an individual ballast tank as a result of the ship's rolling and pitching motion during passage, to agitate and resuspend trapped sediments and provide a salinity shock to biota, which is then discharged in the open ocean.

We further emphasize that many of the recommendations put forth in Item 6 of the Code of Best Management Practices require information on local water quality conditions that is not generally available to the shipping industry, or are often not practical to conduct due to cargo loading and unloading requirements. Therefore, while BMPs, if consistently and repeatedly applied, can reduce the risk of introductions from NOBOB vessels by minimizing the amount of sediment and associated organisms that are transported within ballast tanks, the practical realities and limitations associated with vessel operations makes the existing BMPs inadequate as the lone strategy for reducing the risk of nonindigenous species introductions from NOBOB vessels. The designation and routine use of saltwater flushing as an official BMP would greatly improve the protection framework for the Great Lakes, if aggressively implemented by the shipping industry.

A complete copy of the report and associated appendices can be downloaded from the project web site at: http://www.glerl.noaa.gov/res/Task_rpts/2004/aisreid04-1.html