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Current State of Understanding about the Effectiveness of Ballast Water Exchange (BWE) in Reducing Aquatic Nonindigenous Species (ANS) Introductions to the Great Lakes Basin and Chesapeake Bay, USA: Synthesis and Analysis of Existing Information

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FOREWORD

The worldwide transfer and introduction of nonindigenous species (NIS) by human activities has increased dramatically over the past century, resulting in a broad array of unwanted ecological, economic, and human-health effects. Today, the global movement of ships' ballast water is considered the largest transfer mechanism for aquatic nonindigenous species (NIS). A taxonomically diverse community of organisms is unintentionally entrained and transported within ballast tanks, and has resulted (upon discharge) in many successful invasions of nonindigenous species at ports throughout the world.

Ships arriving to ports of the United States are presently required to conduct ballast water management approved by the U.S. Coast Guard when arriving from outside of U.S. or Canadian waters, in order to reduce the delivery of coastal organisms that can colonize our shores. Such foreign arrivals are required to treat any ballast water prior to discharge in U.S. waters. Mid-ocean ballast water exchange (BWE), by which vessels exchange their coastal ballast water with oceanic water (> 200 miles from shore), is currently the only approved treatment option available for commercial and military ships to reduce the quantities of nonindigenous coastal plankton in their ballast tanks. The ballast exchange procedure is expected to greatly reduce the risk of NIS invasions as most coastal organisms in ballast tanks would be purged, being replaced by oceanic species that occur generally at lower densities and are believed unlikely to survive or reproduce in coastal ecosystems. For freshwater and low-salinity estuarine organisms BWE has the added effect of salinity (or osmotic) shock, which reduces the likelihood that such organisms will survive in ballast tanks after BWE has taken place.

Although there is general consensus that BWE reduces the supply of nonindigenous species delivered to recipient ports, quantitative assessments of the effects of the practice are still emerging. In particular, there are several questions under debate within both the scientific and regulatory communities about the magnitude of reduction for coastal plankton that results from BWE, and its effect on risk of invasion. In addition, ships that legally report no ballast on board (NOBOB, for "No Ballast On Board") can carry residual ballast water and sediments in their tanks that, by themselves, are unpumpable, but that also pose some risk of invasions when combined with new ballast water and subsequently discharged. Although NOBOB ships are, as of summer 2006, being required to flush their tanks in the open ocean before entering the Great Lakes, the comparative invasion risk associated with these ships is not well established.

Language in the FY2005 NOAA Appropriation directed NOAA to review the current state of knowledge of the "effectiveness of ballast water exchange in controlling invasive species in the Great Lakes Basin and the Chesapeake Bay." This review was prepared jointly by NOAA's National Center for Research on Aquatic Invasive Species (NCRAIS), located with the Great Lakes Environmental Research Laboratory (GLERL) in Ann Arbor, Michigan, and the Smithsonian Environmental Research Center (SERC), located in Edgewater, Maryland. McGill University School of Environment and the Michigan Sea Grant/Great Lakes Network Program assisted with the Great Lakes analysis. This report was reviewed anonymously by two independent external experts and one internal NOAA scientist and revised as the current product.

In this report, we examine the current state of knowledge about BWE and its effects as applied specifically to two major U.S. ecosystems, the Great Lakes and Chesapeake Bay, which have been foci for congressional action in preventing new invasions and in restoration efforts. We present a summary of the discovery rates and patterns of invasion in both ecosystems. Although these invasion histories underscore the importance of shipping and ballast water as a source of nonindigenous species, they do not provide sufficient resolution to reliably estimate actual dates of invasion or invasion rate, and therefore cannot be used to evaluate the effect of BWE on invasion rates (see Chapter 1, Section 1.4 for further discussion). Given this limitation, we take an alternate approach to evaluate BWE effectiveness by examining how it has likely affected propagule supply to the Great Lakes and the Chesapeake Bay. We analyze available data to characterize past and present maritime shipping to the Great Lakes and Chesapeake Bay, and attempt to evaluate changes in propagule supply attributable to changes in shipping practices and to BWE, in order to assess the likely effects BWE has had as a prevention strategy applied to these two ecosystems.

STRUCTURE OF THE REPORT

This report starts with a Glossary, followed by a short Synopsis. After a detailed Executive Summary, the body of this report consists of an Introduction (Chapter 1), four main chapters (2-5) each written by different teams of contributing scientists, and a final chapter (6) that provides conclusions and recommendations:

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ACKNOWLEDGEMENTS

GLOSSARY

Algae, algal: aquatic photosynthetic organisms, ranging in size from single-celled forms to the giant kelp. Algae were once considered to be plants but are now classified separately because they lack true roots, stems, leaves, and embryos (after American Heritage® Dictionary).

Ballast Water: water that is carried by a ship for purposes of adjusting and maintaining trim, stability, and draft.

Ballast Water Exchange (BWE): a process by which the water in a ship's ballast tanks is replaced by water from a mid-ocean region, where salinity is above 30 and water is 2000 meters deep or greater.

Ballast Tank: a large void space, or specially designed cargo hold, used to store ballast water on board a ship. Individual ballast tanks can range in size from a cubic meter or less on small vessels, such as fishing boats, to thousands of cubic meters each on large vessels, such as commercial cargo vessels. Each vessel will usually have multiple ballast tanks and there are many different configurations of ballast tanks across and within ship types. Most ballast tanks are subdivided by internal interconnected compartments that make structurally complex and subject to sediment accumulation.

Ballast Tank Flushing: a process by which a ship with ballast tanks that are empty except for unpumpable residual ballast water and sediment draws in saline ocean water sufficient to cover the bottom of the tank to at least a few centimeters or raise the salinity of the residual water to >30, lets it slosh around for a short period of time, and then discharges it. This process is also known as "swish and spit."

Cladoceran: small, mostly freshwater crustaceans of the order Cladocera, which includes the water fleas (American Heritage® Dictionary).

Copepod: any of numerous tiny marine or freshwater crustaceans, lacking compound eyes or a carapace and usually having six pairs of limbs on the thorax, some abundant in plankton and others parasitic on fish. (after Dictionary.com).

Crustacean: predominantly aquatic organisms, including lobsters, crabs, shrimps, and barnacles, characteristically having a segmented body, a chitinous exoskeleton, and paired, jointed limbs (after American Heritage® Dictionary).

Cryptogenic species: a species that cannot be verified as either native or introduced (after Carlton, 1996).

Cubic meter ($1\ m^3$): a volume equal to ~1000 liters or ~264 gallons of water; see also "Metric tonne."

Diatom: microscopic one-celled or colonial algae having cell walls of silica consisting of two interlocking symmetrical valves (after American Heritage® Dictionary).

Dinoflagellate: minute, chiefly marine protozoans, characteristically having two flagella and a cellulose covering and forming one of the chief constituents of plankton. They include bioluminescent forms and forms that produce red tide (after American Heritage® Dictionary).

Efficacy: ability or capacity to produce a desired effect; effectiveness (after American Heritage® Dictionary). In the case of ballast water exchange, a low efficacy (or lower efficacy) means that BWE was less effective at replacing coastal water and/or plankton than desired.

Euryhaline: capable of tolerating a wide range of salt water concentrations. Euryhaline organisms are usually found in estuaries, the interface between rivers and the ocean.

Extirpated: to destroy totally; exterminate (American Heritage® Dictionary).

Invader: a nonindigenous species that has successfully established a reproducing population.

Invasive, invasive species: Although widely used, the term "invasive" is vague and subject to widely inconsistent usage. Biologically it is often related to the relative ability of a species to spread and establish in new areas, while legislatively and politically it is used to characterize a nonindigenous species "whose introduction does or is likely to cause economic or environmental harm or harm to human health" (Executive Order 13112, February 1999). Thus, the term "invasive" has multiple meanings and requires a subjective judgment. In fact, the term "invasive" has been inconsistently applied - for example, it has sometimes been used to represent all nonindigenous species in an ecosystem; however, a species may be considered "nonindigenous" but NOT "invasive" (see "nonindigenous," below). For this report we avoid using the term "invasive" except where it is incorporated into a title or reference, or where the use of direct quotes from another source demand it for accuracy.

Invertebrate: an animal, such as an insect or mollusk, which lacks a backbone or spinal column (American Heritage® Dictionary).

Metric Tonne (t): a unit of measure common to cargo ships, equal to a weight of 1000 kilograms. 1 metric tonne of water (1 t) = ~1 cubic meter (1 m^3) = 0.907 tons (U.S.) = ~264.17 gallons (depends on salinity).

Nautical mile (nm): an international unit of length used for sea and air travel, equal to 1,852 meters (~ 6,076 feet).

NOBOB: a ship carrying no pumpable ballast water in its ballast tanks. "NOBOB" is short for "No-Ballast-On-Board."

Nonindigenous species (NIS): any species or other viable biological material that enters an ecosystem beyond its historic range, including any such organism transferred from one country into another (NISA, 1996). Note that a species may be considered "nonindigenous" without being considered "invasive" if it has not shown any negative or damaging economic, environmental, or human health effects in the ecosystem it inhabits, or if it lacks the ability to reproduce and maintain a population. Also, some nonindigenous species do not establish self-sustaining populations. For example, the European flounder is nonindigenous to the Great Lakes and has been found several times during the 1990s. However, this species has not become established, because it cannot reproduce in a freshwater system such as the Great Lakes and thus cannot expand and maintain a population.

Phytoplankton: minute, free-floating aquatic plants, not self-propelled (after American Heritage® Dictionary).

Plankton, planktonic: the collection of small or microscopic organisms, including algae, protozoans, and zooplankton, that float, drift, or swim in great numbers in fresh or salt water, , and serve as food for fish and other larger organisms. (after American Heritage® Dictionary)

Ponto-Caspian: the area surrounding and including the Black and Caspian Sea basins.

Propagule: any viable life history stage of an organism including larvae, adults, eggs, spores, resting stages, etc.

Propagule pressure: the number and quality of propagules that are being delivered to an ecosystem. Recent bioinvasion theory suggests that propagule pressure is a significant determinant of which species are able to establish a population.

Protozoan: single-celled, usually microscopic organisms, such as amoebas, ciliates, and flagellates (after American Heritage® Dictionary).

Rotifer: minute multicellular aquatic organisms having at the anterior end a wheel-like ring of cilia (after American Heritage® Dictionary).

Vector: the mechanism or activity by which a species is transported from its present geographic range and to a new ecosystem, including regions not historically inhabited. Most vectors for nonindigenous species are related to human trade activity, such as maritime commerce, canals and waterways that connect previously separated ecosystems, trade in live organisms (aquaria, live bait, live food, ornamental plants/horticulture), recreational activities, and aquaculture.

Zooplankton: plankton that consists of animals, most of which are self-propelled and can swim against water currents (American Heritage® Dictionary).

Citations

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SYNOPSIS

This report summarizes the current state of knowledge about ballast water exchange (BWE) as a management strategy by ships to reduce the risk of invasions, with emphasis on two major U.S. ecosystems, the Great Lakes and Chesapeake Bay.

Today, most global trade occurs by shipping among ports, creating unintended opportunities for transfer of aquatic species that result in biological invasions. Ships transfer organisms in their ballast tanks and on their hulls. To reduce the risk of invasions from ballast water discharge, estimated annually to exceed 70,000,000 metric tons in the U.S., ships arriving from foreign ports are required to conduct ballast water exchange (BWE) or alternative treatment before discharging ballast. This management strategy became mandatory in the United States for the Great Lakes and upper Hudson River in 1993, and it has been required for ships arriving to the Chesapeake Bay and all other ports since September 2004.

BWE consists of flushing coastal water from ballast tanks by replacing it with oceanic waters and is intended to reduce the concentration of coastal organisms that may become established in subsequent ports upon ballast discharge. Most oceanic organisms are considered unlikely to colonize coastal habitats, just as many coastal organisms cannot persist in the open-ocean. In addition to removal of organisms, BWE will also expose any residual coastal organisms in the ballast tanks to full-strength seawater, which may cause high mortality for organisms from freshwater ecosystems that are likely to survive in the Great Lakes and upper Hudson River. Such "salinity stress" may thus increase the efficacy of BWE.

Several approaches have been considered to evaluate the effects of BWE on invasion risk. These include the use of (a) invasion records (observations) to estimate changes in invasion pattern associated with ballast water regulations; (b) theoretical models and (c) experimental methods to estimate the <u>per-ship reduction</u> of coastal organisms by BWE; and (d) additive calculations based on both ship arrivals and ballast management practices to estimate the <u>per-ecosystem reduction</u> of coastal organisms due to BWE regulations for each the Great Lakes and Chesapeake Bay. Below, we discuss the inferences and conclusions from each approach.

(a) Invasion Records. For the Great Lakes and Chesapeake Bay, analyses of invasion records clearly indicate the importance of shipping and ballast water as a source for many recent aquatic invasions. Over 150 non-native aquatic species are considered established in each ecosystem, and most are attributed to shipping as a source. However, invasion histories actually describe the <u>rates of discovery</u>, which cannot be used with confidence as a surrogate for actual <u>rates of invasion</u>. Importantly, discovery rate is influenced by biases in sampling effort and taxonomic identification over time, such that significant lag-times (delays) can occur between the initial invasion and detection. At the present time, there exists no program in the Nation to adequately characterize invasion rate, using standardized measures through time. Thus, **<u>existing invasion histories cannot be used to reliably measure changes in the rate of invasion or assess the effects of ballast water management</u>.**

(b) Effect of BWE per Ship: Theoretical Models. While it is possible to estimate the replacement of ballast water during BWE by a <u>simple</u> two-component mixing model, such a model does not take into account the complexities of fluid flow in a ballast tank. In addition, organisms are not passive particles and their removal may differ from water replacement. Thus, theoretical model-based estimates of BWE efficacy must be viewed cautiously when evaluating effectiveness, as they require empirical validation (testing) to confirm the expected reduction in both the initial water and the initial organism concentrations. NOAA has partnered with the U.S. Navy to develop such a model, which thus far has applied only to a few scenarios involving a typical cargo ship ballast tank and only applies to water replacement, not organisms. **Conclusions about BWE effects based only on current theoretical models would be premature and potentially misleading**.

(c) Effect of BWE per Ship: Experimental Methods. Direct experimental measurements on full-scale ships during normal operations demonstrate unequivocally that BWE can be highly effective at replacing coastal planktonic organisms (80-95% reduction in concentration) across ship types, when conducted according to guidelines and regulations. While some residual coastal organisms remain, **BWE clearly results in a large reduction in coastal organisms on a per-ship basis. There is strong empirical and theoretical evidence that such a reduction in propagule (i.e., organism life forms) supply will reduce invasion risk, although the magnitude of risk reduction remains poorly resolved.**

Salinity stress experienced by residual organisms following BWE serves to further reduce the risk of invasion for freshwater ecosystems, such as the Great Lakes and the low-salinity portions of estuaries. The magnitude of this risk reduction is likely to vary geographically, as organisms from different regions may differ in tolerance, but such regional differences have not been addressed to date.

(d) Effect of BWE per Ecosystem: Additive Calculations. Calculations for both the Great Lakes and Chesapeake Bay indicate that a strong decline has occurred over time in total delivery of coastal organisms to these ecosystems by ships' ballast water discharges as a result of BWE. The discharge of untreated (unexchanged) ballast water by ships arriving to the Great Lakes from outside of the St. Lawrence Seaway or ships arriving to the Chesapeake from foreign ports has declined dramatically due to BWE in the past 15 years. In addition to the effects of BWE, changes in the ship trade to the Great Lakes since the mid-1980s resulted in further significant reductions in total ballast water, and thus, propagule, delivery. When combined with estimates of coastal organism concentration, **this approach provides further confidence that total propagule supply and thereby invasion risk has declined for each ecosystem**.

Despite the evident decline in total organisms delivered to each ecosystem, the residual risk of invasion following BWE is not well understood. Not only are there residual organisms in the ballast water (albeit in much reduced numbers), but there is also a pool of organisms in bottom sediments. The latter can occur even for ships that report no-ballast-on-board (NOBOB). This is of particular concern in the Great Lakes, where a majority of the vessels that enter the Great Lakes from overseas are in NOBOB condition, containing small residual amounts of ballast water, sediments, and organisms, some of which are from low salinity sources. Such NOBOB ships can load and discharge additional ballast in U.S. coastal waters and thereby release residual organisms, creating opportunity for invasions to occur. It is noteworthy that some of the new non-native species reported in the Great Lakes since 1993 are consistent with the type of organisms reported in NOBOB residuals and may have resulted from NOBOB discharges.

NOBOB ships were not subject to any required treatment until recently, representing a gap in the protection framework that established BWE regulations. In 2006, U.S. guidelines and Canadian regulations have begun to address this gap for the Great Lakes, requiring residual ballast water to be of high salinity (>30), which presumably disrupts that transfer of low salinity or freshwater organisms. However, current knowledge about discharge and fate of ballast residuals, particularly the associated viable organisms (including resting eggs and spores contained therein), is insufficient to assess the risk NOBOB residuals pose with any reasonable level of confidence.

General Conclusions

- The process of Ballast Water Exchange, whether 100% empty-refill or 300% flow-through can be highly effective at replacing coastal ballast water with mid-ocean water (88-99% replacement of original water) and coastal planktonic organisms (80-95% reduction in concentration) across ship types, when conducted according to guidelines and regulations.

- The use of BWE by vessels has significantly reduced (a) the discharge of coastal organisms in ballast to the Great Lakes, Chesapeake Bay, and other U.S. estuaries and (b) associated risk of invasions.

- Salinity stress during BWE can be an important factor in reducing the risk for a freshwater ecosystem like the Great Lakes and for the low-salinity portions of estuaries. However, considerable variation exists in the response of organisms to salinity stress and some euryhaline organisms exhibit a wide salinity tolerance that could allow them to survive BWE.

- BWE for coastwise traffic is not required by U.S. federal regulations, and is often not applied to coastwise traffic between domestic ports, sometimes due to insufficient time in transit between ports. This represents a sizeable loophole in the framework established to protect against the transfer and spread of nonindigenous species in U.S. waters.

- For the Great Lakes, unregulated NOBOBs represented a significant gap in the protection framework that established BWE regulations. An important step forward in protecting the Great Lakes was the implementation by Canada in 2006 of regulations requiring that almost all ballast water entering the Great Lakes, including NOBOB residual water, be at salinity 30 or greater.

- Current knowledge about discharge of ballast residuals, particularly residual sediments and the viable organisms, especially resting eggs and spore contained therein, is insufficient to quantify the risk NOBOB residuals pose with any reasonable level of confidence.

- To assess the response of invasion patterns and rates to ballast management strategies with any significant and defensible confidence requires implementation of standardized, repeated sampling programs over time. However, there are no national or regional programs designed to comprehensively and explicitly measure changes in the sources and rates of invasion over time. Yet, this is a key step in order to effectively evaluate and further guide policy for ballast water management.

Recommendations

Against this synthesis and analysis, we make the following recommendations.

1. BWE should be considered a useful and beneficial ballast management practice to reduce species transfers and invasion risk. It is a valuable measure, especially because it is available now for immediate use on many vessels and shipping routes, in the absence of proven alternative treatment methods.

2. Research and development to produce alternative ballast treatment methods and technology-based ballast treatment systems should continue as a high priority, in order to improve the efficacy of treatment and expand application of treatment to most vessels and routes.

3. The use of high-salinity water to flush NOBOB ballast tanks should be considered a useful and beneficial management practice to reduce species transfers and invasion risks associated with NOBOB ships entering the Great Lakes. In the absence of proven alternatives, this practice provides some level of protection against some adult and larval life stages, but probably not against resting eggs and spores of zooplankton and phytoplankton.

4. A quantitative, empirical assessment of the actual release of propagules from NOBOB vessels in the Great Lakes is needed for a better risk assessment to guide management and policy in this area.

5. The effects of salinity stress on a broad range of estuarine and freshwater organisms should be further explored and assessed with respect to ballast treatment, focusing especially on the use of high-salinity water to (a) flush NOBOB ballast tanks and (b) treat low salinity ballast water moved by coastwise shipping.

6. A standardized sampling program targeting key coastal ecosystems in the U.S. is needed to provide the high-quality data necessary to delineate and measure the performance of different vector management actions.

7. A significant effort should be devoted to understanding the relationship between propagule supply (dosage) and invasion risk. The quantitative relationship between propagule pressure and invasion establishment remains a fundamental gap in knowledge, yet it is at the core of defining management goals (such as ballast discharge standards) and predicting the effectiveness in preventing future invasions.

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EXECUTIVE SUMMARY

The U.S. Congress enacted legislation in 1990 and 1996 to reduce the risk of biological invasions in the Nation's aquatic ecosystems. The legislation focused primarily on reducing the transfer of nonindigenous organisms in ships' ballast water. Ballast water is used by commercial ships to maintain trim and stability during voyages. Ballast is taken on from surrounding waters, stored in dedicated ballast tanks, and discharged at subsequent ports of calls, resulting in the unintentional but massive transfer of organisms on a global scale. Some of these ballast-mediated transfers have resulted in established populations of nonindigenous species, which spread and cause severe impacts to society.

Following Congressional guidance, regulations were established that require commercial ships to conduct ballast water management aimed at reducing the transfer of organisms associated with ballast materials. Ships arriving to the U.S. are required to treat their ballast water before discharge if it originates from outside of North America (including the continental U.S. and Canada). This ballast management was initially required only for such ships arriving to the Great Lakes and upper Hudson River, but the regulation was expanded more recently to include the entire country. Although various treatment options are being actively explored and developed, ballast water exchange (BWE; i.e., flushing of ballast tanks at sea to achieve at least a 95% replacement of coastal water) is currently the only approved treatment option available to ship operators.

Language in the FY2005 NOAA Appropriation directed NOAA to review the current state of knowledge about the "effectiveness of ballast water exchange in controlling invasive species in the Great Lakes Basin and the Chesapeake Bay." These two major U.S. ecosystems have been foci for congressional action both in preventing new invasions and in restoration efforts. Importantly, each of these systems is relatively well studied with respect to invasions and may serve as indicators for invasion management on a broader scale. It is also useful to note that mandatory ballast water management followed a different time course in these two locations, beginning first in the Great Lakes and later in the Chesapeake Bay.

In this report, we summarize the current state of knowledge about BWE and its effects in the Great Lakes and Chesapeake Bay. Our approach was to synthesize, review, and interpret available information relevant to assessing the effects of BWE, as applied to these two ecosystems and as requested by U.S. Congress. This was intended to provide an up-to-date overview and snapshot of the current understanding about effects of BWE, instead of initiating further primary research.

We focused specifically on characterizing what is known about (1) effects of BWE in reducing the concentration of coastal organisms in ballast tanks, (2) changes in ballast water management over time, and (3) temporal changes in invasion history, describing the number of nonindigenous species established coincident with ballast water management. This analysis is divided among multiple chapters, produced by various combinations of authors to examine these specific issues in the respective ecosystems, the Great Lakes and Chesapeake Bay.

Chapter 1- INTRODUCTION AND BACKGROUND

Biological invasions by nonindigenous species – the establishment of self-sustaining populations outside of their native geographic range - are prevalent in coastal aquatic ecosystems throughout the world. Human activities have surpassed natural dispersal as the primary drivers of aquatic species invasions and have been associated with the majority of biological invasions over the last several centuries.

Most global trade occurs by shipping among ports that are concentrated in bays and estuaries, creating opportunities for species transfers associated with ships' hulls and ballast materials. Although many human-mediated transfer mechanisms (vectors) are active today, the relative importance of shipping appears to have increased. Shipping is presently considered responsible for most invasions in coastal bays and estuaries of the continental U.S., primarily due to the discharge of ballast water and hull fouling. Ships take on ballast water from surrounding water, mostly in ports, but sometimes while underway. Ballast water is needed to replace cargo weight and to adjust trim and maintain stability. This water often contains a diverse assemblage of living organisms, which are transferred and discharged around the globe with ballast operations, creating the opportunity for invasions to occur.

To reduce the risk of invasions to aquatic ecosystems, the U.S. Congress enacted the Nonindigenous Aquatic Nuisance Prevention and Control Act (NANPCA) of 1990, which was reauthorized in 1996 as the National Invasive Species Act (NISA), to establish major policy on ballast water. This led to initial regulations, effective in May 1993, which required ships arriving from outside the U.S. Exclusive Economic Zone (EEZ) to conduct ballast water management when entering the Great Lakes and inland sections of the Hudson River. Under these regulations, ships arriving to these locations could conduct mid-ocean BWE before entering U.S. waters, use an alternate BWE site designated by the Coast Guard, retain unexchanged ballast water on board while in U.S. waters or use a Coast Guard approved alternative method to treat the ballast water.

BWE consists of flushing coastal water from ballast tanks by replacing it with oceanic waters. This is intended to reduce the concentration of coastal organisms in ships' ballast tanks that may become established in subsequent ports upon ballast discharge. In contrast, most oceanic organisms are considered unlikely to colonize coastal habitats, just as many coastal organisms cannot persist in the open-ocean. In addition, it was believed that most organisms likely to survive in the Great Lakes and upper Hudson River – freshwater ecosystems - would succumb to "salinity shock", thus increasing the efficacy of BWE.

In September 2004 the Coast Guard's mandatory ballast management policy was extended to all commercial vessels equipped with ballast water tanks that enter U.S. waters from outside of the EEZ and Canada. Department of Defense vessels are exempt under law, but the U.S. Navy requires BWE on all vessels that arrive to any port after having been overseas, or from another port along a coast.

Existing legislation and regulations allow for use of alternative ballast water treatment methods, but BWE is currently the only approved method that ships can use to reduce the quantities of nonindigenous coastal plankton in ballast water. Many efforts are now underway in the U.S. and internationally to develop alternate technology-based methods to treat ballast water. Such technology development is still at an early stage, and it may be several years before such technologies are available and widely used. In the interim, BWE is viewed broadly as a stop-gap measure that is immediately available for use on most ships and that will likely be in use for the next decade, until it is gradually phased out by the world's fleet as more effective technology-based methods become available.

Until 2006, ballast management policies for the Great Lakes did not require treatment for ships reporting no ballast on-board (NOBOB). However, recent studies have shown the "empty" ballast tanks on NOBOB ships carry residual water and sediment which contain live or viable organisms. In 2006 Canada passed new regulations that require almost all water in ballast tanks of ships arriving from overseas, including the residual water in NOBOBs, to have salinity >30 in order for those ships to discharge their ballast water in the Great Lakes.

Ballast tanks are large void spaces, usually around the outer hull of a ship, specifically designed to contain water. The goal of BWE is to replace coastal ballast water (and entrained coastal organisms) with mid-ocean surface seawater. There are two types of BWE approaches: reballasting (or empty-refill), and flow-through (or flushing). The former requires that ballast tanks be emptied completely and then refilled, at sea, while the latter requires pumping of mid-ocean water, usually entering at the tank bottom, into a full or partially full ballast tank and allowing the water to overflow the tank for at least three tank volumes.

The effectiveness of BWE is a measure of how well it meets the inherent legislative goal of prevention of new NIS introductions to coastal ecosystems. The problem with trying to measure effectiveness in this sense is that we cannot measure something that is prevented; we can only detect failures to prevent. If all other factors are held equal, if we observe a change in invasion rate over time associated with implementation of a preventive mechanism, such as BWE, theoretically we can assess how effective that tool has been. However, accurate measure of the impact of BWE on invasion rate requires a number of conditions that cannot be met at the present time, including

- Comprehensive records (surveys) of aquatic species invasions from periods both before and after implementation of BWE, to assess changes in number of detected species with repeated measures through time.
- The ability to estimate accurately the date of introduction. There can be a significant lag-time of years to decades between the date of introduction and the date of discovery. This lag-time of discovery is dependent on several factors, including how obvious the invader is, how abundant the invader becomes, how much search effort exists and how specific it is, who is looking and their level of taxonomic expertise.
- The ability to distinguish those aquatic invasions that resulted from ballast water discharge from those associated with other pathways, such as hull fouling, canals and waterways, organisms in trade (bait and aquaria commerce), and aquaculture.

At the present time, there exists no program of systematic, standardized, and repeated measures over time that can provide appropriate data to assess changes in number of detected invasions before and after BWE regulations, in the Chesapeake Bay or Great Lakes, or for the Nation. Instead, the discovery of most invaders to date has been serendipitous, such that what is recorded is the date of discovery, which is likely later than the date of invasion due to uncertainty about the associated lag-time. Although the invasion history for the Great Lakes and the Chesapeake underscore the historical importance of shipping and ballast water as dominant sources for recent invasions, the associated discovery rates cannot provide a reliable approximation for invasion rates.

Current theory and empirical studies about invasions indicates that changes in characteristics of nonindigenous organism delivery or supply, especially quantity and frequency of introduction, affect the risk or likelihood of invasion success (propagule supply hypothesis). Given existing limitations on interpreting discovery rates to evaluate invasion risk, we take an alternate approach to evaluate BWE effectiveness by examining how it has likely affected propagule supply to the Great Lakes and the Chesapeake Bay.

This report does not analyze movements of species on the hulls of vessels or other vectors of potential significance, such as canals and waterways, the live organism trade (aquaria, live bait, live food, and ornamental plants/horticulture), recreational activities, and aquaculture.

Chapter 2 - EFFICACY OF BALLAST WATER EXCHANGE

Ships practice two basic types of BWE to replace coastal with oceanic water: Flow-Through Exchange, in which sea water is pumped continuously through a ballast tank to flush out (displace) ballast water of coastal origin; and Empty-Refill Exchange, in which a ballast tank is first emptied of coastal water and then refilled with oceanic water.

BWE can reduce the concentration of coastal biota in ballast tanks in two ways. First, BWE physically removes (flushes out) many of the coastal organisms, replacing them with oceanic organisms that are considered unlikely to colonize coastal ecosystems. Second, BWE can result in "salinity shock", whereby a rapid change in salinity can be lethal, especially for those organisms adapted to freshwater and estuarine (i.e., low salinity) environments. Large changes in salinity can serve to reduce the concentration of any coastal organisms that remain in ballast tanks. Alternatively, changes in some environmental conditions in ballast tanks after BWE, such as changes in nutrients or oxygen level could conceivably enhance survivorship.

Characterizing the effects of BWE initially appears to be a simple case of estimating the percent replacement of the original ballast water, but this approach may not provide a reliable estimate (proxy) for organism reduction. First, complex mixing and flow patterns (fluid mechanics) within ballast tanks can result in retention of original water during flow-through exchange, even after flushing of several tank volumes. While it is possible to estimate the theoretical replacement or mass balance of ballast water by a simple two-component mixing model, such a model does not take into account the complexities of fluid flow dynamics in a ballast tank. An accurate model of ballast tank fluid flow and mixing must take into account internal ballast tank design, the density difference between the two mixing fluids, and the flow rate, and this requires a more complex modeling approach, which has only recently been developed and applied to a few cases. Second, organisms are not passive particles and their removal may differ from water replacement. Planktonic (waterborne) organisms are known to exhibit complex behaviors that affect their distribution, and thus the probability of being removed from ballast tanks during BWE. Thus, theoretical model-based estimates of BWE efficacy must be viewed cautiously, as they require empirical validation (testing) to confirm the expected reduction in both the initial water and the initial organism concentrations.

Until recently there have been surprisingly few empirical studies of the effects of BWE on coastal organisms. Over the past 6 years, the Smithsonian Environmental Research Center (SERC) has conducted more than two dozen shipboard BWE experiments across four main vessel types: commercial oil tankers, container ships, bulk carriers (bulkers), and Navy refuelers. This constitutes the largest body of experimental data available on the efficacy of BWE based on ships transiting US waters.

The SERC experiments found that BWE can be highly effective, removing on average 88-99% of the original coastal water and 80-95% of coastal planktonic organisms from ballast tanks (compared to control tanks), when conducted according to current requirements. The experiments included both methods of exchange and a range of vessel types, focusing on changes in the concentration of zooplankton, but did not evaluate efficacy for phytoplankton. The observed efficacy (measured as decrease in organism concentration) of BWE was lowest for containerships, which may have resulted from the shape, structure and small size of tanks compared to other ships, perhaps causing greater retention of the original water during empty-refill exchange.

The available experimental data demonstrate a strong effect of BWE on reducing abundance of coastal organisms. Despite the relatively high efficacy in removing initial plankton assemblages (average of 80-99%), it is also evident that some coastal organisms remain in ballast tanks following exchange and are thus delivered to U.S. ports following BWE. Moreover, a small subset of species exhibited only small reductions in abundance associated with BWE.

SERC's results for removal of coastal water are consistent with the few previous studies reported to date. However, it is also noteworthy that some earlier studies of zooplankton and phytoplankton reported more variable results for the efficacy of BWE. A great deal of this variation corresponds to differences in experimental design, and method of estimation, as well as the taxonomic groups examined. More specifically, some estimation methods do not adequately account for the effects of initial conditions and time, which may explain the low efficacy estimates reported.

The efficacy of BWE is least clear for waterborne bacteria, viruses, and protists. Although useful in describing bulk microbial characteristics, existing studies of microorganisms have not yet adequately evaluated effects of BWE for coastal forms (taxa) and any conclusion for these groups are premature at this time.

Laboratory experiments conducted by SERC suggest that salinity stress experienced after BWE should enhance the efficacy of exchange when the original ballast water is low salinity. It is clear that some organisms are killed by such shifts in salinity, and that salinity can represent a significant barrier. However, there are few data available to assess the effect of short-term salinity exposure on survivorship or subsequent performance, especially for holoplankton and larval invertebrates commonly found in ballast tanks. There is good reason to believe substantial variation exists in response to salinity stress among species and that it may even vary within species, due to genetic differences, physiological condition, life stage, and local starting conditions (acclimation). Thus, while it's clear that changes in salinity associated with BWE can enhance efficacy, the frequency with which this happens and under what conditions depends on several factors, including the salinity tolerance of the organisms involved and the duration of exposure.

The significance of residual organisms in bottom sediments and on the inner surfaces of ballast tanks is still an open question. These organisms are perhaps least likely to be affected by the flushing effects of BWE, as they are not suspended in the water column and not as prone to being flushed out with ballast water during exchange. However, fresh and brackish water organisms in accumulated sediments are also subject to salinity stress unless the sediment is so thick that it can shield them from exposure. Thus salinity stress during BWE can be an important factor in reducing the risk for a freshwater ecosystem like the Great Lakes and the low-salinity portions of estuaries.

There is no doubt that properly conducted, BWE significantly reduces total propagule supply of coastal organisms, especially for waterborne life stages, but tank bottoms and hard surfaces still harbor organisms (especially microorganisms and cysts) that may pose some risk. The extent to which these latter organisms are released and the likelihood of their establishment remains poorly understood and is an active area of research.

Chapter 3 - GREAT LAKES: RECENT HISTORY OF SALTWATER VESSEL TRAFFIC, DELIVERY OF BALLAST WATER, AND THE EFFECT OF BALLAST WATER EXCHANGE ON AQUATIC SPECIES INVASIONS

The documented invasion history of the Great Lakes spans two centuries and implicates a broad array of vectors, including transoceanic shipping. Ships are believed responsible for aquatic nonindigenous species (ANS) introductions as early as the 1860s, via disposal of solid ballast. Ballast water first shows up as a likely vector in 1938, but became significantly more important after the opening of the St. Lawrence Seaway in 1959.

In order to assess the effectiveness of ballast water exchange (BWE) on Great Lakes aquatic invasions, a history of the amounts and biological characteristics of ballast discharged into the ecosystem is needed. Unfortunately only pieces of the necessary information are available, and are subject to large variations and uncertainties. However, based on the limited information that is available, we can speculate on potential changes in ballast carried into the Great Lakes system and what caused those changes.

In this Chapter we review and compare what is known about vessel traffic patterns and ballast characteristics of saltwater vessels entering the Great Lakes during equal periods of time before (1978-1988, "pre-BWE") and after (1994-2004, "post-BWE") BWE regulation. We also review the nonindigenous species invasion record for the Great Lakes. The transition period between 1989, when voluntary BWE guidelines were issued by Canada, and 1993, when mandatory requirements for BWE were implemented by the United States, is excluded. Records from the St. Lawrence Seaway Development Corporation and the U.S. Coast Guard were the primary sources for much of the vessel traffic information we had.

There are two main categories that define the ballast status of incoming saltwater vessels ("salties") entering the Great Lakes: vessels with pumpable "ballast on board" (BOB), and vessels with "no ballast on board" (NOBOB). NOBOB vessels are considered to be "empty" of pumpable ballast, but some residual unpumpable ballast water and accumulated sediment remain in the tanks of almost all ships even after they completely deballast. There is also a subcategory of the BOB classification which we designated BOB-A. These are ships that carry relatively small volumes of pumpable ballast in one or more ballast tanks, usually to maintain vessel trim.

There was a significant decrease in the number of ships entering as BOB during the post-BWE period, while the number estimated to have entered as NOBOBs was not significantly different. However, NOBOB and coastwise ships were not subject to the ballast water exchange requirements until June 2006, when new Canadian ballast management regulations were established (Canadian coastwise vessels are still exempt).

The size of ships entering the Great Lakes during the two periods, as reflected in gross tonnage, increased slightly during the post-BWE period. In order to estimate ballast quantity, we assumed for each period that the average cargo weight carried by NOBOBs each year was representative of the average amount of ballast that would be carried by BOB ships for the same year. The average of annual cargo weight per transit was about 21% larger for the post-BWE period.

Since the total ballast weight is the sum of the weights of accumulated ballast tank sediments plus ballast water, cargo weight should be reduced by ballast sediment weight in order to calculate the amount of ballast water, but we don't have the data necessary to do this for all categories of ships, so we focus on total ballast load. Thus, for BOB and BOB-A vessels the total ballast load estimated using cargo weight includes the both water and sediment. For NOBOB vessels, limited data are available to examine ballast water and sediment loads separately, but only for the post-BWE period.

Based on a series of assumptions and estimates, we speculate that the total ballast amount (water plus sediment) carried into the Great Lakes potentially declined by ~76% between the pre- and post-BWE periods we compare. This apparent decline was mainly the result of economic changes resulting in fewer ships entering the lakes overall, as well as a decline in the number of vessels carrying ballast, and improvements in ship management and shipkeeping practices. Compared to the amount of ballast potentially carried on BOB vessels, the amounts carried on BOB-A and NOBOB vessels were relatively small fractions of the cumulative total ballast potentially carried into the Great Lakes during either period, although the percentage contributions for both types are greater for the post-BWE period.

Information on sources of ballast water showed that Western Europe and the Mediterranean Sea were probable source regions for half or more of all ballast entering the Great Lakes region, with North and South America also significant. One data set also revealed that the Great Lakes are another significant source region, which often doesn't show on such records because most are based only on the most recent ballast intake, not multiple previous ballast intakes.

In the absence of more appropriate data, we use estimated changes in ballast quantities between the pre- and post-BWE periods as a simple, but coarse surrogate to examine potential changes in propagule (organism) supply during the pre- and post-BWE periods. For this exercise, we used 90% as a representative average for the reduction of coastal organisms achieved by a properly conducted BWE that meets regulatory goals (95% coastal water volume replacement). The results indicate a dramatic reduction in potential propagule supply between the pre- and post-BWE periods, represented by an estimated average decrease of ~97%, or elimination of an average of ~3.3 millions t per year of unexchanged ballast water for the 11 years (1994-2004) after implementation of BWE regulations compared to an equal period prior to BWE (1978-1988). Changes in the economic requirements of the shipping trade as well as changes in ship management practices that started in the mid-1980s, and ballast management (BWE) requirements that were implemented in 1993, were all significant drivers of the projected decrease.

Changes in ballast quantity will not tell a complete or accurate story unless they can be translated into changes in propagule supply, but the information to do so is incomplete and inconsistent. There are a number of important factors that can influence the biological effectiveness of BWE, including salinity shock mortality and the methods used to conduct the BWE process. The biological content of ballast entering the Great Lakes is not well known, and the characteristics and numbers of organisms typically found in ballast water are quite variable and functions of source region, season, and duration of the transit since ballasting. Records relevant to the Great Lakes reveal large variations in the available data. Our estimates suggest that organisms associated with sediment may constitute a potentially large pool of propagules in vessels entering the Great Lakes system, but our knowledge about the discharge of residual sediments and the viable propagules they contain, and the effectiveness of BWE on sediment organisms, is insufficient to assess the risk sediments pose to the Great Lakes with a reasonable level of confidence,

In spite of the lack of quantifiable data, it appears reasonably certain that there was a significant decrease in the overall propagule supply to the Great Lakes between the pre-BWE and post-BWE periods, part of which can be attributed to ballast management regulations and, in particular, BWE. However, no matter how effective BWE can be in reducing coastal and freshwater organisms in ballast water, the protection framework for the Great Lakes ecosystem that established the 1993 ballast management regulations was weakened by the gaps represented by NOBOB and coastwise vessels. The true potential effectiveness of ballast management regulations and BWE cannot be realized unless they are implemented and enforced for all vessels entering the Great Lakes. Implementation of new ballast management regulations by Canada in 2006 appears to be an important step towards eliminating these gaps.

Over the past two centuries, the Great Lakes basin has been invaded by over 180 nonindigenous species, none of which have been extirpated. Analyses of life history, invasion history in other ecosystems, and likely vectors and opportunities for movement between ecosystems, lead to the conclusion that shipping, particularly ballast water release, is the vector responsible for most aquatic invasions in the Great Lakes since the opening of the St. Lawrence Seaway in 1959. Over 40% of all aquatic invaders have been discovered since 1960 and the average rate of discovery since from 1960 through 2003 is one new invader every 30 weeks, higher than any other freshwater system for which long-term data exist and placing the Great Lakes among the most highly invaded aquatic ecosystems in the world.

An analysis of the Great Lakes invasion record during the time periods before (1960-1988) and after (1994-2003) voluntary (1989) and mandatory (1993) BWE shows that the rate of discovery of new invaders has not changed significantly. Between 1960 and 1988, the average rate of discovery of invaders attributable to shipping was 1.0 species per year. After 1993, when BWE became mandatory, the average rate has been 0.9 species per year if only free-living non-parasitic organisms are considered. Note, however, that invasion history and patterns of invasion are to be interpreted with caution, as they are subject to various biases and errors (e.g., changes in sampling effort, lag-time between actual introduction and discovery) that can lead to debatable conclusions about the actual timing and rate of invasions.

Western Europe is the most common location where recent ballasting has occurred prior to vessels entering the Great Lakes, with the Great Lakes themselves being the second most common region where recent ballasting has occurred. Most of the successful invaders recorded since the opening of the St. Lawrence Seaway are Eurasian in origin. Over the past three decades, there have been increasing discoveries of invaders that are native to the Black and Caspian Seas ("Ponto-Caspian") region of Eurasia. The establishment of these species in the Great Lakes coincides with the spread of Ponto-Caspian species into western European ports from which the Great Lakes receives the bulk of its shipping traffic. The Great Lakes appear to be particularly susceptible to Ponto-Caspian species. Previous Ponto-Caspian invaders (such as the zebra mussel, fish-hook waterflea, and round goby) have caused substantial ecological impacts in the Great Lakes and elsewhere. Dozens of Ponto-Caspian species continue to spread to and dominate biota in western European ports, where they are provided increased opportunities for transport to the Great Lakes.

Living organisms are still being delivered to the Great Lakes in residual water and sediments of ballast tanks, and new invaders have been discovered since 1993. Recently discovered introduced species consist primarily of bottom-dwelling invertebrates with broad salinity tolerance. Such species are more likely to survive than others in a ballast tank following BWE, or in residual water and tank sediments of NOBOB ships not previously covered by BWE regulations.

Since the late 1980s, most ships entering the Great Lakes are NOBOB vessels, which were not regulated by ballast management policies to reduce the risk of invasive species transfers. NOBOB ships are known to carry large numbers of benthic invertebrates in ballast residuals of mixed Great Lakes and foreign coastal origins, and can provide a favorable environment for the survival of euryhaline benthic organisms. The Great Lakes NOBOB Assessment Project estimated that a cumulative total of ~26 million fresh and brackish water nonindigenous invertebrates (rotifers, cladocerans and cope-pods) may reside in residual mud of ballast tanks for NOBOB vessels entering the Great Lakes annually, and another ~205,000 may occur in the residual water of these vessels. However, the extent to which the species composition in residuals varies over time and with season, and the extent to which viable organisms are actually discharged (released) to surrounding waters, and their fate of discharged organisms, is not well known or understood.

Invertebrates in residual water likely have a greater opportunity for discharge than those in sediments, and thus organisms in residual-water are thought to pose a greater invasion risk than those in residual-sediment, despite the large disparity in numbers. Thus, while the total propagule pressure (the number and quality of viable biological life stages capable of establishing a population that are being delivered to an ecosystem) associated with foreign ballast water discharges appears to have decreased significantly in the decade after implementation of BWE regulation, NOBOB vessels posed ballast-related invasion risks to the Great Lakes, but the magnitude of that risk is uncertain.

In June 2006 Canada implemented new regulations for management of ballast water that also apply to residual water in NOBOBs, requiring the salinity of almost all ballast water to be 30 or greater. If these new regulations prove equally effective as BWE, they may result in further significant reductions in the propagule pressure posed by the ballast water vector to the Great Lakes.

Chapter 4 - CHESAPEAKE BAY: CHANGES IN BALLAST WATER MANAGEMENT & DELIVERY

The mean number of vessel arrivals to Chesapeake Bay remained fairly constant between 1994 and 2004 and averaged about 4,660 per year. The majority of arrivals were domestic, meaning that the last port of call was another U.S. or Canadian port on the Atlantic Coast or the Gulf of Mexico. The proportion of foreign arrivals differed significantly across years and ranged between 23.5% and 29.5% of the total. There were clear differences in the type of vessels involved in the domestic vs. foreign shipping traffic, with container vessels dominating the domestic arrivals and bulkers dominating foreign arrivals. The majority of ships arriving to Chesapeake Bay reported carrying ballast water. On average, bulkers discharged a much larger volume of foreign water per arrival than any of the other types of vessels.

Pursuant to federal laws and regulations, vessels discharging foreign ballast water in the Chesapeake Bay were asked to voluntarily undergo BWE beginning in 1996, and ballast water management became mandatory in September 2004. The available data document an increase in the percentage of foreign-arriving bulkers that underwent BWE. The frequency of BWE by bulkers was in the range of 20-30% from 1993-1995, increased to 40-55% during 1996-1999, and increased further to >80% for the year 2004. Data from the last three-month period (October-December) of 2004, immediately after imposition of the nationwide mandatory BWE requirement, indicated that 85% of bulkers arriving to Chesapeake Bay reported BWE, and for all vessels discharging ballast water of foreign origin, greater than 70% of arrivals by each vessel type reported conducting BWE. In contrast, the percentage of vessels discharging exchanged domestic ballast water during this period was much lower.

BWE significantly reduced the zooplankton concentrations in ballast water discharged to the Chesapeake. We measured quantitatively a large and significant difference in the concentration of organisms arriving in exchanged versus unexchanged ballast water from foreign sources. Live zooplankton found in unexchanged ballast tanks represent coastal or estuarine zooplankton that survived entrainment and transport in the ballast tank, while zooplankton found in exchanged ballast tanks represent a combination of residual coastal zooplankton (that survived entrainment, transport, and BWE) plus oceanic zooplankton (that survived entrainment during, and transport after, BWE). During the warm season (April to September), when plankton concentrations are generally greatest in the northern hemisphere, average zooplankton concentrations in unexchanged ballast water arriving to Chesapeake Bay were significantly higher than that for exchanged ballast water (3,223 organisms•m^{-3} versus 1,089 organisms•m^{-3}), representing a 3-fold reduction. During the cold season (October – March), the average concentration for unexchanged foreign ballast was 778 organisms•m^{-3} compared to 182 organisms•m^{-3} in exchanged ballast water.

This comparison actually underestimates the effect of BWE on removal of coastal plankton, because the data cited above does not differentiate between zooplankton from a coastal vs. oceanic origin. Organisms in the exchanged ballast tanks are mostly of mid-ocean origin, having replaced the original coastal organisms during BWE. Thus, when the change in total concentration is the metric used, BWE appears to be less effective than it actually is at preventing transfers of coastal biota. A better estimate would likely result from reducing the density of zooplankton measured in the unexchanged ballast water by the estimated reduction in concentration produced by BWE (on average, a 90% decrease in concentration). Using this approach, the resulting zooplankton concentration would decline from a mean of 3,223 organisms•m^{-3} in unexchanged water to 322 organisms•m^{-3} in exchanged water during the warm season, and 778 organisms•m^{-3} to 78 organisms•m^{-3} in exchanged water during the cold season. By either analysis, BWE significantly reduced the zooplankton densities in both seasons.

Due to the increase in use of BWE, there has clearly been a large reduction in the concentration and total number of coastal organisms discharged to Chesapeake Bay by foreign arrivals over the last decade. Nevertheless, the biological significance of BWE, in terms of the reduction of invasion risk, is yet to be resolved. Our results suggest that, on average, the residual coastal organisms in exchanged ballast water may be roughly 10% of the expected concentration without BWE. Therefore, some delivery of coastal organisms from other global regions via ballast still occurs. Although we expect that BWE greatly reduces the likelihood of ballast water-associated invasions, there remains a level of risk greater than zero, and this residual invasion risk is difficult to quantify, due to limited understanding of the relationship between dose (supply) and invasion establishment.

Chapter 5 - CHESAPEAKE BAY: INVASION HISTORY AND THE ROLE OF SHIPPING AND BALLAST WATER EXCHANGE

The Chesapeake is the largest marine estuary in the United States and one of the earliest sites of continuous European settlement in North America. Following the first European settlement at the mouth of the Chesapeake in 1608, the region experienced rapid and sustained growth in human population size, shipping, fishing, and agriculture. Today, the Chesapeake remains a major hub of human activity, and the ports of Baltimore and Norfolk, when combined, have one of the highest ship arrival rates in the U.S.

Since the onset of European colonization in 1608, at least 171 NIS have become established in tidal waters and tidal wetlands of the Chesapeake Bay region. Major taxonomic groups include invertebrates (57 species), algae (8 species), vascular plants (68 species), fishes (27 species), and vertebrates other than fishes (10). The population status of another 38 NIS is considered unknown, including 2 species of algae, 20 invertebrate species, 7 vertebrate species, and 7 species of vascular plants. Chesapeake Bay's largest source region for ballast water is the Northeast Atlantic coast of Europe.

The discovery rate of NIS for Chesapeake Bay increased greatly over the past 50 years. The rate of discovery jumped from 15-22 species per 25-year interval (1855-1954) to 35 species in each of the last two 25-year intervals (1955-2005), representing an increase of >59%. This increase is unevenly distributed among taxonomic groups, with a 4-5 fold increase in invertebrates and algae (combined), but a decrease in the number of new plant discoveries. The temporal patterns for fishes were more variable and without clear change in the recent time periods. Thus, this change in discovery rate also coincided with a shift in invasion history, with recent invasions dominated by invertebrates and algae whereas prior invasions (> 50 years ago) were dominated by plants and fishes.

The observed increase in discovery rate is driven by shipping as a vector, and ballast water and hull fouling are identified as the most important shipping modes of introduction for invertebrates and algae in the Chesapeake Bay region. Ballast water is a possible vector for 51% (28) of the 45 nonindigenous species discovered over the last 50 years (a period of rapid discovery), but for most of these species hull fouling is also a possible vector. Only 11% (5 of 45 species) are attributed solely to ballast water, and ballast water does not appear to play any role in approximately half of all invasions during the last 50-years. In contrast, none of the newly reported nonindigenous plants and fish in the past 50 years are attributed to shipping.

Over the last 10 years (1996-2006), there has been an increase in the frequency of ballast water treatment for ships arriving to the Chesapeake that clearly reduces the density/number of nonindigenous organisms in arriving ballast, yet we do not see any evidence of a decline in the rate of new discoveries of nonindigenous species during this same timeframe. In fact, our data show an increase in new discoveries, but this may result, in large part, from increased sampling and reporting as well as lag times in detection. Thus, it would be erroneous to conclude that ballast water treatment is having no effect, as there are many biases in the existing data on invasion patterns, confounding such assessments (as discussed in Chapter 1).

Although a reduction in ballast-mediated propagule supply should result in reduced risk of invasion, there are several reasons why a strong response may not be observed, in addition to biases in the underlying data. First, it is not evident that ballast water is the most important contemporary vector for aquatic invasions in the Chesapeake. Most invertebrate/algal invasions are attributed to shipping, including both ballast water and hull fouling, and hull fouling may actually be the dominant vector. Second, the expected magnitude of reduction in invasion risk that results from lower propagule supply is not known. The relationship between supply and invasion risk is not likely to be linear, exhibiting instead thresholds where there is a rapid change in probability of invasion. Whether the current ballast water management crosses such thresholds, greatly depressing the invasion risk, remains unknown.

Changes in local conditions in the Chesapeake may also play a role in the observed invasion patterns, interacting with propagule supply. As an urbanized estuary with a large and growing human population in the surrounding watershed, the bay has been subjected to many changes in hydrology, eutrophication, sediment loading, fishing pressure, and habitat alteration. These changes represent major disturbance agents that may operate alone or in combination to affect susceptibility of an ecosystem to invasion. To date, the relationship between these disturbances and invasion susceptibility is not well understood.

Chapter 6 - CONCLUSIONS AND RECOMMENDATIONS

At the present time, it is not possible to accurately estimate the effects of ballast water management on the rate of invasions in <u>any</u> ecosystem. It is clear the BWE has dramatically reduced the supply of coastal organisms discharged in ballast water to the Great Lakes and Chesapeake Bay. While we expect existing ballast water management to reduce the risk of invasion, the exact magnitude of this reduction is poorly resolved, using either theoretical or empirical measures. For empirical measures, interpretation of existing data is confounded by issues related to the intensity and quality of sampling efforts as well as lag times between actual introduction and detection. Data records are unevenly distributed among time intervals, taxonomic groups, and habitats, and there are significant uncertainties about lag-times in detection. Estimates of invasion rates are thus much too coarse to be used with confidence for evaluating ballast management efforts that have only been implemented recently.

In spite of these limitations, we can draw the following conclusions:

A. Efficacy of Ballast Water Exchange

- The process of Ballast Waster Exchange, whether 100% empty-refill or 300% flow-through can be highly effective at replacing coastal ballast water with mid-ocean water (88-99% replacement of original water) and coastal planktonic organisms (80-95% reduction in concentration) across ship types, when conducted according to guidelines and regulations.

- The use of BWE by vessels has significantly reduced (a) the discharge of coastal organisms in ballast to the Great Lakes, Chesapeake Bay, and other U.S. estuaries and (b) associated risk of invasions.

- Salinity stress during BWE can be an important factor in reducing the risk for a freshwater ecosystem like the Great Lakes and for the low-salinity portions of estuaries. However, considerable variation exists in the response of organisms to salinity stress and some euryhaline organisms exhibit a wide salinity tolerance that could allow them to survive BWE.

- BWE does have several limitations. First, some coastal organisms remain even after BWE is completed according to guidelines. Second, to conduct BWE, a ship must have sufficient time in transit (i.e., between ports), acceptable sea state, and be a sufficient distance from shore. As a result, this treatment is often not applied to coastwise traffic between domestic ports, and this represents a sizeable loophole for the transfer and spread of nonindigenous species in U.S. waters.

- Regulations for BWE did not address potential risks associated with NOBOB vessels, and this deficiency represented a gap in the protection framework that established BWE regulations; however, this was of significance primarily for the Great Lakes, since the percentage of NOBOB vessels entering other ports is generally much lower, and has been the focus of additional regulation implemented in 2006 (see below).

B. Great Lakes

- The opening of the St. Lawrence Seaway in 1959 permitted the influx of more and larger vessels carrying large volumes of ballast water and ballast sediments into the Great Lakes, and was associated with an increase in the discovery of new aquatic invaders consistent with ballast water being a significant vector.

- Estimates of Great Lakes saltwater vessel traffic and changes in vessel and ballast characteristics pre- (1978-1988) and post- (1994-2004) BWE suggest a possible 76% reduction in the average total amount of ballast potentially carried into the Great Lakes.

- It appears reasonably certain that there was a significant decrease in the overall propagule supply to the Great Lakes between the pre-BWE and post-BWE periods, part of which can be attributed to ballast management regulations and, in particular, BWE. For a scenario using ballast quantity as a simple coarse surrogate for propagule supply, and applying a 90% reduction of live organisms due to BWE, a net decrease in potential propagule supply delivered to the Great Lakes of 97%, represented by an estimated annual elimination of ~3.3 million t of unexchanged ballast, was calculated for the 11 years (1994-2004) after implementation of BWE regulations compared to an equal period prior to BWE (1978-1988).

- Changes in economic factors that affected trade, changes in shipping practices, and implementation of BWE regulations all contributed to decreasing the propagule supply to the Great Lakes.

- Even with increasingly strict enforcement of BWE requirements, resulting in high compliance rates for vessels arriving from overseas with pumpable ballast, there have been several gaps (NOBOBs and coastwise traffic) in the protection framework for which BWE is the centerpiece.

- Although the magnitudes of the risks associated with NOBOB and coastwise vessels cannot be calculated for the Great Lakes, it is clear that regardless of how effective BWE may be in reducing coastal and freshwater organisms in ballast water when conducted according to guidelines, the overall Great Lakes ecosystem protection framework was weakened by the gaps in application of ballast management regulations represented by these vessels.

- The average rate of ANS discovery in the Great Lakes ecosystem attributable to all vectors since 1960 through 2003 was 1.8 species per year, or one new successful invader discovered every 29 weeks. This discovery rate is higher than any other freshwater system for which long-term data exist and places the Great Lakes among the most highly invaded aquatic ecosystems in the world. However, discovery rate is not the same as invasion rate and the latter cannot be measured with existing methods.

- About 2/3 of all Great Lakes ANS discovered since the opening of the Seaway are attributed to the shipping vector. After 1993 they are more likely to be euryhaline organisms with benthic adult and juvenile lifestyles, and are more likely to be natives of the Ponto-Caspian region of Eurasia. The establishment of these species in the Great Lakes coincides with their spread into western European ports from which the Great Lakes receives the bulk of its shipping traffic.

- An important step forward in protecting the Great Lakes was the implementation in 2006 of Canadian requirements that all ballast water, including NOBOB residual water, be at salinity of 30 or greater. If these requirements prove equally effective as BWE, we would expect significant additional reductions in the propagule supply due to this vector.

C. Chesapeake Bay

- There has been a significant increase in the discovery rate of invasions to the Chesapeake Bay over the last 50 years, particularly for invertebrates and algae. Many of these are conspicuous species not easily overlooked in earlier surveys, providing considerable confidence that a real upsurge in invasions has occurred in the Chesapeake Bay during the last half century.

- There has been a substantial shift in the ballast management practices of ships arriving to the Chesapeake Bay from foreign ports, with the frequency of use of BWE having increased significantly from 1994 to 2004.

- Empirical and theoretical measures for the Chesapeake indicate a significant reduction in coastal organisms being discharged in ballast water has occurred since 1993.

- Shipping is implicated as the predominant source of aquatic invasions, but the relative contribution of ballast water discharge versus hull fouling is unresolved.

- The discovery rate of invasions for the Chesapeake has not declined in the past decade, during which time BWE has increased. However, it is premature to estimate the effect of BWE on invasion rate for such a short time interval, given the same issues (including especially lagtime and sampling effort) as discussed above for the Great Lakes.

- To assess the response of invasion patterns and rates to ballast management strategies with any significant and defensible confidence requires implementation of standardized, repeated sampling programs over time. A solid baseline is required to measure changes in the arrival and abundance of nonindigenous species to key coastal ecosystems. At the present time, no such program exists in the United States.

Recommendations

Against this synthesis and analysis, we make the following recommendations.

1. BWE should be considered a useful and beneficial ballast management practice to reduce species transfers and invasion risk. It is a valuable measure, especially because it is available now for immediate use on many vessels and shipping routes, in the absence of proven alternative treatment methods.

2. Research and development to produce alternative ballast treatment methods and technology-based ballast treatment systems should continue as a high priority, in order to improve the efficacy of treatment and expand application of treatment to most vessels and routes.

3. The use of high-salinity water to flush NOBOB ballast tanks should be considered a useful and beneficial management practice to reduce species transfers and invasion risks associated with NOBOB ships entering the Great Lakes. In the absence of proven alternatives, this practice provides some level of protection against some adult and larval life stages, but probably not against resting eggs and spores of zooplankton and phytoplankton.

4. A quantitative, empirical assessment of the actual release of propagules from NOBOB vessels in the Great Lakes is needed for a better risk assessment to guide management and policy in this area.

5. The effects of salinity stress on a broad range of estuarine and freshwater organisms should be further explored and assessed with respect to ballast treatment, focusing especially on the use of high-salinity water to (a) flush NOBOB ballast tanks and (b) treat low salinity ballast water moved by coastwise shipping.

6. A standardized sampling program targeting key coastal ecosystems in the U.S. is needed to provide the high-quality data necessary to delineate and measure the performance of different vector management actions.

7. A significant effort should be devoted to understanding the relationship between propagule supply (dosage) and invasion risk. The quantitative relationship between propagule pressure and invasion establishment remains a fundamental gap in knowledge, yet it is at the core of defining management goals (such as ballast discharge standards) and predicting the effectiveness in preventing future invasions.

1 INTRODUCTION AND BACKGROUND

1.1 Biological Invasions and Maritime Shipping

Biological invasions – the successful establishment of reproducing populations of nonindigenous (i.e., "non-native") species outside their historic native range - are prevalent in coastal ecosystems throughout the world. The rate of discovery of nonindigenous species invasions in aquatic ecosystems of the United States has increased dramatically over the past century (Carlton 1985, Mills et al. 1993, Cohen and Carlton 1998, Ruiz et al. 2000, Ricciardi 2001, 2006, Hewitt et al. 2004, Sytsma et al. 2004; see also Chapters 0 and 5 of this report). Although the impact of many non-native populations remains unexplored, it is also evident that some species have fundamentally altered the structure and function of coastal ecosystems (Ruiz et al. 1999, Carlton 2001, Crooks 2001, Vanderploeg et al.2002).

Most known coastal aquatic species invasions are documented from protected waters of bays and estuaries, rather than exposed outer coasts. This results at least partly from the concentration of human activities around protected bays and estuaries. Most global trade occurs by shipping among ports, which are concentrated in bays and estuaries, creating opportunities for species transfers associated with ships' hulls and ballast materials (Carlton 1985). In addition, bays are foci for many other activities known to transfer organisms, such as aquaculture, fishing, and outdoor recreation.

Historically, the introduction of nonindigenous aquatic species has resulted from (1) natural dispersal, (2) movement of organisms on the bottom of ships, (3) movement and/or intentional release of aquaculture and fisheries species along with their rich assemblage of associated organisms, (4) release of species associated with pet industries, gardens, or management, and (5) release of organisms in the ballast materials of ships (Elton 1958, Carlton 1979, 1985, 1989, 1992, Ruiz et al. 2000). Human activities (2-5 above) have surpassed natural dispersal as the primary drivers of aquatic species invasions, and the majority of biological invasions over the last several centuries have been associated with human activity.

Although most of these human-mediated transfer mechanisms (or vectors) remain active today, the relative importance of shipping appears to have increased over time, contributing strongly to the observed increase in invasion rates in coastal ecosystems (Carlton 1979, Carlton and Geller 1993, Mills et al. 1993, Cohen and Carlton 1998, Ruiz et al. 2000, Ricciardi 2001, 2006, Holeck et al. 2004). On a national scale, shipping is considered responsible for most invasions in bays and estuaries of the continental U.S. (Ruiz et al. 2000), and the global movement of ballast water (Carlton 1985, 2001; Carlton and Geller 1993) is a major transfer mechanism for nonindigenous species (NIS) to both freshwater and marine systems.

In the past ships primarily transported marine organisms associated with dry ballast and on the outer submerged surfaces (e.g., hulls, rudders, propellers). Ships began using water for ballast in the late 19th century with the advent of steel-hulled ships, replacing the use of dry ballast and creating a new transport mechanism for aquatic organisms (Carlton 1985, National Research Council 1996). Ports can receive relatively large volumes of ballast water originating from source regions throughout the world. For example, the United States and Australia each receive >79 million metric tonnes of ballast water that is discharged annually by ships arriving from foreign ports (Kerr 1994, Carlton et al. 1995).

Ships take on ballast from the surrounding waters in port, and elsewhere while underway, using this water for trim and stability during transit, often discharging this ballast water at or near subsequent ports of call. A taxonomically diverse community of organisms is thereby entrained and transported within ballast tanks. In general, the concentration of organisms increases with decreasing body size. Concentrations of organisms per liter of ballast water are routinely on the order of 10^0-10^2 zooplankton, 10^3-10^6 phytoplankton, 10^8-10^9 bacteria, and 10^9-10^{10} viruses (Carlton and Geller 1993, Subba Rao et al. 1994, Smith et al. 1999, Dickman and Zhang 1999, Hines and Ruiz 2000, Drake et al. 2001). A single ballast tank can contain hundreds of species (Hülsmann and Galil 2002). When scaled to the volume of ballast discharged within the U.S. alone, the cumulative number or organisms and diversity of species delivered annually by this mechanism is very large indeed. A subset of these organisms are able to establish self-sustaining populations outside their historical range, resulting in biological invasions in bays and estuaries throughout the world (e.g., Carlton and Geller 1993, Cohen and Carlton 1995, Smith et al. 1999, Hines and Ruiz 2000, MacIsaac et al. 2002, Ruiz and Carlton 2003).

1.2 Legislative Summary

In response to the increasing number of invasions and their associated economic and ecological impacts, management strategies and policies are being advanced at various state, national and international levels. For coastal systems, much of these efforts have focused on ballast water management, to reduce the concentrations of organisms in ships' ballast water. This has advanced at different rates in various parts of the United States, under both federal and state laws.

To reduce the risk of invasions to aquatic ecosystems, the U.S. Congress enacted the Nonindigenous Aquatic Nuisance Prevention and Control Act of 1990 (NANPCA, P.L. 101-646) and the National Invasive Species Act of 1996 (NISA, P.L. 104-332), both of which established major policy on ballast water. NANPCA called for specific ballast water management for ships entering the Great Lakes and upper Hudson River. The resulting regulations are found in 33 CFR Part 151 subpart C and were implemented in 1993 (Federal Register, 58 FR 18330) for the Great Lakes and in 1995 (Federal Register, 59 FR 67632) for the Hudson River north of the George Washington Bridge. They required that ships arriving from outside the U.S. Exclusive Economic Zone (EEZ) treat their ballast water before discharge in these local waters to reduce the concentration of coastal organisms being transferred. Under these regulations, ships could either (a) conduct mid-ocean BWE before entering U.S. waters, in which case the salinity of the exchanged water must exceed 30, (b) use an alternate BWE site designated by the U.S. Coast Guard, (c) retain unexchanged ballast water on board while in U.S. waters, or (d) use a U.S. Coast Guard approved alternative method to treat the ballast water. To date, no alternative treatment method has been approved for routine use by the U.S. Coast Guard.

Implementation of the 1993 U.S. BWE requirement was preceded a few years by voluntary guidelines issued by Canada (1989) and the U.S. (1990), with high rates of compliance reported during the period 1990-1993. In order to monitor compliance with BWE requirements for the Great Lakes, the U.S. Coast Guard boarded and checked ships' ballast logs and sampled the salinity of ballast water in randomly selected ballast tanks.

NISA expanded NANPCA and required the U.S. Coast Guard to establish national voluntary ballast water management guidelines for ships arriving from outside the EEZ, specifying that if compliance with the guidelines (including mandatory reporting of ballast management practices) was inadequate, then mandatory nationwide ballast water management would be implemented.

Under a nationwide program initiated in 1998, voluntary ballast water management was established for a trial period of 24-30 months, including a requirement for reporting on the discharge and management of ballast water upon arrival to U.S. ports. The U.S. Coast Guard determined that the rate of compliance with the reporting requirement during this trial period was inadequate, and ballast water management became mandatory in September 2004 for all vessels equipped with ballast water tanks that enter or operate within U.S. waters (Federal Register, 69 FR 44952). These regulations also require vessels to maintain and implement a ballast water management plan that is specific for that vessel. Similar regulations exist in several other countries, including Australia and New Zealand.

U.S. Coast Guard regulations apply to commercial ships, but vessels of the Department of Defense are exempt as specified in NISA. The U.S. Navy requires BWE on all vessels that arrive to any port after having been overseas, or from another port along a coast. The exchange must be conducted outside of 12 nautical miles (nm) of shore. The guidelines are specified by OPNAVINST 5090.1B, as follows:

> "If it is necessary for a surface ship to load ballast water in an area that is either potentially polluted (as defined in paragraph 19-10.2) or within 3 nm from the shore (e.g., amphibious ships operating in such waters and ballasting to operate landing craft or tankers ballasting to replace offloaded cargo), the ship shall pump the ballast water out when outside 12 nm from shore and twice fill the tank(s) with clean sea water and pump prior to the next entry within 12 nm from shore. Surface ships will effect a ballast exchange twice in clean water, even if ballast water was pumped out before exiting the polluted waters or 3 nm limit, since residual water remaining in a tank after emptying it may still contain unwanted organisms, that could be transferred during the next ballasting evolution."

1.3 Ballast Water Exchange and Ballast Tank Architecture

Ballast tanks are void spaces, usually along the outer edge of the hull of a ship, that have been specifically designed to contain and move water around. Most ballast tanks have a complex internal structural design (*Figure 1-1*) that must be strong enough to support the weight of the ship, withstand the rigors of a voyage, and yet allow water to flow more or less freely to fill and empty the tank.

The goal of BWE is to replace coastal ballast water (and entrained organisms that may become established in other coastal ecosystems upon ballast discharge) with mid-ocean surface seawater. There are two types of BWE approaches: reballasting (or empty-refill), and flow-through (or flushing). The former requires that ballast tanks be emptied completely and then re-filled, at sea, while the latter requires pumping of mid-ocean water, usually entering at the tank bottom, into a full or partially full ballast tank and allowing the water to overflow the tank for a three tank volumes (Rigby and Hallegraeff 1994, Hay and Tanis 1998, Rigby 2001). It must be noted that the flow-through target of overflowing three tank volumes is based on a theoretical calculation that assumes perfect and instantaneous mixing between the original ballast water and the incoming mid-ocean water (Hay and Tanis 1998). In practice, the mixing dynamics within a ballast tank are determined by the density difference between the original and incoming fluids, the flow rate, and the tank geometry and structural components.

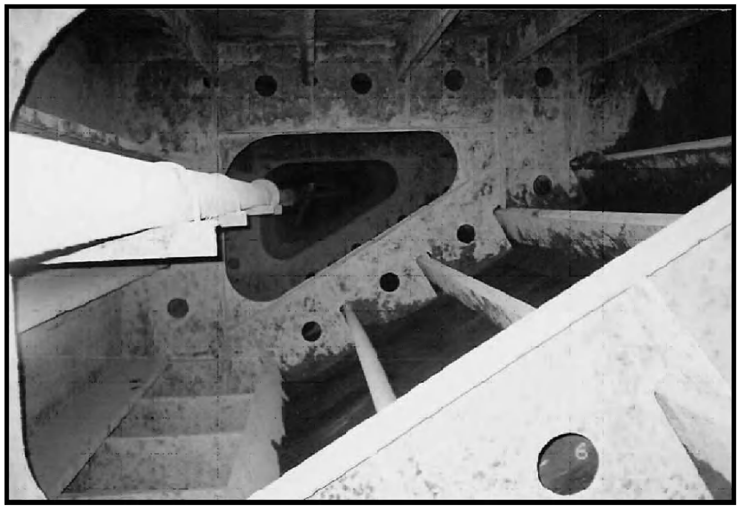

Figure 1-1: View inside an upper wing ballast tank. There are many structural components that provide traps for sediment and that may create dead zone during ballast water pump-out. Photo credit: Great Lakes NOBOB Program

There are perceived logistical and safety constraints on the routine use of BWE for some ship types, routes (especially coastal voyages of limited duration), and sea conditions. Over the past several years, many efforts in the U.S. and internationally are promoting development of alternate technology-based methods to treat ballast water. Such technology development and demonstration is still at an early stage. No technology is currently approved for use by U.S. Coast Guard to meet its requirements for ballast water management. It may be several years before technologies are available and widely used. In the interim, BWE is viewed broadly as a stop-gap measure that is immediately available for use on most ships and that will likely be in use for the next decade, being gradually phased out by the world's fleet as more effective technology-based methods become available. Chapter 2 provides additional information about BWE and experiments to measure its efficacy with respect to regulatory goals.

Although organisms transported in large volumes of water in filled ballast tanks have received most attention, organisms can also be transported in ships that report to have "No-Ballast-On-Board" (NOBOB). Such ships often carry small amounts of residual water and associated sediments which pose some risk of species transfer during subsequent ballast operations and discharge. For example, Johengen et al. (2005) showed that the water and sediment ballast residuals in NOBOB vessels, although small by volume when compared to ballast tank full of water, can house substantial numbers of live or viable (eggs, cysts) organisms, a portion of which are nonindigenous and not yet present in the Great Lakes. Their data also suggested that the abundance of NOBOB-related nonindigenous species may be lowered with conscientious and consistent application of good management practices, especially flushing NOBOB tanks with saltwater on the open ocean whenever possible unless BWE has occurred since the last uptake of low-salinity coastal ballast water.

Coincident with the publication of the NOBOB-A Final Report (Johengen et al. 2005), the U.S. Coast Guard conducted a public hearing and a technical workshop in May 2005 to address management of NOBOB vessels entering the Great Lakes. In August 2005 the U.S. Coast Guard issued voluntary NOBOB management guidelines calling for ships entering the Great Lakes and northern Hudson River to take steps to assure that the salinity of their residual ballast water is over 30, either through BWE or ballast tank flushing, as appropriate and safe (Federal Register / Vol. 70, No. 168 /August 31, 2005, pp 51831-51836; see also http://www.uscg.mil/hq/g-m/mso/nobob.htm). In June 2006 Canada implemented new legislation establishing mandatory management of NOBOB ballast tanks, including a requirement that residual water salinity be >30 (Transport Canada 2006).

1.4 BWE Efficacy vs. Effectiveness and Using Invasion Rate as a Measure

The efficacy of BWE is a measure of its ability to meet a goal, in this case, the replacement of 95% of the water in coastal ballast water and organisms by mid-ocean water, which is the regulatory goal. In this report (Chapter 2) we examine the results from over 30 direct on-board experiments to assess the efficacy of BWE in meeting the 95% water and organism replacement goal.

The effectiveness of BWE is a measure of how well it meets the inherent legislative goal of prevention of new NIS introductions to coastal ecosystems. The problem with trying to measure effectiveness in this sense is that we cannot measure something that is prevented; we can only detect failures to prevent. If all other factors are held equal, if we observe a change in invasion rate over time associated with implementation of a preventive mechanism, such as BWE, theoretically we can assess how effective that tool has been. However, accurate measure of the impact of BWE on invasion rate requires a number of conditions that cannot be met at the present time:

- Comprehensive systematic records of aquatic species invasions from periods both before and after implementation of BWE must be available. While invasion records are available for both the Great Lakes and Chesapeake Bay ecosystems, they are neither comprehensive nor systematic, and contain inherent biases (see below).

- We must be able to separate aquatic invasions that resulted from ballast water discharge from those associated with other pathways, such as hull fouling, canals and waterways, organisms in trade (bait and aquaria commerce), and aquaculture. We are not able to unequivocally assign each NIS to a unique pathway or vector; in fact, the specific vector of introduction of many existing invaders is unknown or uncertain.

- The date of introduction resulting in a successful invasion of each ballast water associated invader must be precisely known so that those that entered before BWE can be clearly differentiated from those that entered after BWE was implemented. The discovery of a new invader in an ecosystem is dependent on several factors, including how obvious the invader is, how abundant the invader becomes, who is looking, and what they are looking for. In general, the more obvious and visible the invader, the more likely its discovery. For example, an invader that inhabits a remote habitat, such as the bottom of a lake, and increases slowly in population size, may not be discovered for years to decades after its actual introduction.

Most critically, there exists no program of systematic, standardized, and repeated measures over time that can provide comparable data to assess changes in number of detected invasions before and after BWE regulations, in the Chesapeake Bay or Great Lakes, or for the Nation. Instead, the discovery of most invaders to date has been serendipitous, such that what is recorded is the date of discovery, not necessarily the date of invasion. Ruiz et al. (2000) discussed potential biases in invasion discovery data, including uneven spatial and temporal search effort and bias towards conspicuous taxonomic groups relative to smaller organisms. Growing scientific attention to aquatic invasive species is a relatively new phenomenon, having started in earnest after the zebra mussel invaded the Great Lakes in the late 1980s. Prior to that, there was little scientific attention paid to aquatic NIS. Costello and Solow (2003) showed mathematically that the discovery curve for NIS can increase even when there is no increase in either the introduction rate or the sampling rate. Thus, discovery rate is not a reliable approximation for invasion rate.

Although we cannot presently use discovery rates to reliably assess the effectiveness of BWE (i.e., invasion rate), these available data do document the increasing importance of shipping as a transfer mechanism. We present a summary of the discovery rates and patterns of invasion from this perspective, to underscore the present state of knowledge about ship-mediated invasions.

1.5 Hull Fouling

Movement of species on the hulls of vessels also remains an active transfer mechanism, especially for marine and estuarine (i.e., saltwater) ecosystems. Recent analyses demonstrate that most commercial ships carry marine organisms that are attached to the hulls and other underwater surfaces, sometimes in large numbers (Gollasch 2002, Godwin 2003, Coutts and Taylor 2004). Smaller recreational vessels are also colonized by marine life (Floerl and Inglis 2003). This form of ship-mediated transfer is thought to be responsible for many invasions (e.g., Carlton 1979, Reise et al. 1999, Hewitt et al. 2004). Thus, both modes of ship transfer can be important sources of invasions, and some uncertainty exists about the relative importance of hull fouling versus ballast water for coastal marine systems (Fofonoff et al. 2003). This dichotomy appears much less pronounced for freshwater habitats, like the Great Lakes, as many organisms attached to hulls are not thought to withstand the transition between marine and freshwater salinities associated with transits between oceanic and estuarine or freshwater ecosystems.

Other vectors of potential significance, but not considered further in this report, include canals and waterways, the live organism trade (aquaria, live bait, live food, and ornamental plants/horticulture), recreational activities, and aquaculture.

1.6 Approach to Evaluate Effects of BWE

In this report, we summarize the current state of knowledge about BWE and its effects in the Great Lakes and Chesapeake Bay. Our approach was to synthesize, review, and interpret available information relevant to assessing the effects of BWE, as applied to these two ecosystems and as requested by U.S. Congress. This was intended to provide an up-to-date overview and snapshot of the current understanding about effects of BWE, instead of initiating further primary research.

Current theory and empirical studies about invasions indicates that changes in characteristics of nonindigenous organism delivery or supply, especially quantity and frequency of introduction, affect the risk or likelihood of invasion success (Ruiz et al. 2000). In particular, a decrease in supply should result in a decrease in invasion probability. Given existing limitations on interpreting discovery rates versus invasion rates, we take an alternate approach to evaluate BWE effectiveness by examining how it has affected propagule supply to the Great Lakes and the Chesapeake Bay.

Here, we analyzed available data to characterize past and present maritime shipping to the Great Lakes and Chesapeake Bay, and evaluate changes in propagule supply attributable to changes in shipping practices and to BWE, in order to determine if BWE has been effective as a prevention strategy. We focused specifically on characterizing what is known about (1) effects of BWE in reducing the concentration of coastal organisms in ballast tanks, (2) changes in ballast water management over time, and (3) temporal changes in invasion history, describing the number of nonindigenous species established coincident with ballast water management. This analysis is divided among multiple chapters, produced by various combinations of authors to examine these specific issues in the respective ecosystems, the Great Lakes and Chesapeake Bay.

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2 EFFICACY OF BALLAST WATER EXCHANGE

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2.1 Introduction

Ships practice two basic types of BWE to replace coastal water with mid-ocean water: Flow-Through Exchange and Empty-Refill Exchange. In Flow-Through BWE, ocean water is pumped continuously through a ballast tank to flush out (displace) the original coastal water. In Empty-Refill BWE, a ballast tank is first emptied of coastal water and then refilled with ocean water. Each method may vary in the efficacy of exchange due to amount of water pumped and to practical constraints in plumbing and tank configuration. For example, during Flow-Through BWE, the ocean water mixes with coastal water in the ballast tank, as water is simultaneously being displaced from the tank, and removal of coastal water is presumably less efficient than for Empty-Refill BWE. For this reason, multiple volume exchanges (300%) are required for Flow-Through BWE, whereas 100% volume exchange is required for Empty-Refill BWE. Also, during Empty-Refill Exchange ballast tanks cannot be completely emptied, and some residual of coastal plankton may remain.

A third method approved by the International Maritime Organization (IMO), called the Brazilian Dilution Method, is a variant of the flow-through exchange. During BWE by this method, the incoming water enters from the top of the tank as water is discharged from the bottom, through the standard ballast system. A total of three times the tank volume is still required to flow through the ballast tank during this procedure. However, this method is not widely practiced and is not considered further in this report.

BWE can reduce the concentration of viable coastal biota in ballast tanks, and the chances of subsequent invasions, in two ways. First, BWE physically removes many of the coastal organisms. This process flushes coastal organisms into the open ocean, far from shore, where they are unlikely to survive. Although oceanic organisms are brought into ballast tanks during BWE, these are considered unlikely to colonize coastal ecosystems. Second, the exchange process alters the environmental conditions within the ballast tanks, which can affect survivorship of any residual coastal organisms that remain following BWE. The change in environmental conditions may be most extreme for organisms that originate in low salinity waters, since the rapid change in salinity caused by BWE can be fatal. Such "salinity shock" (i.e., toxic effects of salinity) should serve to further reduce the concentration of viable organisms delivered by ballast tanks. However, changes in some environmental conditions, such as changes in nutrients or oxygen concentrations, could conceivably enhance survivorship.

Characterizing the BWE process is not a simple matter. While it is possible to estimate the theoretical replacement of ballast water during flushing, there can be differences in the removal rate of water versus organisms. In general, the efficacy of BWE depends upon both (a) the complexities of water movement (fluid mechanics) within ballast tanks during exchange and (b) the behavior and distribution of organisms. Ballast water mixing and replacement during exchange can be estimated by a simple two-fluid mixing model, however, the actual mixing and flow in a ballast tank is a complex function of fluid densities, flow rate, and internal tank structure and geometry, and requires application of a much more complex fluid dynamics-based model (Wilson et al. 2006). Such calculations have been applied to very few cases, and empirical validation on full-scale ballast tanks (let alone across the diverse range of ballast tank types) has not yet been performed. Clearly the most complex situation results from Flow-Through BWE in a highly structured tank, where complex mixing patterns can result in retention of initial water even after flushing several tank volumes. A model of Flow-Through BWE fluid dynamics has been developed that should improve our understanding of the water replacement process during BWE, but to date the model has only been applied to a single tank architecture under a limited range of conditions and verification with full-scale experiments has yet to be conducted (Wilson et al. 2006; D. Reid personal communication).

However, being able to predict the removal rate of original (coastal) water from a ballast tank during BWE may not provide a good proxy for the removal of resident (coastal) organisms. Organisms are not passive particles and their removal may differ greatly from that of water. Instead, planktonic (waterborne) organisms are known to exhibit many behaviors, such as vertical migration and swimming ability, which can affect their distribution and thus the probability of being removed from ballast tanks during BWE. Many of these behaviors are species-specific and depend on conditions at the time, making it difficult to translate water removal into an estimate of organism removal during BWE. Thus, theoretical model-based estimates of BWE efficacy must be viewed cautiously, as they require empirical validation (testing) to confirm the expected reduction in both the initial water and the initial organism concentrations.

Other theoretical approaches have been used to predict the effect of BWE (MacIsaac et al. 2002, Minton et al. 2005, Wonham et al. 2005), but these often have a very limited empirical basis, and make untested assumptions. In essence, theoretical treatments provide useful hypotheses about the BWE process or the effects of BWE, but these predictions have yet to be widely tested and validated. As a result, we focus our attention on direct empirical measures of BWE effects, and several recent studies have greatly expanded the scope of available empirical data on this topic.

2.2 Methods: Evaluating Effects of BWE

There are several key variables to consider in evaluating existing information on BWE efficacy, as these may greatly affect the results, such as (a) type of ship or ballast tank, especially size or shape, (b) types of organisms, (c) method of BWE (empty-refill or flow-through) as discussed above, (d) geographic location, (e) environmental conditions, such as salinity, (f) voyage duration, and (g) sampling and experimental design. For example, the effect of BWE may differ greatly between two different studies because of differences in the tank type, organism type, or exchange method (empty-refill versus flow-through). Moreover, the mortality of residual organisms may be far greater following BWE for ships originating in low salinity ports than high salinity ports, simply due to salinity stress experienced during and after exchange.

Several methodological approaches that have been used to empirically estimate the efficacy of BWE and each has very different assumptions. In general, there are four different approaches that have been used to date. Only one of these approaches (#4) controls for the high variation that can exist in initial conditions (e.g., diversity and concentration of species), survivorship over time, and voyage conditions to examine the independent effects of BWE. The four general approaches are listed below:

1. *Comparison among Ships upon Arrival*: This approach compares organism concentrations in ballast water of ships that have exchanged to those of ships that have not exchanged. These data indicate that, compared to ships that have not conducted mid-ocean BWE, ships with exchanged ballast water on average have reduced abundance of coastal plankton (e.g., Locke et al. 1993, Smith et al. 1996, Zhang and Dickman 1999, Hines and Ruiz 2000). However, with this approach, it is not possible to control for independent variables such as (a) the observed high seasonal and spatial variation in initial plankton densities, (b) effects of specific voyage conditions, or (c) the percentage of water exchanged among voyages. Thus, any estimates of BWE effects are confounded by several other factors, and interpretation is limited.

2. *Comparison within Ships upon Arrival*: This approach compares organism concentrations, on a single ship, in ballast water of tanks that have undergone exchange to those of tanks that were not exchanged, using only measurements made after exchange is complete and upon arrival to port (i.e., at the end point). Resulting data suggest a reduction has occurred (Smith et al. 1996, Ruiz and Hines 1997), but interpretation is also limited with this design. Although this method of analysis controls for voyage conditions (1b, above), initial conditions can be quite different among tanks on the same ship, depending upon the timing (e.g., day vs. night) and sequence of ballasting, and this can create potentially large differences among tanks independent of BWE.

3. *Uncontrolled, Before-After Exchange*: This approach compares organism concentrations in ballast water of a tank immediately before and after exchange of ballast water. Although these data provide a clear measure of temporal change within a single tank during the exchange process and show a reduction in organism concentrations (e.g., Rigby and Hallegraeff 1994, Levings et al. 2004), they do not adequately control for temporal changes that are known to occur in the absence of exchange (e.g., see Gollasch et al. 2000a,b, Wonham et al. 2001). Thus, this approach measures the change in organism abundance caused by a combination of exchange effects and exchange-independent effect, and lacks a control treatment to separate the relative contribution of each factor to the total effect.

4. *Controlled, Before-After Experimental Exchange*: This approach compares changes in organism concentrations in ballast water of a tank that has undergone exchange to a control tank that has not undergone exchange. Identical measures for the experimental (exchanged) and control (unexchanged) tank are used on the same ship, at the same times, and with the same source biota. To date, few studies have used this design to measure BWE efficacy (Wonham et al. 2001 and results summarized below). This approach provides the highest quality data and strength of inference about the effects of BWE, because it controls for variation due to voyage, tank configuration, time, and initial densities. As a minimum, this approach includes samples at one time point before and one time point after exchange; at its highest resolution, this approach includes a time series of measures, with some immediately before and immediately after exchange.

Despite the now widespread use of BWE, there are relatively few (<10) published studies that empirically measure its effects or efficacy in reducing the concentrations of coastal organisms in ballast tanks. Here, we review the current state of knowledge about immediate effects of BWE on propagule supply delivered by ships' ballast, focusing on empirical data collected by our research group. The ultimate effect of BWE on invasion risk and outcome is discussed in Chapters 0 and 5.

2.2.1 SERC's On-board BWE Experiments

Over the past 6 years, the Smithsonian Environmental Research Center (SERC) has conducted shipboard BWE experiments across a variety of vessel types, using a controlled, before-after experimental approach (#4 above). To date, we have conducted experiments on approximately 26 ships transiting US waters and our data constitute the largest body of empirical measurements available on the efficacy of BWE. This research has been funded by multiple agencies (U.S. Fish and Wildlife Service, Prince William Sound Regional Citizens' Advisory Council, American Petroleum Institute, the Port of Oakland, Great Lakes Protection Fund, and Office of Naval Research, Smithsonian Institution, and U.S. Coast Guard). Some of the resulting data exist in technical reports (Ruiz et al. 2005a, 2005b, 2006) and are still being analyzed and prepared for publication. We present an overview of these experiments and results in this report, and discuss other studies that have been done on this topic.

2.2.1.1 Experimental Design, Sample Collection and Analysis

The experiments used a paired design that was replicated on commercial oil tankers, containerships, bulk carriers, and naval supply vessels (oilers). On each voyage, we compared changes in organism concentrations in one or more ballast tanks that underwent experimental treatment (BWE) to a ballast tank (control tank) that did not undergo BWE. The control tank allowed us to account for changes over time in organism concentrations in the ballast water that occurred during each voyage and were independent of exchange treatment. Some voyages included both types of BWE, empty-refill and flow-through, but most included only one type of BWE (empty-refill). For voyages with only one exchange treatment, the ships were routinely unable to conduct empty-refill BWE due to safety concerns.

Ships were asked to nominate paired ballast tanks that would be available for the experiments on each voyage, and treatments were assigned randomly among these tanks. Tanks were selected to be similar in size and shape, including paired port and starboard wing tanks. Ships filled their ballast tanks at the departure port. During the filling process, rhodamine water-tracing dye (an inert and non-toxic dye) was added to each tank and allowed to mix, to achieve a concentration of 100 μg per liter.

Ships were asked to perform BWE during a regular, working voyage. All exchange occurred at least 100 nautical miles from land for commercial vessels and >12 miles from shore for U.S. Navy vessels. Experimental treatment tanks underwent either empty-refill or flow-through BWE. For empty-refill BWE, ships emptied tanks of coastal water and reballasted with oceanic water, constituting approximately 100% volumetric exchange. For flow-through BWE, ships pumped water into the tanks, in an estimated amount equivalent to 300% of the tank volume. The respective volumes for empty-refill and flow-through methods correspond to those required by U.S. Coast Guard and recommended by the International Maritime Organization for ships arriving from overseas.

We measured the effect of 100% empty-fill exchange and 100-300% flow-through exchange by sampling all tanks (including the control tank) before and after exchange. Specifically, we measured changes in concentration of the original water mass and plankton in the water column.

Rhodamine dye was used to measure removal of the original (coastal) water mass during BWE. For each time point, we collected replicate samples from multiple locations within the tanks, including at least two depths (surface, 10m or bottom). Samples were stored in amber glass jars for analysis. We measured rhodamine dye concentration using a fluorometer (Turner Designs, Model 10AU) with appropriate excitation and emission filters, and employing standard methods. Concentrations were estimated to the nearest 0.2 µl. We estimated efficacy of BWE in removing the initial coastal water, comparing rhodamine concentrations between treatments within each voyage. For each voyage, efficacy was estimated as the % difference in rhodamine concentration between BWE and control tanks: [(Control Tank) – (Exchange Tank) / (Control Tank)] X 100. All samples for each time point and tank were used to estimate the average concentration.

We also measured the effect of exchange on concentrations of coastal zooplankton. For each time point, we collected replicate samples from the same access points as above, using either a net tow or pumped sample that was concentrated by an 80µ mesh plankton net. Each replicate zooplankton sample was preserved in 5-10% buffered formalin for subsequent analysis. We estimated concentrations of coastal zooplankton taxa by direct counts under a dissecting microscope. More specifically, we focused our analysis on "target" species or taxonomic groups, which met several criteria. First, we selected organisms that were known to be coastal in origin and that are considered unlikely to occur offshore (i.e., > 100 nautical miles). This was done to avoid any compensatory changes that could result from the influx of target organisms with oceanic water during BWE. Second, we further selected among this group only taxa that were relatively abundant (mean concentration > 25/m3) at the start of the voyage; this approach avoids the difficulty, or lack of sensitivity, in measuring changes over time for low concentrations.

First, we estimated percent change in concentration of target zooplankton taxa over time for each tank. It is important to note that plankton concentrations often decline significantly through time, even for control tanks independent of BWE (Lavoie et al. 1999, Gollasch et al. 2000a, Wonham et al. 2001, Verling et al. 2005; but see also Gollasch et al. 2000b). Second, we estimated the efficacy of BWE in reducing concentrations of target zooplankton taxa, comparing changes in BWE tanks to those in control tanks over the same time periods (see Figure 2-1). This approach controls for temporal changes in abundance in the control tank, providing a measure of BWE effects alone.

Thus, for each taxon and voyage, we estimated efficacy separately for 100% empty-refill and 300% flow-through BWE as:

% Efficacy = (X-C)/(C+1), where

(i) X is the percent change in the BWE tank expressed as ((x0-x1)/x0) X 100, and

(ii) C is the percent change in the Control tank expressed as ((c0-c1)/c0) X 100.

(iii) x0 is the organism concentration in the exchanged tank at time T0, x1 is the organism concentration in the exchanged tank at time T1

(iv) c0 is the organism concentration in the control tank at time T0, c1 is the organism concentration in the control tank at time T1

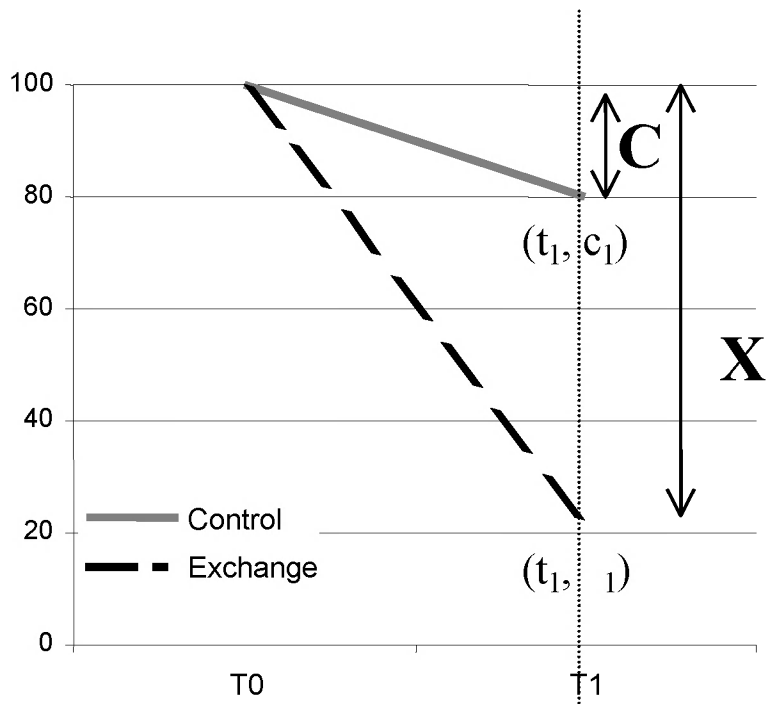

Figure 2-1: Calculation of BWE for Target Zooplankton. Efficacy is estimated as a function of change in concentration over time (T0 to T1) in exchanged tank (X) relative to those observed in the control tank (C). See text for further detail.

2.3 Effect of Salinity Shock associated with BWE on Survivorship

The methods described in the previous sections examine the efficacy of BWE across many different ship types and environmental conditions, not distinguishing the effect of removal from any possible mortality due to environmental changes. Moreover, many of our experimental BWE measures (Section 2.2.1.1) were taken immediately following BWE, so they examine primarily the effect of removal. In cases where there are large changes in salinity, we would expect to see additional mortality to occur due to "salinity shock", in response to the post BWE tank conditions.

Our laboratory has recently undertaken salinity tolerance experiments (funded by the Great Lakes Protection Fund) to begin measuring the direct effect of salinity changes for organisms originating in low salinity ports and exposed to high salinity conditions as experienced during mid-ocean BWE. Specifically, we designed experiments to approximate the rate of change in salinity that is experienced during BWE by both flow-through and empty-refill methods. We compare the survivorship of organisms in control conditions (i.e., no salinity change) to those that are exposed to conditions simulating either rapid (empty-refill, E-R) or more gradual (flow-through, F-T) BWE. For each species examined, replicates (10 ind/replicate with 4 replicates for each treatment (Control, F-T and E-R) are maintained in individual vessels (culture dish or beaker) at constant temperature, using the temperature at which organisms were collected. Survivorship is measured over 48 hours and compared among three different treatments:

- To simulate empty-refill BWE, salinity is raised directly from ambient concentrations to 34 in a single step.

- To simulate flow-through BWE, we elevate salinity concentrations systematically over time (e.g., 10/hour).
- As a control, we maintain organisms in the original source salinity.

We are conducting the experiments on organisms across multiple taxonomic groups and geographic locations. We include organisms commonly found in ballast tanks, such as copepods, mysids, amphipods, rotifers, and cladocerans. The experiments are being conducted on organisms collected from low salinity ports of the Baltic Sea, the primary source of recent invasions to the Great Lakes (Ricciardi 2001). Additional experiments are being conducted at San Francisco Bay, Chesapeake Bay, the Great Lakes, and several other geographic locations. Here, we report on our initial findings from the Baltic Sea experiments.

2.4 Results & Discussion

2.4.1 Removal of Coastal Water

BWE was highly effective in removing the original water from ballast tanks. Figure 2-2 summarizes the efficacy of 100% empty-refill BWE on four different vessel types examined by the SERC shipboard experiments. For the three commercial ship types (tankers, containers, and bulkers), the mean efficacy for empty-refill BWE ranged from 97-99%, indicating that nearly all of the original water was removed from the ballast tank upon exchange. The mean efficacy for containerships was lower (88%), with a much greater standard error (shown by bars in Figure 2-2) among ships of this type compared to the other types. We hypothesize that this difference in containerships results from the small ballast tank volume and the internal tank design (shallow and compartmentalized), allowing relatively high retention of the original water.

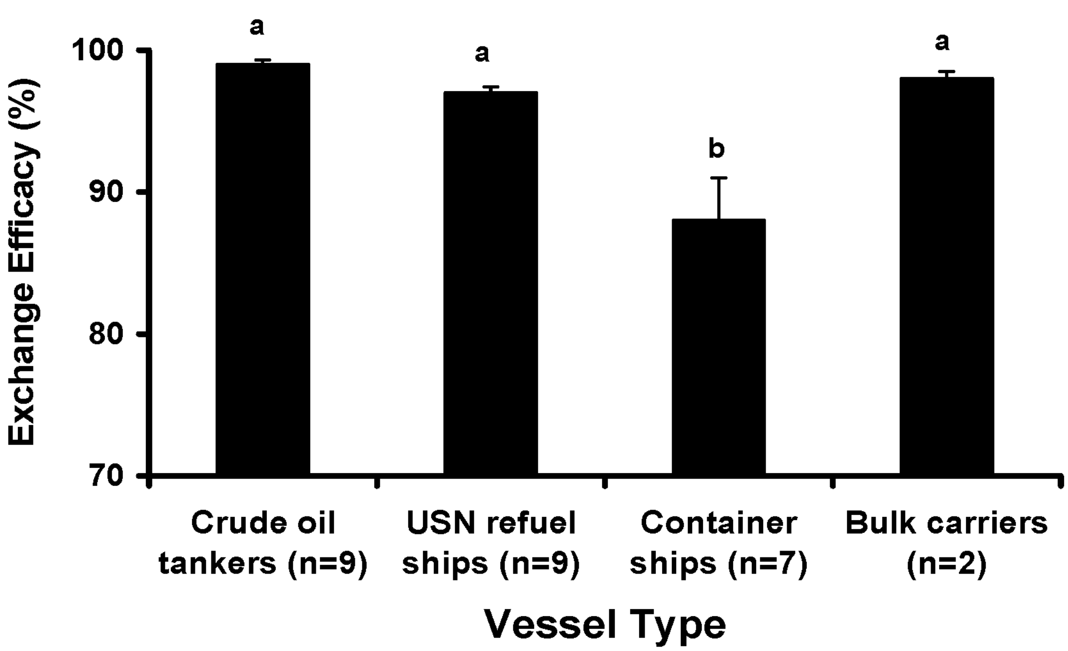

Figure 2-2: BWE Efficacy for Removal of Rhodamine Dye by the Empty-Refill Method. The mean efficacy (+se) is shown for each ship type and sample size, shown on the x-axis.

In experiments from oil tankers, where both exchange methods were used on 6 of the 8 voyages, it appears that 300% flow-through BWE was equally effective as 100% empty-refill BWE in removing the initial water from ballast tanks (Ruiz et al. 2005a). . At 100% flow-through BWE, there was still a significant amount of the initial water in ballast tanks, differing statistically from 100% empty-refill BWE. However, once ships had conducted 300% flow-through BWE, as required by current regulations, the efficacy converged on that for 100% empty-refill and there was no statistical difference.

Taken together, these data show that both methods of BWE, when performed properly, remove 88-99% of the initial water from the ballast tanks. This measure controls for changes in a paired control tank, where dye concentrations were relatively stable over time. We expect this removal rate to approximate that for planktonic organisms (i.e., those in the water column) that are neither strong swimmers nor distributed unevenly through the tank. The next section reviews the results for such plankton.

2.4.2 Removal of Planktonic Organisms

Table 2-1 (page 43) provides summary statistics (mean, median, mode, range, and standard error) of the BWE efficacies for biota as measured by SERC for each ship type. These are reported for 100% empty-refill BWE, for which data were available on all vessel types. Summary statistics are shown separately for zooplankton (> 80μ in size, measured on all ship types), and phytoplankton (diatoms and dinoflagellates, measured on only two ship types). In each case, the mean is estimated for all individual taxa within ship type, and the number of taxa and voyages are shown.

BWE greatly reduced the concentrations of coastal organisms in ballast tanks, relative to control tanks. As observed for removal of the original water from ballast tanks by BWE (above), containerships had the lowest efficacy for removal of zooplankton species (mean = 80%, median = 84%). In contrast, the mean and median BWE efficacy for removal of zooplankton on the other vessel types was ≥ 90%. Although available for only two of the vessel types, a similar pattern is observed for coastal phytoplankton, where BWE efficacy was lower for container ships (mean=75%, median = 86%) compared to oilers (mean = 93%, median = 95%).

To date, our analysis of the efficacy for flow-through BWE has been restricted to zooplankton on crude oil tankers (Ruiz et al. 2005a). Although our data indicate a significant reduction of zooplankton also occurs with 300% flow-through BWE, there is more variation among coastal organisms and it is not as effective compared to 100% empty-refill BWE on the same vessels, representing a significant difference between methods.

Overall, our data show a very strong effect of BWE on coastal plankton, reducing concentrations on average 80-95% across ship types and many taxonomic groups. The lowest values were observed for empty-refill BWE on containerships, resulting perhaps from the shape and small size of tanks compared to other ships. For containerships, the standard deviation was much greater than observed for other vessel types, indicating the response (efficacy) among species was most variable for this ship type. The range for BWE efficacy was large for all ship types, indicating that a low reduction (efficacy) occurred for a few species across the ship types, affecting the mean values of BWE efficacy. Nonetheless, the median values indicate that BWE efficacy for 50% of the species was above 97% for these other ship types, and the standard deviations suggest relatively tight clustering around this value (Table 2-1, page 43). Even containerships exhibited a significant reduction of zooplankton from BWE, with a median value of 84% BWE efficacy.

Several other features are noteworthy from the SERC experiments on BWE efficacy:

- There is often a significant decline in plankton concentrations over time in the control tanks, independent of BWE treatment. This has been highlighted in previous publication (Lavoie et al. 1999, Wonham et al. 2001, Verling et al. 2005; but see also Gollasch et al. 2000b). Thus, if changes in the BWE tank were examined alone, it would not be possible to distinguish the effect of time from that of BWE.

- Tremendous variation existed in initial plankton densities among voyages, and sometimes among ballast tanks on the same ship, such that it is also important to know initial starting conditions to measure the effect of BWE. Comparison of a control tank on one ship to an exchanged tank on another ship can produce a highly misleading result, as there are cases where exchanged ballast water has higher densities (even of coastal organisms) than unexchanged water, resulting from differences in the initial densities, survivorship, or the combination.

- The BWE efficacy for the US Navy ships is a minimum estimate, as these ships conducted exchange relatively close to shore (compared to the other vessels), where coastal organisms could be entrained in the incoming replacement water during the exchange process. This would serve to underestimate the efficacy of the BWE process, simply because the addition of coastal organisms during exchange would augment residual organisms in the ballast tank, although our measures suggest the BWE was still highly effective for these ships. In contrast, other research in the English Channel suggests the efficacy of BWE that occurs close to shore can sometimes be much more limited, due to high densities of coastal organisms in some areas (T. McCollin pers. comm.).

2.4.3 Effect of Salinity Shock associated with BWE on Survivorship

Our data indicate that some organisms from low salinity coastal water experience a rapid and high level of mortality when exposed to seawater, as would occur during BWE. To date, we have completed experiments for 14 species collected from the Baltic Sea (Curonian Lagoon, Klaipeda, and Lithuania), and exposed to high salinity. All species of cladocerans (5 species) and copepods (5 species) were completely killed by both flow-through and empty-refill treatments within 48 hours of experimental exposure to higher salinity (Figure 2-3). Survival of these species in controls (not exposed to high salinity but otherwise maintained under identical conditions) was either near or at 100%. A Kruskal-Wallis test with ranked (within species) percentages yielded significant differences between controls and salinity treatments among all cladoceran and copepod species ($P<0.01$). Since no animals survived at 48 hours after initiation of the experimental treatments, there were no differences between flow-through and empty-refill methods.

In contrast to the results for cladocerans and copepods, two mysid species survived both experimental treatments at proportions greater than 50%, whereas the mysid *Paramysis lacustris* was completely eliminated within flow-through and empty-refill conditions. A Kruskal-Wallis test with ranked (within species) percentages yielded significant differences between the controls and experimental treatments among all three species of mysid. Barnacle (*Balanus improvisus*) nauplii were unaffected by the flow-through treatment but did experience significant mortality (>40%) in the empty-refill treatment (Figure 2-3). For the remaining species tested, all showed a significant increase in mortality with salinity treatments.

These experiments suggest that salinity stress experienced after BWE should enhance the efficacy of exchange, when starting with low salinity waters. It is clear that some organisms are greatly compromised by such shifts in salinity, and others have suggested or shown that salinity can represent a significant barrier (Locke 1993, Smith et al. 1999, Hines and Ruiz 2000). This is no surprise, simply because many organisms have limited salinity distributions in the wild, and relatively few species occur from freshwater to full seawater salinities. However, there are few data available to assess the effect of short-term salinity exposure on survivorship or subsequent performance, especially for holoplankton and larval invertebrates commonly found in ballast tanks.

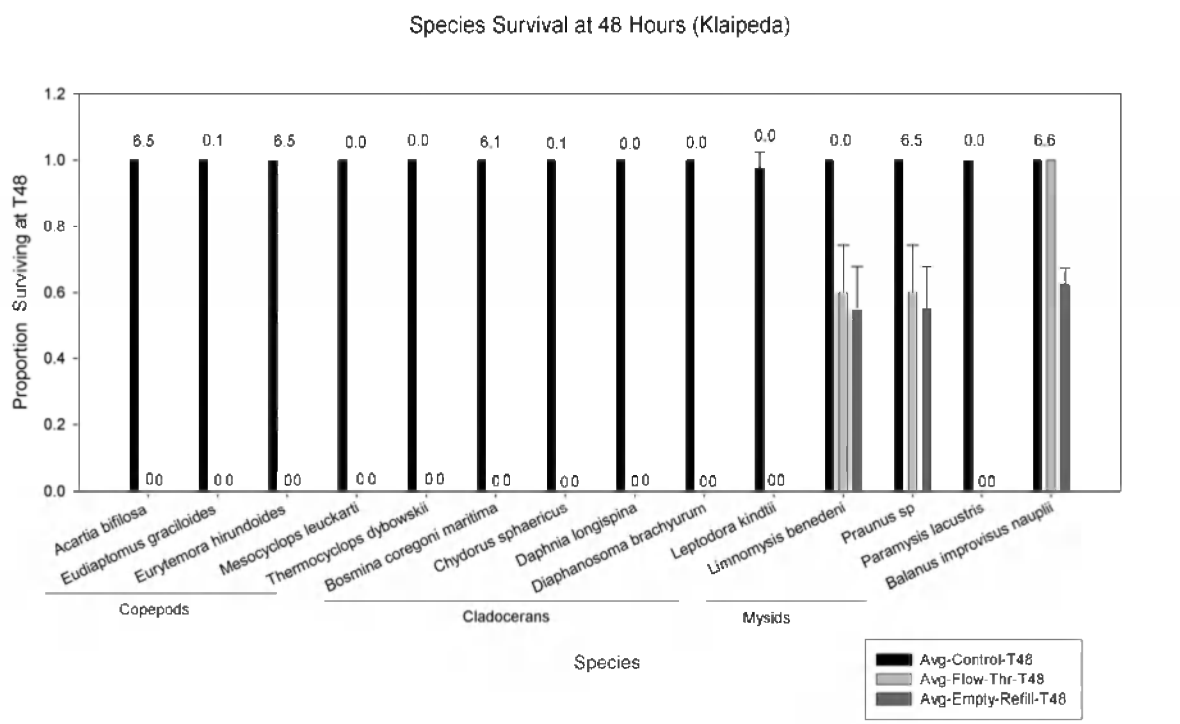

Figure 2-3: Survivorship of Plankton Exposed to High Salinity. Shown is the survivorship for organisms exposed to high salinity treatments that simulate two types of BWE (empty-refill and flow-through) compared to control treatments without salinity changes. Organisms were collected from low-salinity waters in the Baltic Sea (initial salinity shown above bars). Each bar represents the mean survival at 48 hours. Error bars represent one standard deviation of the mean. Standard error not used due to number of replicates = 4 for each treatment.

To fully evaluate the effect of salinity stress requires further experiments, testing the performance of different taxonomic groups, from different regions, and under different starting conditions. There is good reason to believe substantial variation exists in response to salinity stress among species and that it may even vary within species, due to genetic differences, physiological condition, life stage, and local starting conditions (acclimation). Considerable literature exists on variation in response to environmental change associated with each of these factors, operating alone or in concert. Thus, while it's clear that changes in salinity associated with BWE can enhance efficacy, the frequency with which this happens and under what conditions currently remains unresolved.

2.5 Conclusions

It is clear the BWE is highly effective at removing coastal water and coastal planktonic organisms from ballast tanks, when conducted according to current requirements. Our data show that 100% empty-refill BWE removed ≥97% of the original water mass for three vessel types, reducing the concentrations of coastal species on average ≥ 90% for these same vessel types, relative to unexchanged control tanks on the same voyages. The corresponding efficacies were lower for containerships (87% of the water and average reductions of 80% and 75% for zooplankton and phytoplankton, respectively), and this difference may result from the size/shape of tanks on containerships, having a lower total volumes and perhaps a proportionally greater residual water after deballasting compared to other vessel types (Dickman & Zhang 1999, Ruiz et al. 2005b).

For commercial oil tankers, we found no difference between 100% empty-refill and 300% flow-through BWE in removing coastal water from ballast tanks, as both methods removed 99% of added dye tracer (Ruiz et al. 2005a). The latter had a lower efficacy in removing coastal zooplankton, as the results were more variable than observed for empty-refill exchange, however both methods had efficacies > 90% on average for coastal zooplankton. We did not conduct evaluation of flow-through BWE for other vessel types or for phytoplankton.

These results for removal of coastal water are consistent with the few other studies to date. Rigby and Hallegraeff (1994) measured changes in dye concentration for flow-through BWE on a bulk carrier, reporting that 300% volume exchange removed approximately 95% of the water (see also AQIS 1993 for further description). Wonham et al. (2001) found that 100% volume exchange empty-refill BWE removed 96-100% of the original coastal water aboard a bulk carrier, based upon changes in salinity. Both of these studies sampled before and after BWE. In addition, Ruiz and Hines (1997) found similar salinity differences, comparing exchanged and unexchanged ballast tanks aboard individual oil tankers.

Reports on the effect of BWE on biota appear much more variable, but a great deal of this variation corresponds to differences in taxonomic group and method of estimation. Wonham et al. (2001) report a decline in concentration of coastal zooplankton from 80-100%, comparing densities before and after empty-refill BWE (collected within a day of each other) for three different tanks on the same voyage. Levings et al. (2004) also found large changes in the concentrations of selected coastal zooplankton taxa before and after exchange, showing > 90% reduction of mean abundance (across five different voyages of a cargo vessel). However, they compared sample from the same tank before and after exchange, noting that it is not possible to estimate efficacy of BWE due to the long time period (9-18 days) between samples that do not control for mortality over time, independent of the exchange treatment (i.e., there was no control tank; see Section 2.2 for discussion).

For phytoplankton, Zhang and Dickman (1999) reported "harmful species of diatoms and dinoflagellates" were reduced 87% by BWE, when comparing ships that arrived following BWE to those from the same source that did not exchange. These samples were taken across all seasons of a year on ships arriving to Hong Kong from California, exhibiting a high degree of variation in species abundance. Dickman and Zhang (1999) made a similar comparison for ships that conducted BWE versus those that did not, traveling from Manzanillo Mexico to Hong Kong, and reported BWE was "48% effective in reducing diatom and dinoflagellate abundance". However, a comparable approach to the first study would have examined harmful species, which were reduced 61%.

In contrast, Rigby and Hallegraeff (1994) reported a much higher efficacy of BWE for phytoplankton, and their results were similar to the estimates from the SERC experiments. This difference may result from the methods used to estimate efficacy. Interpretation of results from former studies (Dickman and Zhang 1999, Zhang and Dickman 1999) is confounded by several variables, where many factors differed among ships in addition to BWE, leading to potentially erroneous conclusions about BWE efficacy. The SERC experiments and those or Rigby and Hallegraeff (1994) control for more of these factors, comparing the same tanks over time (both studies) and also using control tanks (SERC studies).

The effect of BWE is less clear for waterborne bacteria, viruses, and protists (other than dinoflagellates). Drake et al. (2002) found no significant reduction in total bacteria or viruses following BWE on a bulk carrier. Their study compared changes (before-after BWE) in exchanged tanks and control tanks on the same voyage, providing a high level of control. However, these were bulk measures of total microbial assemblages, instead of tracking changes in individual species composition (as noted by Drake et al. 2002). Thus, compensatory shifts in species composition (between coastal and oceanic forms) would have gone undetected. Although useful in describing bulk microbial characteristics, this and other studies of microorganisms have not yet adequately evaluated effects of BWE, and any conclusion for these groups are premature at this time.

While all available data demonstrate a strong effect of BWE on reducing abundance of coastal organisms, it is also evident that residual coastal organisms remain in ballast tanks following exchange. This is the inevitable conclusion with efficacies < 100%, and several studies have found coastal organisms in ships that had reportedly undertaken BWE (e.g., Rigby and Hallegraeff 1994, Dick & Zhang 1999, Levings et al. 2004, Choi et al. 2005). Although there is no way presently to verify the extent to which BWE occurred, and whether exchange approached the 100% empty-refill or 300% flow-through as required, there can be no doubt that some organisms are delivered to U.S. ports upon discharge of exchanged ballast water. The extent to which residual coastal zooplankton and phytoplankton constitutes a significant risk is not well understood (see discussions by Ruiz and Carlton 2003, Levings et al. 2004).

Even less understood is the significance of residual organisms in bottom sediments and on the inner surfaces of ballast tanks (Johengen et al. 2005, Drake et al. 2005). These organisms are perhaps least likely to be affected by BWE, as they are not suspended in the water column and not as prone to being flushed out with ballast water during exchange (see Rigby and Hallegraeff 1994). <u>There should be no confusion that BWE significantly reduces total propagule supply of coastal organisms</u>, especially for waterborne life stages, but bottom and hard surfaces still harbor organisms (especially microorganisms and cysts) that may pose some risk. The extent to which these latter organisms are released and the likelihood of their establishment remains an active area of research.

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Table 2-1: Efficacy of BWE Measured in Controlled, Shipboard Experiments. Shown are the summary statistics (mean, median, mode, standard deviation, range, and sample size (n)) for BWE efficacy of coastal zooplankton or phytoplankton associated with each vessel type, using 100% empty-refill BWE. The number of coastal taxa (n) by organism type, and the number of voyages per ship type (n) is also provided.

		BWE efficacy Zooplankton %	BWE efficacy Phytoplankton %
Container Ship (n=8)	mean	80.1	74.8
	median	84.0	86.0
	mode	98.0	95.0
	sd	21.4	26.5
	range	16-100	2-100
	n	41	23
USN Oiler (n=9)	mean	92.1	92.8
	median	97.0	95.5
	mode	97.0	100.0
	sd	13.3	8.6
	range	37-100	69-100
	n	46	48
Crude Oil Tanker (n=9)	mean	90.2	not measured
	median	97.9	
	mode	100.0	
	sd	17.2	
	range	20-100	
	n	68	
Bulk Carrier (n=1)	mean	94.9	not measured
	median	97.5	
	mode	100.0	
	sd	6.0	
	range	84-100	
	n	10	

3 GREAT LAKES: RECENT HISTORY OF SALTWATER VESSEL TRAFFIC, DELIVERY OF BALLAST WATER, AND THE EFFECT OF BALLAST WATER EXCHANGE ON AQUATIC SPECIES INVASIONS

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3.1 Introduction

The documented invasion history of the Great Lakes spans two centuries and implicates a broad array of vectors, including transoceanic shipping. Ships are believed responsible for aquatic nonindigenous species (ANS) introductions as early as the 1860s, via disposal of solid ballast. Ballast water first shows up as a likely vector in 1938, but became significantly more important after the opening of the St. Lawrence Seaway in 1959 (Mills et al. 1993, Ricciardi 2001, 2006). Ships and the discharge of ballast water are considered the most likely vector for many of the aquatic species invasions to the Great Lakes basin in modern times (Mills et al. 1993, Ricciardi 2001, 2006, Holeck et al. 2004). The establishment of the zebra mussel in the late 1980s brought considerable attention and regulatory action targeting this vector in the United States, resulting in the establishment of mandatory ballast water management regulations in 1993 for all ships entering the Great Lakes and upper Hudson River with pumpable ballast water – see Chapter 1. Ballast water exchange was and presently remains the only approved treatment option if water is to be discharged. Mandatory ballast management regulations were extended nationally to all ports in the United States in 2004.

Recent bioinvasion theory suggests that propagule pressure (organism supply) is a significant determinant of new species invasion success, and in its simplest form, propagule pressure should be proportional to the magnitude, frequency, and duration of biological inoculations events (Ruiz et al. 2000, Verling et al. 2005). Based on this, the risk associated with ballast water discharges should be proportional to the volume, organism content, and frequency of ballast water delivery to a specific ecosystem. Therefore, one way to gauge the effectiveness of BWE is to assess its effect on the delivery of live organisms (propagules) to the ecosystem.

Chapter 2 summarized our scientific knowledge to date concerning the effects of BWE on organism content of ballast water. However, in order to assess changes in risk to the Great Lakes associated with BWE we have to be able to assess all the factors that may have affected the volume and nature of Great Lakes ballast water discharges. In addition, sediments have been identified as a repository for viable organisms and life stages (Johengen et al. 2005), so we must also be able to evaluate the contribution of ballast tank sediments to risk, and the effects of BWE on sediment organisms. Changes in trade (ballast water source regions), regulations, and shipboard management practices can affect typical ballast conditions (amount of water carried, amount of sediment accumulated, number of viable propagules) in ships, and changes in the economics of ship operations can affect ship management practices.

In this Chapter we review what is known about vessel traffic patterns and ballast characteristics based on data from various sources for saltwater vessels entering the Great Lakes during equal periods of time before (1978-1988, "pre-BWE") and after (1994-2004, "post-BWE") BWE regulation. We identify and speculate on the characteristics and potential changes in the volume of ballast (water and sediment) carried into the Great Lakes system as a result of changes in economic climate and global competition that affected the shipping trade, as well as implementation of BWE, and how resultant changes may have affected propagule pressure and thus, invasion risk. We also review the nonindigenous species invasion record for the Great Lakes relative to BWE regulation. Our analyses exclude the transition period between 1989, when voluntary BWE guidelines were issued by Canada, and 1993, when mandatory requirements for BWE were implemented by the United States.

3.2 <u>Recent History and Characteristics of Saltwater Vessel Traffic to the Great Lakes</u>

3.2.1 Vessel Categories

There are two main categories that define the ballast status of incoming saltwater vessels ("salties") entering the Great Lakes: vessels with pumpable "ballast on board" (BOB), and vessels with "no ballast on board" (NOBOB). NOBOB ships are fully loaded with cargo and require no ballast water. While NOBOB vessels are considered to be "empty" of pumpable ballast, some residual unpumpable ballast water and accumulated sediment remain in the tanks of almost all ships even after they completely deballast. The ballast intake/pumpout port (called a "bellmouth") in a typical ballast tank must be positioned some distance – at least several centimeters – above the bottom deck plating of the ballast tank (Figure 3-1) and thus, ballast water and sediment below the bottom edge of the bellmouth cannot be completely pumped out.

By the early 1990s, considerable attention was focused on ballast water as a vector for aquatic species invasions. As a result, the U.S. Coast Guard started compiling records specific to the actual ballast status (BOB and NOBOB) of saltwater vessels entering the Great Lakes to check compliance with ballast management guidelines, as mandated by the Nonindigenous Aquatic Nuisance Prevention and Control Act of 1990. An early scientific study by Bio-Environmental Services, Ltd (1981) provided a detailed biological characterization of ballast water in 55 ships bound for the Great Lakes in 1980, and additional scientific studies were initiated during the early 1990s (Locke et al. 1993).

The St. Lawrence Seaway authorities (St. Lawrence Seaway Development Corporation (SLSDC, United States), St. Lawrence Seaway Management Corporation (Canada)) have maintained detailed records of ship entries and their cargo since the Seaway opened, since such information is needed for collection of Seaway fees. The Seaway categorizes ships entering the Seaway as either "in cargo" or "in ballast." Their designation "in ballast" is used for ships carrying no cargo, which, for this report, are assumed to be loaded to capacity with ballast water (however, this will not be strictly true, because draft restrictions for transiting the Seaway often require ships to load to less than their full capacity). The Seaway records also list total number of entries for each year, and total annual cargo weight carried by upbound ships. It should be noted that total entries do not equal the number of unique ships entering the system, because some ships are in regular Great Lakes trade throughout the season and enter multiple times.

Figure 3-1: The bottom edge of the intake/pump-out port (bellmouth) in ballast tanks must be positioned far enough off the bottom deck plate to achieve the high flow rates required to fill and empty the tank (Photo courtesy of the Great Lakes NOBOB Assessment Project).

We have reliable records from the SLSDC for both the pre- and post-BWE periods that document the number and size (gross tonnage) of vessels that entered the Seaway and the amount (weight) of cargo carried by ships "in cargo". We have parallel records for the post-BWE period from the U.S. Coast Guard in which each entry was classified as either BOB (ballast-on-board) or NOBOB (no-ballast-on-board), and in the case of BOBs, some additional information about the amount of ballast water and its origin.

Grigorovich et al. (2003) and Colautti et al. (2004) presented retrospectives of saltwater vessel traffic into the Great Lakes covering the entire time period since the opening of the St. Lawrence Seaway in 1959 through the year 2000. Their data were based on records compiled from various government agencies and private individuals. They did not have any direct ballast status data and therefore deduced the likely ballast status of each ship based on its record of operation in the Great Lakes. It must be noted that both the Grigorovich et al. (2003) and Colautti et al. (2004) analyses were based on the same data set. Their results are in close, but not exact agreement with the results we obtained using only the SLSDC data. Where the disagreement was significant (e.g., number of BOB vs. NOBOB entries) we use the SLSDC records, which we believe are more verifiable and accurate since ship entries are the economic basis for the Seaway's income.

We discovered that the U.S. Coast Guard and SLSDC data do not completely agree because of differences in the way each classifies the ballast status of vessels. The Coast Guard classifies a ship as a BOB if it is carrying any pumpable ballast water, even if only in one tank and even if taken after entering the mouth of the Seaway to adjust trim or compensate for cargo removed at a port within the Seaway. The SLSDC, on the other hand, identifies a ship as 'in ballast' only if it entered the Seaway carrying no cargo. In addition, the SLSDC records include coastwise ships that enter the Seaway but not the Great Lakes, and these cannot be separated from the total. Thus the SLSDC data generally recorded a greater number of total entries, and a greater number of NOBOB entries compared to the U.S. Coast Guard. The Coast Guard records include more specific data on ballast than do the cargo-based Seaway records, but similar Coast Guard data are not available for the pre-BWE period, since U.S. ballast management regulations did not start until 1993.

Analysis of Coast Guard ballast records since 1993 revealed that ~15% of the vessels listed by SLSDC as 'in cargo' also carry relatively small volumes of pumpable ballast in one or more ballast tanks, to maintain vessel trim. These vessels are considered to be 'in ballast' by the Coast Guard and thus required to treat their pumpable ballast according to regulations, although most of their ballast tanks contain only residual ballast material. Such ships are typically classified as NOBOB in analyses based on cargo records (Grigorovich et al. 2003, Colautti et al. 2004, SLSDC records). Due to these different ballast status classification criteria, the percentage of NOBOB vessels reported by the U.S. Coast Guard for the post-BWE period (~75%) is significantly lower than the NOBOB percentage estimated by either Colautti et al. (2004) or from the SLSDC data (both >90%). For our analyses we reassigned 15% of the total SLSDC-designated NOBOB vessels for each year of each period (pre- and post-BWE) to a new category designated "BOB-A", representing ships that entered the lakes with partial ballast. After 1993, BOB-A ships would have been subject to BWE requirements if they came from outside the U.S. EEZ. However, an unknown number of these ships may have been involved in coastwise trade and in that case, would not have been subject to BWE requirements.

Thus, the following reconstruction of saltwater vessel traffic and ballast characteristics and quantities entering the Great Lakes is based on only partial and indirect data and therefore, is speculative and subject to various assumptions.

3.2.2 Characteristics of Saltwater Vessel Traffic In the Great Lakes

3.2.2.1 Total Vessel Entries

When the records from all three data sets (Grigorovich et al. 2003, Colautti et al. 2004, SLSDC 1978-2004) are overlapped, they show that annual vessel entries (transits) to the Great Lakes basin since the Seaway opened increased to a high of >1400 in the late 1960s, then generally decreased to a low of ~400 in the early 1990s, after which the number rose slightly and has since varied within a range of 450-670 per year. As noted above, the first species introductions attributed to ballast water were recorded in 1938 (three diatom species). Prior to opening the Seaway, saltwater vessel traffic into the Great Lakes was considerably less, but was not zero, because a system of canals allowed limited passage up the St. Lawrence River to Lake Ontario, and the Welland Canal connected Lake Ontario to the rest of the Great Lakes (P. Jenkins, pers. comm.).

Based on the SLSDC records, the average number of annual entries for the pre-BWE period (1978-1988) was 831 ± 193 (s.d.), while the average number of annual entries for the post-BWE period (1994-2004) was 572 ± 75 (s.d.). Significantly ($p=0.001$, t-test for two samples with unequal variance) fewer ships entered the Great Lakes system during the post-BWE period than entered in the equivalent pre-BWE period. Total entries since 2004 continued to be in the range reported for the post-BWE period.

3.2.2.2 Vessel Ballast Status

The nature of the ballast condition of ships entering the Great Lakes changed significantly ($p=0.0001$, t-test for two samples with unequal variance) between the two periods. Figure 3-2 shows the distribution of annual vessel entries by ballast category from 1978 through 2004. The percentage of salties entering as NOBOBs (after redesignation of 15% as BOB-A) during the pre-BWE period (1978-1988) averaged 55 ± 13 % (s.d.), while post-BWE it averaged 77 ± 4 % (s.d.). Similarly, 35 ± 16 % (s.d.) of the vessels that entered during the pre-BWE period were BOBs vs. 9 ± 5 % (s.d.) that entered as BOBs during the post-BWE period. The remainder entered with partial ballast (BOB-A), and averaged 10 ± 2 % during the pre-BWE period and 14 ± 1 % during the post-BWE period. It should be noted that the BOB-A ships, <u>if examined at the tank level</u>, contain a combination of tanks in BOB and NOBOB condition.

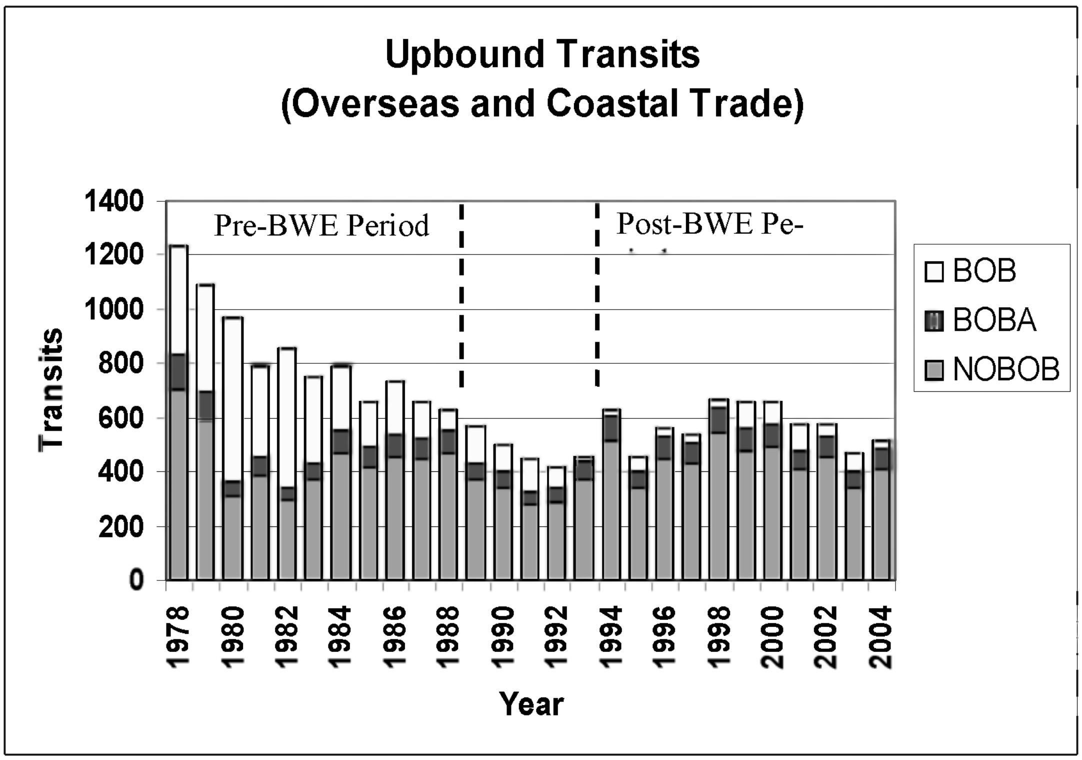

Figure 3-2: Estimated ballast condition of vessels entering the Great Lakes from 1978 through 2004. Post-BWE (1994-2004) ballasted traffic was significantly less than pre-BWE (1978-1988) ballasted traffic (SLSDC).

Although the percentage of both BOBs and NOBOBs changed substantially across periods, examination of Figure 3-2 shows that the most dramatic change (decrease) was in the number of ships entering as BOB, and in fact, the actual number estimated to have entered as NOBOBs averaged 446 ± 165 over the pre-BWE period and 441 ± 65 over the post BWE period, not significantly different. It should also be noted that the proportion of vessels in NOBOB condition is not nearly as great for most other North American ports or coastal ecosystems (Smithsonian Environmental Research Center-National Ballast Water Information Clearinghouse, Personal

Communication), which makes the ballast vector to the Great Lakes significantly different from the rest of the country.

3.2.3 Compliance with Ballast Water Exchange Regulations

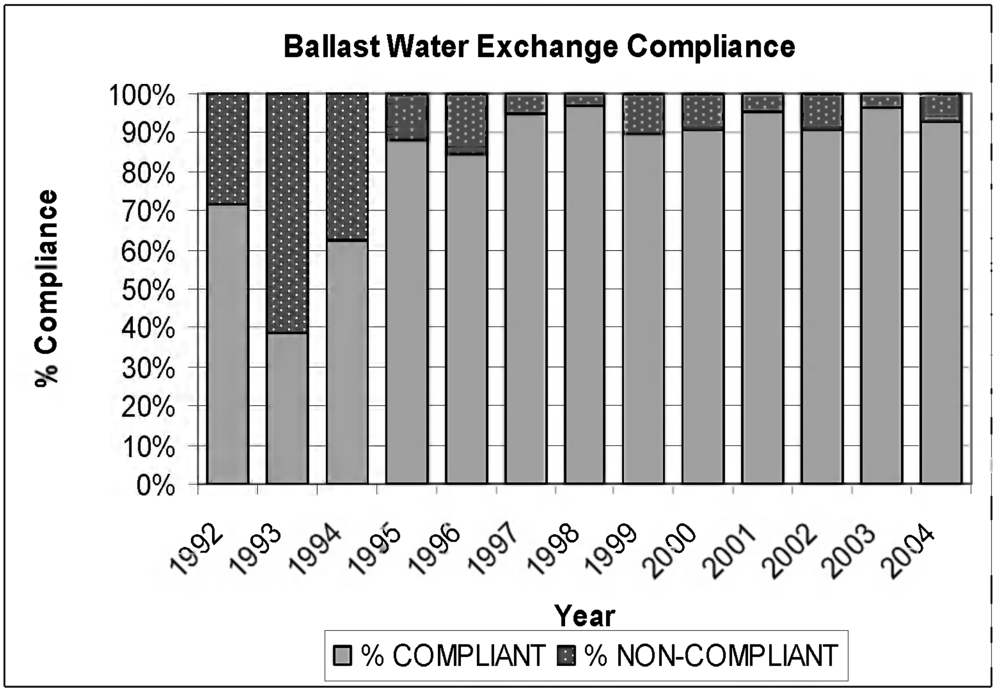

Figure 3-3: Reported rates of compliance with BWE regulations by ships carrying pumpable ballast water. Data provided by U.S. Coast Guard Detachment, Massena, NY.

Since 1993 all ships entering the Great Lakes with pumpable ballast water from beyond the U.S. EEZ have been required to use BWE to replace foreign coastal water with mid-ocean water. Since 1994, most, if not all vessels with reportable ballast have been inspected. Inspections consist of checking the salinity of ballast water in the tanks using standard methods. Not every tank was inspected, but a minimum of two randomly chosen tanks and not less than 10% of the tanks on each vessel were checked for salinity compliance. Salinity greater than 30 was considered compliant, if logs also showed that the water was exchanged. The U.S. Coast Guard reported high rates of compliance (Figure 3-3) during most of the post-BWE period, averaging 89 ± 10 %. Vessels found not in compliance were prohibited from discharging non-compliant ballast water into the Great Lakes and were subject to severe legal penalties for violations.

NOBOB ships, which do not contain pumpable ballast water as defined by the U.S. Coast Guard, were not subject to the ballast water exchange requirements of the regulations implemented in 1993. However, in 2005 the U.S. Coast Guard issued new voluntary guidelines for NOBOB vessels to raise the salinity of residual water in their tanks to >30. In June 2006 new Canadian regulations were established that, as enforced, require the salinity of almost all ballast water entering the Great Lakes be >30. Canadian coastwise vessels are still exempt. The reported rate of compliance by NOBOBs with the new salinity criteria increased quickly during the latter half of 2006 (Transport Canada, pers. comm.).

3.3 Estimating Ballast Quantities Carried Into the Great Lakes

Analyses based only on vessel entry records (numbers of ships) do not present a complete picture of ballast history or how changes in shipping practices and economics may have affected biological propagule pressure (Verling et al. 2005). Most relevant for purposes of this report are the amounts and biological characteristics of ballast water (exchanged, unexchanged) and sediments discharged during the time periods of interest. Unfortunately only pieces of the necessary information are available, and direct data on ballast water characteristics are incomplete, inconsistent, and subject to large uncertainties. Even so, we can examine the characteristics of the shipping trade and how factors associated with ballast water may have changed between the two periods of interest, and speculate about how those changes may have affected propagule pressure to the Great Lakes.

3.3.1 Ships Departing Without Deballasting and Changes in the Economics of Shipping

Ships that departed the system without deballasting posed no risk of introducing invasive species through ballast water discharge. Ballasted vessels presumably entered loaded with ballast water in order to obtain cargo and likely did not depart without deballasting. On the other hand, Colautti et al. (2004) estimated that between 1994 and 2000, on average, ~49% of NOBOB vessels departed the Great Lakes system without discharging ballast. However, their data for the individual years show that the annual percentage of NOBOB vessels departing without deballasting declined significantly, from ~60% in 1994 to just ~30% in 2000.

Anecdotal information from the SLSDC and other shipping experts suggests that this downward trend was real. The economic climate during most of the pre-BWE period allowed ships to trade profitably into the lakes without carrying full cargo both ways. In addition, the shipping industry reportedly went through a period of poor ship management during the 1970s to mid-1980s, with corresponding deterioration of shipkeeping, including poor maintenance of ballast tanks and the likelihood of greater residual sediment accumulation (Johengen et al. 2005, P. Jenkins, pers. comm.). Accumulation of ballast tank sediment adds weight, which burns more fuel and reduces cargo capacity. By the early 1990s the rising costs of fuel, rising costs of tariffs and fees associated with the Seaway, changes in market conditions that affected the export of grain, and global competition, forced more efficient ship operations in order to survive. In addition, improvements in the standards of ship-keeping were initiated by the industry and specific sediment management guidelines aimed at reducing ANS introductions were introduced by the International Maritime Organization during the mid-1980s and started taking effect in the 1990s (Johengen et al. 2005, P. Jenkins, pers. comm.). The European Community also initiated Port State Control during this period, which also contributed to improved operating standards.

Ships today generally cannot operate profitably in Great Lakes trade unless they carry and maximize cargo loads in both directions (P. Jenkins, pers. comm.). Thus, a transition during the mid-1990s from a higher to a lower percentage of NOBOB vessels departing the Great Lakes without taking on return cargo and not deballasting is consistent with the timing of changes in the economic realities of the shipping industry. However, we don't have estimates for this factor for years other than 1994-2000, so we can only speculate that more ships may have departed without deballasting during the pre-BWE than during the post-BWE period. Fewer NOBOBs departing without deballasting means a greater potential contribution by NOBOBs to propagule pressure.

3.3.2 Average Pre- and Post-BWE Size of Vessels

Schormann et al. (1990) reported that ships lacking cargo on international voyages, and therefore in ballast, may carry between 25% and 35% of their deadweight tonnage (a measure of ship capacity) in the form of ballast water to provide trim and stability. Thus, within the same vessel class, larger vessels are likely to have larger ballast capacities. Most saltwater ships entering the Great Lakes have total ballast tank capacities of 10-20 thousand metric tonnes (t), but total ballast tank capacities can range from less than 1000 to greater than 25000 t (equivalent to less than 264,000 gallons to greater than 6.5 million gallons). The size of ships entering the Great Lakes during the two periods, as reflected in gross tonnage (volume of all enclosed spaces measured to the outside of the hull framing, approximately equal to cargo capacity plus personnel and operating space), increased from an average of 12,475 ± 612 t during the pre-BWE period, to an average of 13,864 ± 901 t during the post-BWE period (data from the SLSDC).

Table 3-1 summarizes the general characteristics of ships entering the Great Lakes during the pre- and post-BWE periods of interest to this report.

Table 3-1: Characteristics of Ships Entering the Great Lakes

	Pre-BWE	Post-BWE
Total Annual Entries (Average)	831 ± 204	572 ± 31
Entered as BOB (Average)	307 ± 164 (37%)	53 ± 28 (9%)
Entered as BOB-A (Average)	79 ± 21 (9%)	78 ± 11 (14%)
Entered as NOBOB (Average)	446 ± 120 (54%)	441 ± 65 (77%)
Average Size (Gross Tonnage)	12,475 ± 612	13,864 ± 901

3.3.3 Estimating Ballast Loads

We used the SLSDC annual data on cargo weight carried by ships entering "in cargo" (= NOBOB) to calculate an annual average cargo weight carried per transit. We assumed that the characteristics (size, cargo capacity) of ballasted ships were not, on average, significantly different from those of NOBOB ships within each period (NOBOB ships could be considered BOB or BOB-A ships that deballasted prior to entering the Great Lakes) and that the average cargo weight carried by NOBOBs each year is representative of the average amount of ballast that would be carried per transit by ships that entered "in ballast" (= BOB) for the same year. The range of average annual cargo weight per transit for the pre-BWE period was 8,534 – 12,940 t, with an average of 11,186 ± 1,249 t. The range of annual cargo weight per transit for the post-BWE period was 11,873 – 15,176 t, with an average of 13,492 ± 1,264 t. Thus vessels entering the Great Lakes during the post-BWE period carried significantly more cargo per vessel ($p=0.0003$, t-test for two samples with equal variance) and likely carried significantly more ballast per vessel as well.

Since the total ballast weight is the sum of the weights of accumulated ballast tank sediments plus ballast water, the average cargo weight should be reduced by the average sediment weight in order to calculate the amount of ballast water. We don't have good values for average sediment weight over the pre- and post-BWE periods, so we focus on total ballast load. For BOB and BOB-A vessels the total ballast load calculated as stated above includes the both water and sediment. For NOBOB vessels, limited data are available to examine ballast water and sediment loads separately, but only for the post-BWE period.

3.3.3.1 BOB Ballast Loads

Based on the pre-BWE number of BOB transits per year and a calculated average cargo (= ballast) load for each year, we estimate that fully ballasted (BOB) vessels could have been carrying an average of 3.25 ± 1.4 (s.d.) million t per year of unexchanged ballast into the Great Lakes during the pre-BWE period (1978-1988), and 0.69 ± 0.31 (s.d.) million t per year of mostly exchanged (see Section 3.2.3) ballast during the post-BWE period (1994-2004). We were able to compare the 1980 result from this method against partial ballast quantity data from Bio-Environmental Services (1981). The total cargo tonnage reported by the SLSDC for 1980 divided by the number of transits reported as "in cargo" results in an average of 8,534 t. Bio-Environmental Services (1981) reported the actual ballast being carried for each of 55 ships they sampled during 1980. Those data give an average of 7,070 ± 4,150 (s.d.) t per ship. These results are in remarkably close agreement since the SLSDC average is based on the assumption that average cargo tonnage is a proxy for average ballast tonnage and the 1980 data are from a only a small subset of total ship entries. It must be noted that the standard deviation of the 1980 average is quite high and reflects the variability of ballast volumes carried by ships. Therefore, while cargo load is usable as a proxy for ballast volume, it is, at best, a coarse approximation.

3.3.3.2 BOB-A Ballast Loads

Limited Coast Guard records that contain data on the amount of ballast in BOB-A ships are available for part of the post-BWE period. We calculated an average of 1,517 ± 2,269 (range 1-16,700) t per transit for BOB-A ships from these records. The average number of BOB-A entries per year for the post-BWE period was estimated as 78 ± 11 (15% of NOBOB entries). Based on these values, BOB-A ships could have carried an average of 0.12 ± 0.02 (s.d.) million t of ballast per year into the Great Lakes during the post-BWE period, most of which should have been exchanged.

We can estimate that an average of 79 ± 21 BOB-A ships (15% of NOBOB entries) entered the Great Lakes each year during the pre-BWE period, but we don't have BOB-A related data for that period. Given the different economic climate during that period (see Section 3.3.1), it is possible that BOB-A ships carried a higher average partial ballast load compared to the post-BWE average of 1517 t per ship, and it is unlikely that they carried less. Although we can't calculate an average for BOB-A ballast loads for the pre-BWE period, we are reasonably confident that it was equal to or more than that for the post-BWE period (at least 0.12 million t), and in addition, during the pre-BWE period it would have all been unexchanged. On a weight basis, BOB-A ships probably contributed less than 15% of the total ballast carried into the Great Lakes in either period.

3.3.3.3 NOBOB Ballast Water Loads

Johengen et al (2005) provided direct observations of the amounts of both residual water and residual sediment from 41 ballast tanks on NOBOB vessels in the Great Lakes. Here we present the NOBOB ballast water component, and below (Section 3.3.4), we discuss the sediment component. Duggan et al. (2005) used the ballast tank observations for 38 NOBOB vessels they sampled as part of the Great Lakes NOBOB Assessment (Johengen et al 2005) between 2001 and 2003 to estimate averages of 47 t of residual water per ship (with individual tanks varying from 0–153 t) and 15 t of residual sediment per ship (with individual tanks varying between 0.1–65 t). However, when we reviewed the complete set of ballast tank records (Johengen et al. 2005, Appendix 2), we calculated averages of 38 ± 30 t of residual water (n=41, range 0-153 t) and 16 ± 20 t of residual sediment (n=41, range 0.5-100 t) per ship. Niimi and Reid (2003) reported an average of 50 ± 30 t (range 1-250 m^3) of residual water in 34 bulk carriers surveyed from 1999 through 2000. They estimated the total ballast volume per ship using ballast depth measured through the sounding tubes of each tank and did not enter any of the tanks for direct observations. If any of these ships were not at even keel, water would have been unevenly distributed and that would lead to over- or under-estimation by their method. All these averages are qualitative at best, as all require extrapolation of observations from a few ballast tanks on each ship to the whole-ship. For this report we use the averages calculated from Johengen et al (2005), Appendix 2.

There are no data about the amount of residual ballast water carried into the Great Lakes by NOBOBs during the pre-BWE period. If we assumed that the amount is simply proportional to ship size, then the pre-BWE value could be estimated by reducing the post-BWE estimate from the Great Lakes NOBOB Assessment (Johengen et al. 2005) by ~10%, to allow for the average size difference between ships in Great Lakes trade during these periods (see Section 3.3.2). As previously noted, the shipping industry reportedly went through a period of poor ship management during the 1970s through the mid-1980s. An outcome of poor shipkeeping can be the accumulation of relatively large amounts of sediment. However, unless there is so much accumulated sediment that the holes and slots of the tank's lower drainage system are blocked, the amount of residual water should not have been much more than that on well-managed and maintained ships. Thus, it is possible that, in spite of trade and economic factors, the amounts of residual ballast water carried in pre- and post-BWE NOBOB ships was not substantially different.

We assume that the average amount of residual ballast water in NOBOBs was the same for both the pre- and post-BWE periods. We don't adjust for the smaller ship size given the qualitative nature and magnitude of variance (uncertainty) in this value. Based on the number of NOBOB transits per year and an average residual ballast water load of 38 t per vessel, we estimate that NOBOB vessels could have been carrying an average of 17,000 ± 4,550 (s.d.) t per year of unexchanged residual ballast water into the Great Lakes during the pre-BWE period (1978-1988) and also 17,000 ± 2,460 (s.d.) t per year of unexchanged ballast water during the post-BWE period (1994-2004). The pre- and post-BWE averages are the same because we assume the same average amount of residual water per ship, and as noted previously, the number of NOBOB entries was essentially the same for the pre- and post-BWE periods. However, these estimates are for total residual ballast water carried into the Great Lakes, not for water discharged to the lakes. In order to estimate the latter, a correction for the number of NOBOBs departing each year without deballasting should be applied, but the necessary data are not available, especially for the pre-BWE period. This correction would reduce the average NOBOB contribution, possibly by a significant amount. As noted previously, the contribution of NOBOBs to the total ballast weight carried into the lakes is estimated to be less than 5%, so a correction for NOBOB departures would have a very small effect on the overall total, the majority of which was ballast water.

3.3.4 Estimating Sediment Loads

3.3.4.1 Sediment Discharge during Deballasting

When a ship takes in ballast water it often also takes in sediment. Depending on operational strategy, location, and attentiveness to ballast tank condition, sediment accumulation can either be kept to a minimum or can become relatively significant. Many of the ballast tanks entered during the Great Lakes NOBOB projects (Johengen et al. 2005, Reid et al. 2007) had similar sediment distribution patterns, with little sediment accumulation near the bellmouth (Figure 3-4a), light to moderate accumulation in areas adjacent to and in longitudinal line with the bell-mouth bay (Figure 3-4b), and heaviest accumulation along the outer bilge areas of the tanks (Figure 3-4c; the curved area of the hull where bottom and sides meet) and in the forward bays (Figure 3-4d) furthest from and in transverse position relative to the bellmouth bay. This pattern reflects differential sediment resuspension and scouring that varies with position in the tank.

Water follows paths of least resistance, and in the early stages of discharge as well as during flow-through exchange, ballast water can flow though a myriad of openings towards the bell-mouth, especially the large lightening holes between the bays, and smaller slots (where the stiff-eners pass through walls separating the bays) and drain holes through various other structural members (Figure 3-4b,d,e). Therefore, flow velocities at the bottom of the tank (through slots and drain holes) are probably not sufficient to cause much resuspension or scour except in the immediate vicinity of the bellmouth while the water level is above the bottom edge of the light-ening holes. However, once the water level is below the bottom edge of the lightening holes, there are fewer options, and flow is restricted to the slots and drain holes in the lower part of the tank.

In bays aligned longitudinally (i.e., in a fore-aft direction) with the bellmouth bay there are fewer barriers and restrictions to flow and longer reaches of unobstructed space between the stiffeners along the route the water must take. As long as the water is above the top edge of the stiffeners (generally 10-14 inches tall) the path of least resistance will be above the stiffeners in a trans-verse direction, and parallel to them in a longitudinal direction leading to the slots in the bay walls. During this stage of deballasting the flow must reach much higher velocities to maintain the same outflow rate as when the water was above the lightening holes, resulting in some areas between stiffeners where the bottom plate is swept almost clean (Figure 3-4b). In order to main-tain the flow rate at the bellmouth, the velocity of water squeezing through the slots must be even higher, and possibly jet-like, since the total open area of the slots is much less than the total area of the lightening holes and is also much less than the total area between stiffeners.

During the final stages of deballasting, the water level falls below the top edge of the stiffeners and in the transverse direction can only flow through the small drain holes in the bottom of the stiffeners. Based on visual evidence (Figure 3-4c, e), significant focused sediment scour occurs at and between these drain holes in a transverse direction. The outcome is incomplete sediment (and presumably organism) resuspension and discharge from the ballast tank such that sediment deposited closer to and in-line with the bellmouth is more likely to be discharged. Based on di-rect observations and photographs from ballast tanks entered during the Great Lakes NOBOB Assessment (Johengen et al. 2005), and the sediment accumulation patterns discussion above, we suggest that that resuspension and removal of sediment occurs in variable amounts affecting be-tween 30% and 80% of the bottom area, depending on proximity to the bellmouth. The extent of significant resuspension and removal will also depend on tank design, deballasting flow rate, and previous ballasting and sediment management history (e.g., length of time sediment had to ac-cumulate and whether it is compacted), all of which can vary widely among ships.

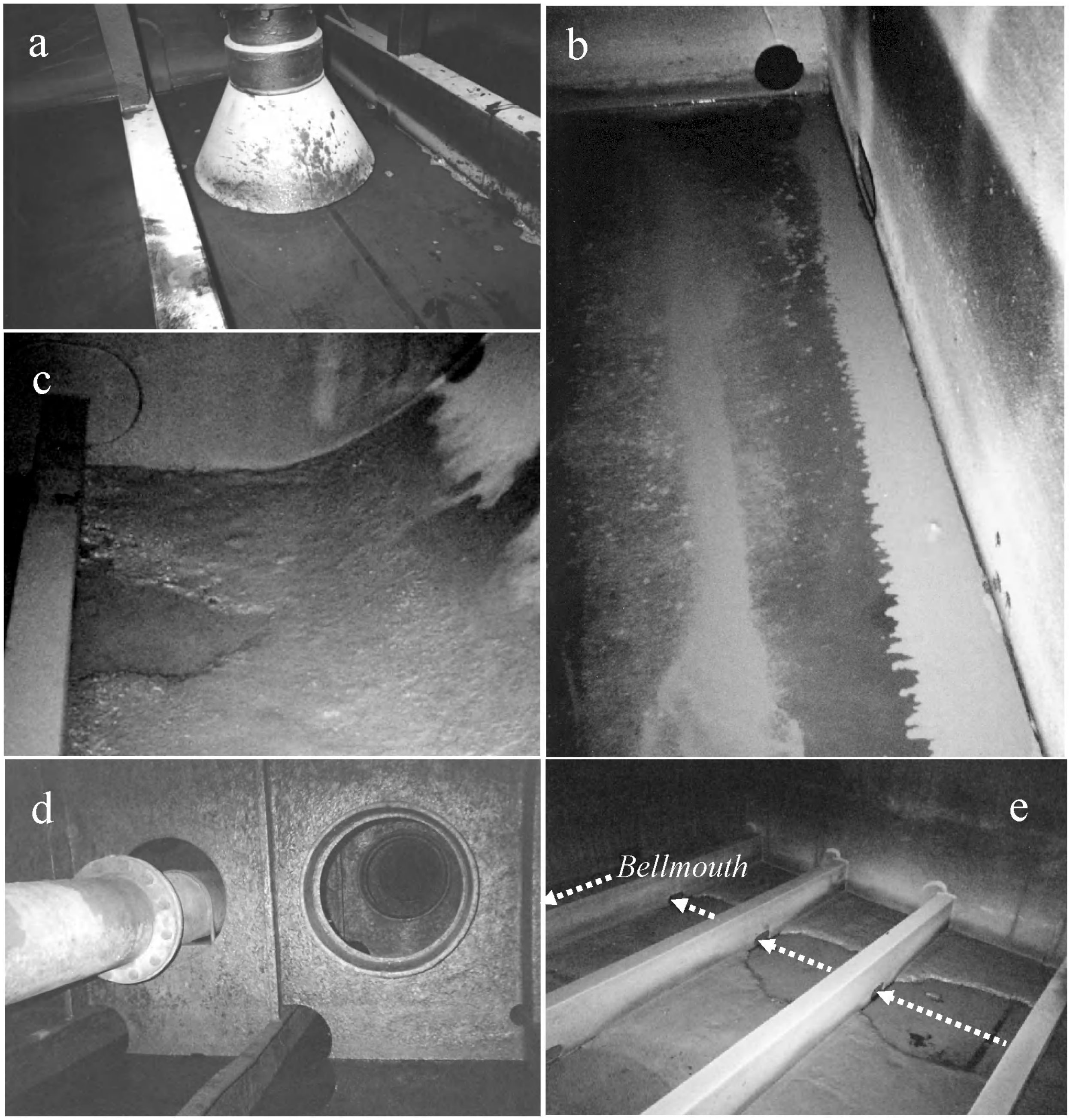

Figure 3-4: a) Area around bellmouth is free of accumulated sediment. Deck plating is clearly visible. b) Longitudinal scour associated with bays aligned with the bellmouth bay. c) Heavy accumulation of sediment along the outer bilge. d) Large holes and slots provide path of least resistance during early stages of deballasting. e) Well-defined paths of transverse sediment scour between drain holes of adjacent stiffeners. (Photos courtesy of the Great Lakes NOBOB Assessment Project).

Forsberg et al (2005) concluded that deballasting is extremely inefficient at removing small particles from ballast tanks based on the persistence of 1-micron fluorescent microbeads added during studies of ballast water exchange. Their observation is consistent with our discussion, especially for tank bottom areas not in close proximity to the bellmouth. It must also be remembered that detailed scientific data on sediment resuspension and discharge during ballasting, deballasting, and exchange are not available, so the above discussion is speculative at best.

3.3.4.2 Sediment Loads, Pre- and Post-BWE Period

There are no data for the amount of sediment accumulated in BOB and BOB-A ballast tanks during the post-BWE period. It is reasonable to assume that they also accumulated sediment in the same manner as NOBOBs – on average, NOBOBs ships should be no different than BOBs or BOB-As, except that they have already discharged their ballast water before entering the Great Lakes, while BOB and BOB-A ships should have undergone ballast water exchange during the post-BWE period, another form of deballasting. Thus there is no reason that one category of vessels would have accumulated substantially more or less than the others. Based on the discussion of sediment discharge during deballasting (see Section 3.3.4.1), each ship that deballasted while in the Great Lakes might have discharged, on average, more than 5 t (30%) and less than 13 t (80%) of sediment during the post-BWE period, based on 16 t total per vessel.

While we can use the data from Johengen et al. (2005) to estimate the annual amount of residual sediment that might have been discharged into the Great Lakes during the post-BWE period (above), we do not have similar data for the pre-BWE period. Sediment can be difficult to flush from a ballast tank unless doing so is incorporated as a regular and consistent activity in a ship's management plan (Johengen et al. 2005). Anecdotal information suggests that sediment accumulation and retention during the pre-BWE period was relatively high (compared to post-BWE) due to poor shipkeeping, especially related to ballast tank management practices (see Section 3.3.1). The NOBOB that had the largest estimated amount of residual sediment during the Great Lakes NOBOB Assessment Project (Johengen et al, 2005) was estimated to have ~100 t of sediment (plus ~30 t of water). Based on a review of ship history and related records, that ship was identified as likely having operated for a year or more under conditions that may have mimicked the 1970-1980 period of poor shipkeeping. As such it probably contained a reasonable representation of residual amounts that might have been carried in ships entering the Great Lakes during the 1970s-1980s (P. Jenkins, pers. comm.).

There are several other factors that would have affected the potential sediment load carried into the Great Lakes during the two periods. The average size of ships was ~10% less during the pre-BWE period (see Section 3.3.2**)** so the estimate in the previous paragraph from a poorly managed post-BWE vessel could possibly be decreased by 10% for the pre-BWE period, but we have no data to correlate ship size with sediment accumulation. The number of NOBOBs that departed without deballasting (Section 3.3.1) could have a significant affect, but we do not have any data for the pre-BWE period, and only the Colautti et al. (2004) estimates covering part of the post-BWE period (1994-2000). As noted above, the 1990s were likely a transition period during which changes in shipkeeping and economics of trade resulted in significant differences in some operating characteristics compared to previous decades. Colautti et al. (2005) estimated that the percentage of NOBOBs departing without deballasting decreased from ~60% in 1994 to ~30% in 2000. If all other pre- and post-BWE characteristics were equal, more NOBOB ships departing without deballasting during the pre-BWE period would mean a decrease in the amount of sediment available to be discharged compared to the post-BWE period. However, it is possible that pre-BWE ships may have carried significantly more sediment in their ballast tanks due to poor management practices. We suggest that ballast sediment load most likely decreased (thus decreasing the potential contribution to propagule supply) between pre- and post-BWE periods as shipkeeping improved and the accumulated sediment in ballast tanks decreased over time for all categories of ships, but we can't reliably estimate the magnitude of this change.

Since we don't have good values for average sediment weight over the pre-BWE period, we evaluated various average sediment load scenarios up to 450 t per vessel (4.5 times the estimated total sediment in a poorly managed NOBOB surveyed during the Great Lakes NOBOB Assessment project) to determine the sensitivity of the calculated total ballast load to various amounts of pre-BWE sediment loads. In all cases sediment load was a small percentage (<5%) of the total annual ballast load even under assumed severe sediment accumulation conditions. Therefore, for purposes of estimating total ballast carried into the Great Lakes we did not differentiate between pre- and post-BWE sediment loads for NOBOB vessels, and used the total average ballast load (54 t of sediment plus water per NOBOB vessel) for both periods. This equates to an estimated total ballast load contributed by NOBOB vessels of .024 ± .004 (s.d.) million t during each period.

3.3.5 Summary of Estimated Ballast Potentially Carried Into the Great Lakes

Table 3-2: Summary of estimated average total annual amounts of ballast (water plus sediment) potentially carried into the Great Lakes during the pre- and post-BWE periods.

Period	# Entries	Estimated Ballast (Average per year, Million t)	% of Total
Pre-BWE			
BOB	307 ± 164	3.25 ± 1.4	96%
BOB-A	79 ± 21	0.12 ± 0.03	3.5%
NOBOB	446 ± 120	0.02 ± 0.006	0.7%
Total	831 ± 204	3.39 ± 1.42	
Post-BWE			
BOB	53 ± 28	0.69 ± .31	83%
BOB-A	78 ± 11	0.12 ± .02	14%
NOBOB	441 ± 65	0.02 ± 0.003	2.9%
Total	572 ± 71	0.83 ± 0.31	
Estimated Change (Post vs. Pre-BWE Totals):	-31%	-76%	

Table 3-2 summarizes the estimated totals of ballast loads (water plus sediment) potentially carried into the Great Lakes by ships for the pre- and post-BWE periods based on the estimates and assumptions outlined in the previous sections. Even though the number of ship entries declined by only about 31% (see Section 3.2.2.1), under these estimates the total ballast amount carried into the Great Lakes potentially declined by ~76%. This apparent decline is mainly the result of changes in the economics of Great Lakes trade that made carrying ballast water not profitable, resulting in fewer ships entering the lakes overall, and within those ships, a decline in vessels carrying ballast. Compared to the amount of ballast potentially carried on BOB vessels, the amounts carried on BOB-A and NOBOB vessels are relatively small fractions of the cumulative total ballast potentially carried into the Great Lakes during either period, although the percentage contributions for BOB-A and NOBOBs are greater for the post-BWE period. It must also be noted that the apparent increase in BOB-A as a percentage of the total for the post-BWE period reflects the fact that the total amount of ballast decreased, while the total number NOBOB vessels remained almost the same, and BOB-A entries are derived from the NOBOB entries. Of particular importance is that the ballast water carried in most BOB and BOB-A vessels (i.e., those in compliance with BWE salinity requirements) after 1993 was of oceanic, not coastal origin, except for ships that were in coastwise trade, and thus are presumed to have posed a reduced risk of introducing species that could survive in the Great Lakes. It is also important to keep in mind that these results are for estimates of ballast carried into the Great Lakes in ballast tanks, and do not reflect estimates of ballast amounts actually discharged.

3.4 Origins of Ballast Water Discharged to the Great Lakes and Origins of Residual (NOBOB) Ballast

Several sources were used to compile information about the origins of ballast water being carried into the Great Lakes. Figure 3-5a summarizes data from Bio-Environmental Services (1981) for 55 ships sampled between August and October 1980.

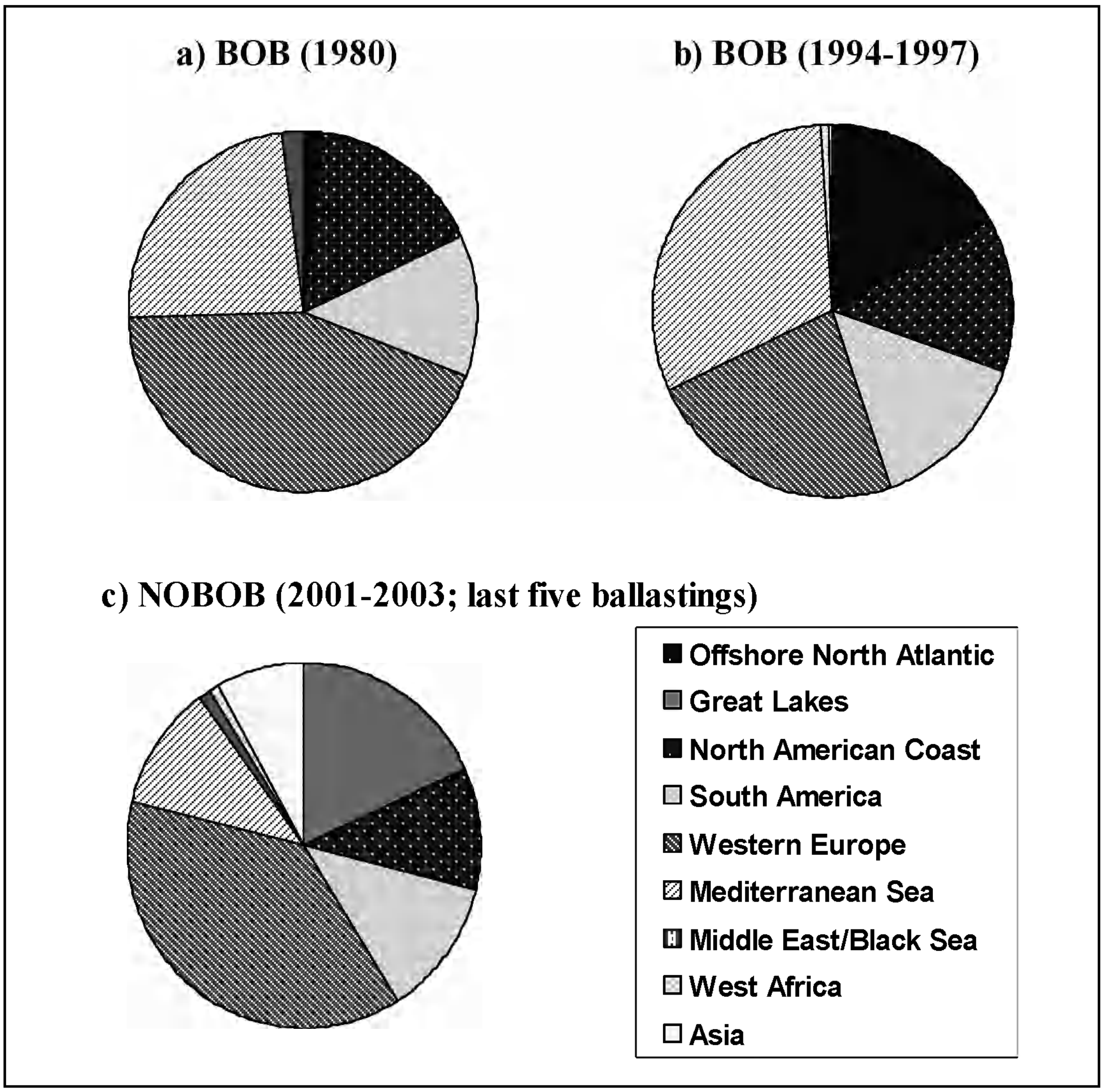

Figure 3-5: (a) Origins of Ballast in BOB vessels sampled in 1980 (Bio-Environmental Services Ltd. 1981). (b) Origins of ballast from U.S. Coast Guard records, 1994-1997. (c) Sources of ballast water taken on last five ballast operations on NOBOB ships entering the Great Lakes, 2001 - 2002 (Johengen et al. 2005).

Figure 3-5b presents similar information compiled from U.S. Coast Guard boarding records of BOB vessels over the period 1994-1997. A sample of 64 records judged to be complete and of high quality, reporting a total of 348,804 t of ballast in 89 tanks, was used. Information in both of these data sets was for the most recent ballast intake only. Johengen et al. (2005) compiled data for the last five locations of ballast water intake for the NOBOB ships they surveyed and were thus able to characterize the most common ballast sources by specific region (Figure 3-5c, representing a total of 160 recent (2000-2002) ballast operations). In all three figures, Western Europe and the Mediterranean Sea stand out as the source region for half or more (49-67%) of all ballast water, with North American coastal waters (11-18%) and South America (12-14%) also significant. Also of note is that the offshore North Atlantic was a minor source in 1980, prior to BWE regulations (2%, Figure 3-5a), but became a much more significant source with implementation of BWE regulations (17%, Figure 3-5b). An apparent change seen in Figure 3-5c is the presence of the Great Lakes as a significant source (18%), but this is only because data from five previous ballast intakes for each ship were captured for this figure. Inclusion of multiple past ballast water intake records is probably more representative of potential sources of foreign organisms, since the viable biota in ballast tanks, especially resting eggs and spores in ballast sediment, will have been accumulated from many previous ballast water intakes. These results are generally consistent with those reported in other studies (Niimi and Reid 2003, Colautti et al. 2004) except for the identification of the Great Lakes themselves as being a probable major source of ballast residuals returning to the Great Lakes. However, the data sets on which these figures are based were all small subsets of the entire population of ships entering the Great Lakes during the periods of record, and as such, may not adequately represent all source regions.

3.5 Estimating Propagule Pressure: What's in Ballast?

Determination of the specific effectiveness of BWE in protecting (i.e., reducing ANS risk to) the Great Lakes by reducing propagule pressure requires knowledge of the time history of the numbers and behaviors of ships while in the ecosystem, the effects of any treatments, such as ballast water exchange, and the percentage of ships subject to those treatments, the quantity of ballast actually discharged, the number of viable nonindigenous organisms in both ballast water and ballast sediments in each ship at the time of ballast discharge, and how much of each population is discharged upon deballasting. Most of the necessary information is not available or not well known, and quantitative detailed calculations are not possible at the present time, and may never be. In this section, we look first at a simple model of propagule pressure based on ballast quantity, and then discuss factors which are not included in the simple model which have bearing on the actual propagule supply.

3.5.1 Using Ballast Quantity as a Surrogate for Propagule Supply

In the absence of more appropriate data, it can be instructive to use ballast quantity as a surrogate for propagule pressure. We use estimated changes in ballast quantities between the pre- and post-BWE periods as a simple surrogate to examine the potential effects of changes in shipping practices, economics of the trade into the Great Lakes, and BWE regulations may have had on propagule supply. We used the data described and summarized in Sections 3.2 and 3.3 to develop a time series of ballast quantity potentially carried into the Great Lakes during the pre- and post-BWE periods. Note that we don't have data for actual ballast quantity and instead, assumed that the average annual cargo load of NOBOBs was representative of the average annual ballast amount per vessel carried by BOB vessels for each year. In addition, since we can't estimate the sediment component of the total ballast (see Section 0), we make no adjustment for it, and treat the total as if it were all ballast water.

Several studies have reported the efficacy of ballast water exchange, with most reporting a removal of 80-100% of target taxa (Wonham et al. 2001, Chapter 2 of this report). The results of SERC's on-board experiments (Chapter 2) ranged from 80-95% reduction in concentration of coastal invertebrates across ship types. Locke et al. (1993) analyzed biological data from 14 ships that entered the Great Lakes in 1990-1991 after having completed BWE and achieving a final salinity of >30. They calculated an average BWE effectiveness of 86%, but it was based on the number of ships (2 of 14) that still contained live freshwater species, rather than the actual number of freshwater species that survived in tanks after exchange. Thus their derived BWE effectiveness is not equivalent to that calculated by SERC and is misleading in that it is ship based, and not based on changes in organism supply before and after in-tank sampling.

In the simple model below, we use 90% as a representative average for the reduction of coastal organisms by a properly conducted BWE that meets regulatory goals, based on the SERC on-board experiments. Although the data behind these estimates are limited to coastal invertebrates, coastal phytoplankton are likely to be swept out in the same proportion as the original water (88-99%, see Chapter 2), because most pelagic phytoplankton are not capable of self-propulsion and generally move where water currents take them. If we assume that BWE achieves the prescribed 95% volumetric replacement of coastal water, then the assumption of 90% biological reduction applied to phytoplankton is probably on the low side. In addition, salinity shock (see below) is another factor that should increase the biological effectiveness of BWE against many fresh- and brackish water biota. So our use of an overall average of 90% is likely conservative for application to the effectiveness of BWE in the context of the Great Lakes.

Figure 3-6a shows the annual total ballast estimated to have been carried into the Great Lakes by BOB, BOB-A, and NOBOB vessels with no adjustments of post-BWE data for ships not compliant with salinity requirements (ships not in compliance are barred from discharging their ballast water) or for the affects of exchange. Figure 3-6b shows the same data after adjusting the post-BWE data for non-compliant vessels and for the effects of BWE. In order to present these results in terms of potential propagule supply, the number of BOB and BOB-A vessels that entered during the post-BWE period were reduced by the percentage of non-compliant vessels reported for each year by the U.S. Coast Guard (Figure 3-3) and the resulting ballast quantities associated with compliant vessels were reduced by 90% to imitate the expected 90% effectiveness of BWE on the actual organism content. For this illustration, we approximate that a 90% reduction in live coastal organisms (i.e., the effect of BWE) is equivalent to and can be represented by a 90% reduction in coastal water volume carried into the lakes.

The results show dramatic reductions in potential propagule supply (propagules potentially carried into the Great Lakes) between the pre- and post-BWE periods. Figure 3-6a reflect changes in the both the number of ships that entered the system and changes in their ballast status between the two periods (see Sections 3.2.2.1 and 3.2.2.2), both resulting from changes in ship management practices and changes in the economic requirements of the shipping trade. Figure 3-6b shows the additional effects of BWE regulations on the remaining post-BWE total potential propagule supply.

Note that these estimates do not differentiate between water and sediment, and from a propagule supply standpoint, sediments appear to be a potentially large and possibly significant pool of propagules (see below), but we don't have a good understanding about sediment load or sediment propagule discharge. The results would likely change, perhaps significantly, if we had appropriate data for detailed analyses of each component. In addition, these results show the potential ballast supply that may have entered the Great Lakes during each period, but we do not attempt to estimate the actual propagule discharge, nor do we attempt to establish the percentage of propagules likely to be nonindigenous and not already in the Great Lakes ecosystem.

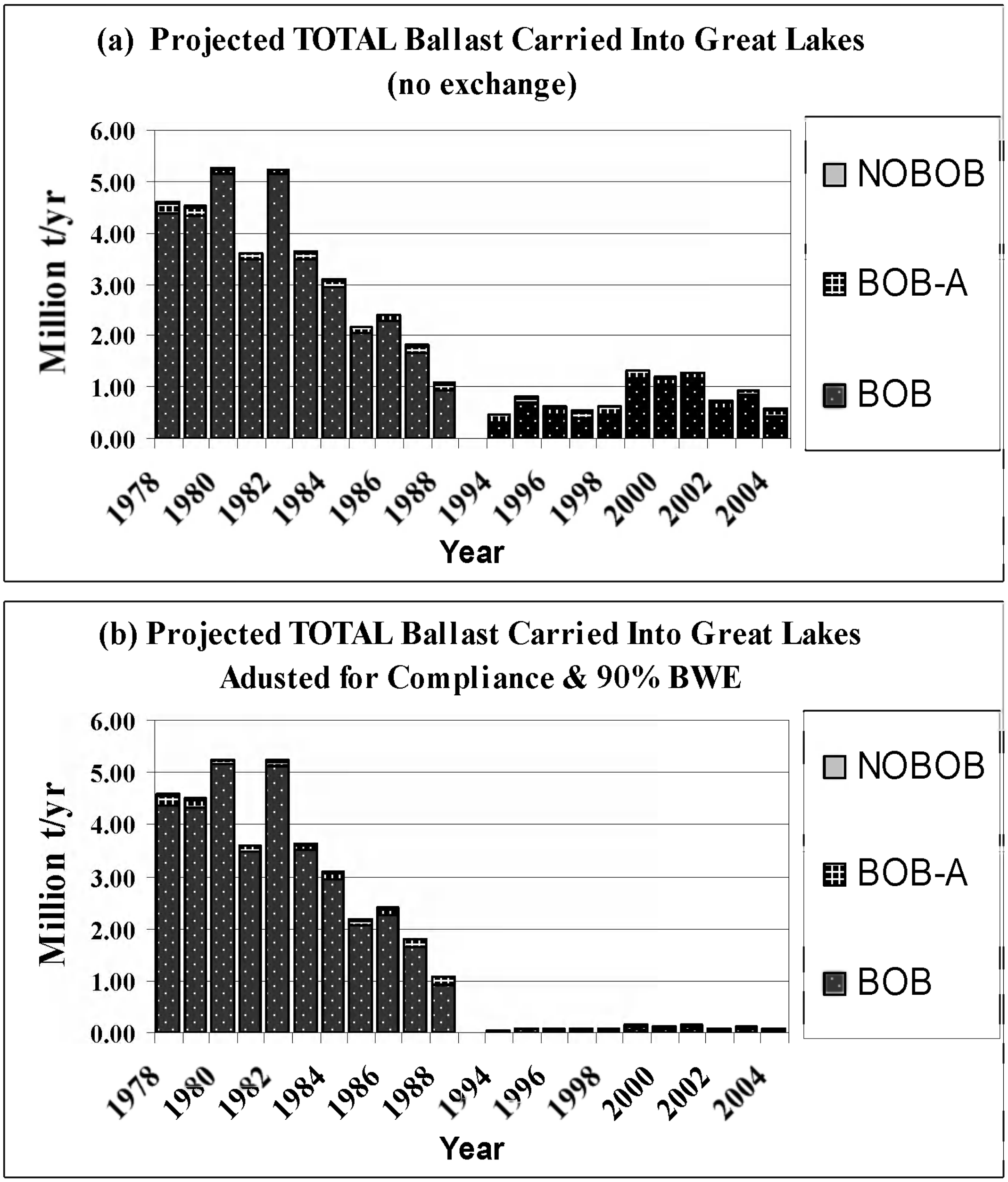

Figure 3-6: *(a) Potential ballast quantity equivalent to unexchanged ballast water (as a surrogate for propagule supply) carried into the Great Lakes based only on changes in number of vessel entries. (b) Potential ballast quantity equivalent to unexchanged ballast water carried into the Great Lakes after reductions for non-compliant vessels and BWE (1994-2004 only). Note scale break between 1988 and 1994.*

Table 3-3 summarizes the average contributions of BOB, BOB-A and NOBOB vessels shown in Figure 3-6 as percentages of the total estimated ballast quantity for the pre- and post-BWE periods. It is important to note that the percentages calculated for each period are relative to the total quantity of ballast estimated to have potentially been carried into the Great Lakes during each period, and thus, represent different total amounts. Based on these estimates, NOBOBs would have contributed less than 1% of the total during the pre-BWE period, but 25% of the total during the post-BWE period when regulatory compliance restrictions (i.e., no discharge of non-compliant water) and BWE is taken into consideration.

Table 3-3: Contributions of BOB, BOB-A, and NOBOB vessels to potential ballast quantity (as a surrogate for propagule supply) carried into the Great Lakes, by period. Pre-BWE quantity is totally unexchanged. Post-BWE quantity is the equivalent remainder of unexchanged ballast after removal of vessels not compliant with salinity requirements and reduction of the remaining ballast by 90% for the effects of BWE.

	BOB		BOB-A		NOBOB	TOTAL
	UNEXCH	EXCH	UNEXCH	EXCH	UNEXCH	(Mt)
Contribution to Total Pre-BWE Quantity	96% (3.25 Mt)	N/A	3.5% (0.12 Mt)	N/A	0.71% (0.02 Mt)	3.4
Contribution to Total Post-BWE Quantity	N/A	65% (0.06 Mt)	N/A	11% (0.01 Mt)	25% (0.02 Mt)	0.10

Based on the data, calculations, and discussions we've presented, it appears reasonably certain that there has been a significant decrease in the overall propagule supply to the Great Lakes between the pre-BWE and post-BWE periods. However, while BWE has contributed to this decrease, changes in the economics of the Great Lakes trade and improvements in ship management practices also had a substantial impact.

Table 3-4 summarizes the <u>total</u> estimated decrease in ballast quantity (as a surrogate for potential propagule supply), comparing pre-BWE total ballast potentially brought into the Great Lakes against the equivalent total ballast potentially available in the Great Lakes calculated after reducing ship entries by the annual percentage of vessels reported as not in salinity compliance each year during the post-BWE period, and adjusting the reminder for 90% effective BWE. Based on the assumptions and data we used, the estimated overall decrease in <u>total potential ballast quantity</u> (and therefore, potential propagule supply) from pre- to post-BWE periods was ~97%, equivalent to eliminating ~3.3 millions t per year of unexchanged ballast water.

These results show that unplanned factors, especially economic forces, can have a large influence on propagule supply associated with a vector tied to commerce. Economic forces alone caused a decrease in the quantity of ballast entering the Great Lakes of 76%. However, it is important to note that even if there were no market-driven changes to ballast quantity entering the Great Lakes, application of BWE alone would result in an overall decrease of 88% in total propagule supply. This (88%) is the result of combining a 100% reduction to propagules associated with non-compliant vessels (which were not allowed to discharge), a 90% reduction to propagules from vessels subject to BWE, and a 0% reduction to NOBOB vessels, which were not required to exchange. As market forces redirect the proportions of vessels in each category (particularly NOBOB vessels not subject to exchange) they have a secondary effect on the overall efficacy of BWE regulations by causing greater or fewer numbers of vessels to be subject to regulations.

Table 3-4: Estimated ballast water supplies as a surrogate for propagule supplies, by ship type and contributions from changes in trade and shipping practices, and from 90% effective BWE. Post-BWE Equivalent Unexchanged Ballast Quantity (Row 4) is equal to Post-BWE Unexchanged Ballast Quantity (Row 2) corrected for percent of vessels compliant with the salinity standard as reported by the U.S. Coast Guard, and reduced for 90% effective BWE.

	BOB	BOB-A	NOBOB	OVERALL
Total Pre-BWE Unexchanged Ballast Quantity (t/yr)	3,253,000	119,000	24,000	3,396,000
Total Post-BWE Unexchanged Ballast Quantity (after changes in trade & ship management practices, t/yr)	689,000	118,000	24,000	831,000
Decrease in ballast quantity compared to Row 1 due to trade and ship management practices	*-79%*	*<1%*	*0%*	*-76%*
Total Post-BWE Equivalent Unexchanged Ballast (Propagule) Quantity (changes in trade & ship management practices, plus adjustments for compliance & 90% BWE, t/yr)	62,000	10,000	24,000	96,000
Decrease in propagule supply (equivalent ballast quantity) compared to Row 2 due to BWE	*-91%*	*-92%*	*0%*	*-88%*
Total Change after Compliance & BWE* (t) *(Decrease compared to Row 1)	-3,191,000 *(-98%)*	-109,000 *(-92%)*	0 *(0%)*	-3,300,000 *(-97%)*

3.5.2 Variables Influencing the Effectiveness of BWE

It is tempting to use ballast quantity as a surrogate for propagule pressure, as illustrated above, and such an approach can be instructive in the absence of other appropriate data. However, ballast quantity will not tell a complete or accurate story unless it can be related to propagule pressure. The following discussion summarizes information that is available related to factors that may influence propagule pressure applicable to the Great Lakes.

There is considerable information in the published literature concerning salinity tolerances of organisms, as well as recent experimental results (Gray et al. 2006, S. Santagata, pers. comm.), that suggest salinity shock associated with BWE can be highly effective against freshwater and low-salinity estuarine organisms, especially if exposure is long enough (at least 24 hrs; Santagata, pers. comm.). The SERC on-board experiments, for the most part, did not start with low-salinity water, so their results do not include the potential effects of salinity shock. Freshwater and estuarine organisms pose the most risk to the Great Lakes, so assuming only a 90% reduction for ships that conducted BWE according to guidelines and achieved the requisite minimum salinity of 30 is probably conservative for estimating risk reduction for the Great Lakes.

A concern is raised by a recent Australian study (Hall and Wilson 2006) that shows the flow-through BWE target of 95% volume replacement may not be achieved when multiple tanks on the same ship are pumped simultaneously for BWE. The problem stems from the fluid dynamics of flows in the piping system, which can produce unequal flows into the tanks being pumped are not at a similar location relative to the ballast pump. The outcome can be significant under- or over-flushing. Another problem raised by this study is the apparently common assumption that ballast pumps, regardless of age, are still pumping according to specifications for new pumps. Wear and tear on ballast pumps, however, can significantly reduce their actual pumping rate. BWE conducted assuming ballast pump outflow is greater than it really is, as could be the case with old or worn pumps, would not achieve the targeted three tank volume overflow and would under-exchange the ballast tanks. We don't have any information about the age or maintenance of ballast pumps on ships, or the degree to which shipboard engineering staff know the actual (vs. assumed) pumping rates. We have no information on the frequency with which ships coming to the Great Lakes conduct flow-through BWE on dissimilar tanks. Both of these factors could lower the actual efficacy of BWE as conducted, compared with what is assumed for BWE that achieves a complete three-tank volume flow-through.

3.5.3 Biological Content of Ballast

The biological content of ballast entering the Great Lakes is not well known, and variations in concentrations and species of organisms typically found in ballast water are also functions of source region, season, and duration of the transit since ballasting (Bio-Environmental Services 1981, Wonham et al. 2001, Verling et al. 2005). Some ships carry water that is nearly 'clean' in contrast to other ships that have been reported to carry more than a million organisms per tonne of ballast water (see Table 3-6, page 83). Even ballast tanks within the same ship can carry vastly different densities of organisms (Wonham et al. 2001). Typical ship deballasting pipelines are not designed to facilitate sampling of the actual ballast discharge stream, so most assessments use the total number of organisms contained in ballast as a measure of propagule pressure. This approach overestimates actual propagule pressure because it does not correct for species likely to be retained in the tank or killed during discharge, and does not correct for species that are indigenous or that have already invaded or that will be unlikely to survive in the receiving system. Alternately, some BWE experiments have documented increases in some species, presumably via reproduction (Gollasch et al. 2000, Johengen et al. 2005).

3.5.3.1 Ballast Water

The ranges of reported organism densities in ballast shown in Table 3-6 are instructive of the limitations we face when trying to assess risk associated with ballast water discharge. In general there are few data on ballast water organism densities specific to ships arriving to the Great Lakes.

Locke et al. (1991) reported maximum zooplankton concentrations in the tens of thousands per t in ballast tanks of ships entering the Great Lakes, but in most cases the abundance of zooplankton was much less than the maxima. However, their data included both live and dead organisms and did not differentiate quantities of each. A number of studies have found significant mortality of organisms in ballast tanks over the course of a transit, depending on the length and conditions of the transit (Williams et al. 1988, Gollasch et al. 2000, Wonham et al 2001, Verling et al.

2005). Inclusion of dead organisms in total counts strongly biases the reported densities and overstates the risk, although some dead organisms could present risk via the presence of viable resting eggs associated with their remains. Also of direct relevance to the Great Lakes, Bio-Environmental Services (1981) sampled ballast water in 55 ships entering the Great Lakes in 1980 and performed very detailed biological counts and identifications, including differentiating between apparently live and dead organisms. Summing over all their data, which included live phytoplankton, zooplankton, and unknown invertebrates, the overall average organism density was 41,800 ± 158,250 per t (range 0 – 1,135,000 organisms per t). Their average invertebrate density was 26,600 ± 154,200 organisms per t (range 0 – 1,135,000 organisms per t). These results – with a standard deviation almost 4 times the average – illustrate the problems associated with attempting to generalize the biological characteristics of incoming ballast water on an annualized basis for purposes of propagule pressure calculations. Furthermore, all samples for the Bio-Environmental Sciences study were taken during the late summer and fall and thus do not capture the full potential seasonal range and species composition of the ballast water.

Duggan et al. (2005) reported an average concentration of ~10,900 live invertebrates per t (range 0 – 143,500 per t) of residual water in NOBOB vessels sampled in the Great Lakes between December 2001 and December 2003. Note that these results were for invertebrates only and did not include phytoplankton. While it is possible that some benthic organisms were captured in these samples, benthic organisms did not constitute a significant percentage of the total abundance (C. van Overdijk, pers. comm.).

3.5.3.2 Ballast Sediment

Duggan et al (2005) reported an average concentration of ~1.3 million live invertebrates per t (range 24,000-19,900,000 per t) of residual sediments from NOBOB ballast tanks sampled in the Great Lakes between December 2001 and December 2003. Bailey et al (2005) reported an average concentration of invertebrate resting eggs (dormant stages) of ~3.5 million per t (range 40,000 - 91,000,000 per t) from the same samples. Bailey et al. (2004) showed that resting stages may be resistant to salinity shock, and even though the hatch rate of several diapausing eggs in ballast sediments was reduced during experiments that exposed them to salt water, the eggs were not killed and generally remained quite viable. Thus, while BWE would inhibit hatching of eggs (and kill any salinity intolerant organisms that hatched from eggs prior to BWE), it does little to reduce viability of unhatched eggs, and unhatched eggs could provide a significant pool of potentially available propagules.

3.5.4 Relative Contribution of Sediment and Water Phases to Propagule Supply

In the simple model in which ballast quantity is used as a surrogate for propagule pressure, sediment and water phases of the ballast are implicitly considered to represent equal propagule pressure per ton ballast. However, as shown above, a wide range of live pelagic organism densities can be found in ballast water just prior to discharge. The average and maximum recorded densities of live sediment-associated invertebrates may be, respectively, on the order of 49 and 18 times the average and maximum recorded densities of live ballast water column invertebrates (Bio-Environmental Services (1981) data), and the average and maximum recorded densities of dormant invertebrate egg densities may be, respectively, on the order of 132 and 80 times the average and maximum recorded densities of ballast water column invertebrates. Thus, propagule pressure per tonne of ballast differs significantly among the ballast phases (water, sediment; live, dormant), with residual sediments providing a potentially much larger pool of viable organisms per tonne. Although ballast water discharge has been considered the most significant vector for invasive species introduction, organisms associated with sediment may constitute a much greater potential propagule pool in vessels entering the Great Lakes system.

Residual sediments are of importance to the invasive species issue only to the extent that the organisms likely to be found with sediments are nonindigenous to the Great Lakes and are likely to be discharged during deballasting. Bailey et al. (2004) reported that only ~2.5% of the resting egg species they identified in residual ballast sediments were nonindigenous to the Great Lakes. Sediment-dwelling mobile organisms do not tend to stay in the water column voluntarily, and are only likely to be entrained in ballast discharge from areas of very high near-bottom flow rates from which they can't escape. Many entrained organisms would have ample opportunity to escape narrow areas of high flow, such as may exist when the ballast water depth is below the level of the large intra-tank openings, so that water is forced to jet through drain holes and slots near the bottom of the tank. It is likely that benthic organisms can avoid being swept out by hiding in quiet (low-flow) zones, unless they're entrained very near the bellmouth. Similarly, many resting eggs of invertebrates are dense enough to sink and accumulate in bottom sediments. Since resting eggs and spores are not generally mobile, they are more likely to act like sediment particles, so we can speculate that resting eggs and spores may be discharged in proportion to sediment discharge during deballasting, while live mobile adult forms would be less likely to do so.

Duggan et al. (2005) estimated that, excluding all species already present in the Great Lakes, an average of ~26 million fresh and brackish water *nonindigenous* invertebrates (rotifers, cladocerans and copepods) may be present in the residual sediment of NOBOB vessels entering the Great Lakes annually, and another ~205,000 (average) may be present in residual water of NOBOB ballast tanks entering the Great Lakes annually. Since sediment-associated animals are believed to have a low probability of being swept out with discharging ballast water, Duggan et al. (2005) despite finding that residual sediments contain much higher densities of nonindigenous propagules overall, concluded that the greatest risk for introduction of invertebrates is associated with residual ballast water, because water-borne animals are much more likely to be entrained with discharging ballast water.

The above discussion about sediment-related organism discharge is highly speculative. Current knowledge about discharge of residual sediments, especially resting eggs and spores contained therein, and the effectiveness of BWE on sediments is insufficient to assess the risk NOBOB residuals and other sediments pose to the Great Lakes with a reasonable level of confidence. The volume of residual sediments is difficult to quantify and can vary quite widely among vessels. The discharge of sediment or organisms during deballasting has not been studied due to the inherent difficulties associated with access to ballast discharges during outflow. Ballast flow rates can vary considerably depending on the rate of intake or discharge needed for ship operations, and this will affect the amount of sediment resuspension and sediment and organism discharge.

3.6 Conclusions About BWE Regulations

When BWE requirements were implemented for the Great Lakes in 1993, ships with residual unpumpable ballast water from overseas were simply not recognized in the U.S. regulatory scheme (or in the earlier Canadian guidelines), which was put in place to specifically to address ballast water discharge. This was a potentially significant gap in the protection framework for the Great Lakes, and was not addressed until mid-2006, when new Canadian regulations specified a salinity requirement applicable to most vessels entering the Great Lakes, including those with tanks containing unpumpable water.

Coastwise vessels not traveling beyond the U.S. and Canadian EEZs were, and still are, also exempt under U.S. regulations, although recent Canadian ballast regulations exempt only Canadian coastwise vessels. The estimates and illustration presented in this Chapter do not account for the volume of unexchanged coastwise vessel ballast that may have entered and continues to enter the Great Lakes. Thus, even with increasingly strict enforcement of BWE requirements, resulting in high compliance rates for vessels arriving from overseas with pumpable ballast, there have been several gaps (NOBOBs and coastwise traffic) in the protection framework for which BWE is the centerpiece. Although the magnitudes of the risks associated with NOBOB and coastwise vessels cannot be calculated for the Great Lakes, it is clear that regardless of how effective BWE may be in reducing coastal and freshwater organisms in ballast water when conducted according to guidelines, the overall Great Lakes ecosystem protection framework was weakened by the gaps in application of ballast management regulations represented by these vessels.

These gaps resulted from several factors, including: a) lack of appreciation and understanding of the complexities of the shipping trade and the ballast water vector into the Great Lakes (thus ignoring NOBOBs until recently), b) lack of rapid development of technologies to solve the ballast discharge problem quickly and efficiently (which would essentially eliminate the risk from all vessels, even coastwise), and c) legislatively-driven mandates aimed at avoiding undue hardship on the domestic shipping industry (thus allowing coastwise trade to be exempt from BWE requirements). The true potential effectiveness of BWE can not be realized as long as it is not implemented and enforced on 100% of the vessels entering the Great Lakes and as long as some ships, even a small percentage, are exempt and thus allowed to carry and discharge unexchanged ballast water into the Great Lakes.

In the rest of this Chapter we examine the invasion record in the Great Lakes and how it relates to the ballast vector.

3.7 Analysis of Recent Great Lakes Aquatic Nonindigenous Species Invasion History

This section examines the composition of invaders recorded in the Great Lakes, as well as their rate of discovery, before and after BWE. It is substantially based on work already published by Ricciardi (2001, 2006). As discussed in Chapter 1, it is rare when we have indisputable verified records of the actual date of introduction or invasion of ANS, and this is especially true for those ANS attributed to the ballast (ship) vector. The rate of discovery is not an unbiased estimator or reliable surrogate for the actual rate of invasion on decadal and shorter time scales, and it is the latter that would be required to directly assess the cumulative effectiveness of BWE regulations to date. However, it is instructive to examine the history of ANS discovery and changes in the composition of new species over time.

3.7.1 Data compilation and statistical analyses

Ricciardi (2006) compiled and analyzed a comprehensive database of nonindigenous species of vascular plants, algae, invertebrates and fishes that have been reported as invaders in the Great Lakes basin (which includes each of the Great Lakes and their drainages, as well as the upper St. Lawrence River from the outflow of Lake Ontario to the Island of Montreal). For the purposes of this discussion, “nonindigenous species” are defined as species that have no previous evolutionary history in the Great Lakes basin and were introduced there during the past few hundred years, i.e. since the beginning of European colonization. Ricciardi (2006) identified a species whose evolutionary origin is unknown as "nonindigenous" if it met at least three of the following criteria: (1) the species appeared suddenly where it has not been recorded previously; (2) it subsequently spread within the basin; (3) its distribution in the basin is restricted compared with native species; (4) its global distribution is anomalously disjunct (i.e. contains widely scattered and isolated populations); (5) its global distribution is associated with human vectors of dispersal; and (6) the Great Lakes basin is isolated from the ecosystems possessing the most genetically and morphologically similar species.

In order to designate an invader as established within the Great Lakes basin, Ricciardi (2006) required records of multiple discoveries of adult and juvenile life stages over at least two consecutive years. Given that successful establishment often requires multiple introductions of an invader (Kolar and Lodge 2001), he deliberately excluded records of single discoveries of only one or a few non-reproducing individuals whose occurrence may reflect transient species or unsuccessful invasions (e.g. Manny et al. 1991, Fago 1993). Species that are considered indigenous to any part of the Great Lakes basin were also excluded, even though they may be expanding their range into new parts of the basin. For each identified invader, the year of its discovery (or year it was first documented in the literature when the actual date of discovery was not reported), its endemic region, and the most plausible mechanism of its introduction (usually provided in the published report of its discovery), were identified. In a few cases, Ricciardi (2006) replaced the year of first collection with the year of introduction when the latter could be estimated through analysis of archived samples or sediment cores (e.g. Edlund et al. 2000).

In order to examine and analyze the invasion history of the Great Lakes, each invader was assigned one of the following vector categories based on the most plausible means of introduction for that species: (1) shipping – transport by ballast water; (2) shipping – transport by hull fouling; (3) deliberate release (for cultivation and stocking); (4) aquarium release; (5) accidental release (including ornamental escape, research escape, bait bucket release, and unintended release of parasites/pathogens through fish stocking); (6) canals, used as a dispersal corridor; and (7) unknown or other vectors. In the case of multiple implicated vectors, the vector assumed responsible for the initial introduction to the basin was chosen. Transoceanic shipping was assumed to be the vector for species whose nearest potential source population was located overseas, with the exception of species known to be associated with organisms-in-trade commerce, such as the aquarium industry. Data were obtained from major reviews by Mills et al. (1993), MacIsaac (1999), Cudmore-Vokey and Crossman (2000), Bronte et al. (2003), Duggan et al. (2003), and Spencer and Hudson (2003), as well as through a literature search using internet databases (e.g. Aquatic Sciences and Fisheries Abstracts).

Ecological characteristics of free-living (i.e. non-parasitic, non-pathogenic, non-commensal) invaders assumed to have been transported to the Great Lakes basin by ships were compared during two time periods: 1960-1988 (prior to BWE guidelines) and 1994-2003, immediately after BWE became mandatory. The last year included in the records compiled by Ricciardi (2006) was 2003. Characteristics included in the comparison were the invader's endemic origin, whether the adult and juvenile stages are benthic or pelagic, whether the species possesses a resting stage, and whether the species is euryhaline – as inferred from whether it occurs in brackish water as well as freshwater habitats. Fisher Exact Tests on categorical data were used to evaluate whether ballast water regulation and the increasing prevalence of NOBOB ships have imposed filters that are permeable to euryhaline benthic organisms with resting stages. Species discovered during the transition period from 1989-1993 were not included, because voluntary guidelines introduced by Canada were in place starting in 1989, but the mandatory regulations implemented by the United States were not implemented until mid-1993. Records provided by the U.S. Coast Guard (see Figure 3-3) suggest varying levels of compliance with BWE guidelines before the mandatory regulations were in effect, but much higher and consistent compliance shortly after mandatory BWE regulation and enforcement. Thus there is no clear basis for determining in which category (pre- or post-BWE) the species discovered during this transition should be included.

3.7.2 Invasion status of the Great Lakes

Since the early 19th century, over 180 nonindigenous species have invaded the Great Lakes (Ricciardi 2006), none of which have been totally eliminated. This is a conservative estimate, because potentially many additional invasions have gone undetected (cf. Taylor and Hebert 1993). Over 40% of all Great Lakes ANS have been discovered since the opening of the St. Lawrence Seaway in 1959, which is singularly the most significant event relevant to Great Lakes shipping and the ballast vector other than the 1993 implementation of BWE regulations. The average rate of species discovery attributable to all vectors since 1960 through 2003 is 1.8 species per year, or one new successful invader, on average, approximately every 29 weeks (Figure 3-7). This discovery rate is higher than any other freshwater system for which long-term data exist (Biró 1997, Mills et al. 1997, García-Berthou and Moreno-Amich 2000, Sytsma et al. 2004). It is comparable to the rates observed for some coastal marine regions (e.g. Chesapeake Bay, see Chapter 5 of this report), placing the Great Lakes among the most highly invaded aquatic ecosystems in the world.

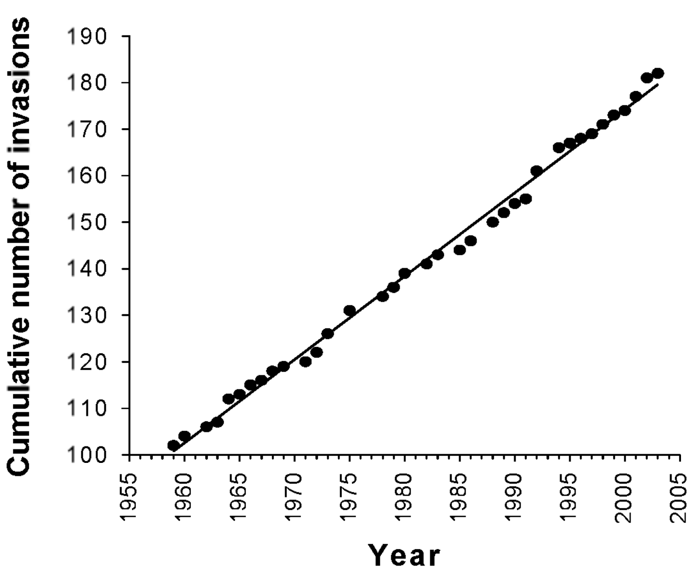

Figure 3-7: Accumulation of invaders discovered in the Great Lakes basin from 1959 through 2003. After Ricciardi (2006).

3.7.2.1 The role of transoceanic shipping

Ricciardi (2006) calculated that between 1960 and 1988, the average rate of discovery in the Great Lakes of free-living non-parasitic invaders attributed to shipping was 1.0 species per year. For the period 1994 to 2003, during which BWE was mandatory, the average rate of discovery was 0.9 species per year, not significantly different. However, as discussed in Chapter 1, the interpretation of invasion history from discovery records must be approached with caution because of potential biases in the data and how data are collected. The distinction between free-living and parasitic plus pathogenic species is important, since the latter are more likely to have entered with a host species and thus would not represent separate invasions. In addition, parasites are generally not easily noticed unless they are specifically targeted, and new technologies have made detection and identification of parasites and pathogens easier and more accurate in recent decades. During the early 1990s targeted assessments of parasites and pathogens associated with recent fish invaders (gobies, ruffe) resulted in 8 new species being documented. While their discovery is recorded in the mid-1990s, their host species were already present prior to 1992. This is a good example of how an increased level of scrutiny can produced biased results if the assigned discovery dates are taken as equivalent to date of invasion. Therefore, parasites and pathogens were not included in this evaluation.

Some of the species discovered after 1993 may have escaped detection for many years and thus could represent pre-BWE introductions. An example is the Ponto-Caspian amphipod, *Echinogammarus ischnus*, discovered in 1994, and three nonindigenous testate amoebae discovered in 2001 and 2002. Conversely, other invaders were likely detected soon after their introduction. One example of the latter is the fishhook waterflea *Cercopagis pengoi*, which was discovered in Lake Ontario in 1998 (MacIsaac et al. 1999). Given its unique morphology, conspicuous behavior in the open water, and its rapid rate and multiple modes of reproduction, it is suspected to have resided in the Great Lakes for only a few years, at most, prior to being detected. A construction of a basic population model of the species suggests that it could achieve observed population densities within only two years (Dr. Hugh MacIsaac, University of Windsor, pers. comm.). Two additional crustaceans discovered in nearshore sediments of Lake Michigan in the late-1990s, the Ponto-Caspian copepod *Schizopera borutzki* and another copepod *Heteropsyllus* sp. may have been recent invasions because they dominated the areas in which they were found but did not appear in previous intensive surveys of benthic crustaceans in the lake (Horvath et al. 2001). The bloody-red mysis, *Hemimysis anomala* (Pothoven et al. 2007) is another example of an invader that is suspected of having been introduced after implementation of BWE. Although it's a nocturnal organism that is difficult to locate because it avoids brightly lit areas and prefers to hide during daylight in rocky cracks and crevices near the bottom, it also exhibits a unique swarming behavior that improves the chances that it would be noticed during daylight. This is how it was first observed near Muskegon, Michigan in 2006 (reconfirmed in April 2007). On the other hand it was reported in the Baltic Sea in 1992 and many of the recent Great Lakes invaders are believed to come from the Baltic after they invaded there. It is possible that any of the species in the above examples could have been delivered to the Great Lakes in the early 1990s or before, and simply not discovered right away.

Table 3-5 summarizes the discovery records for ten-year periods starting in 1939, two decades prior to opening of the Seaway, through 2003. The years 1989-1993 are not included since these were the transition years during which BWE was voluntary and resulted in only partial compliance with BWE procedures. In addition, a number of parasites and pathogens reported during 1994-2003 were the result of specifically targeted research focused on a small number of fish invaders, and therefore are also not counted. As seen in Table 3-5 the average number of new free-living ANS attributed to shipping per decade increased dramatically with the opening of the Seaway in 1959, and has varied within a small range since then, averaging 10 ± 0.8 (s.d.). Examination of the total record shows that about 2/3 of the free-living ANS discovered since the Seaway opened (1960-2006) are attributed to shipping, whereas for the equal period of time prior to the opening of the Seaway (1912-1958), only ~20% of the free-living ANS discovered in the Great Lakes were attributed to shipping.

Table 3-5: Discovery record by decade of nonindigenous aquatic species (all vectors) in the Great Lakes since 1939. BWE transition period 1989-1993 is not included.

Decade	Total Number of Free Living ANS Discovered (All Vectors)	Number of Free Living ANS Attributed to Shipping
1939-1948	6	2
1949-1958:	13	1
1959-1968	17	11
1969-1978	15	9
1979-1988	14	10
1994-2003	13	10
Decade Average since 1959	15	10
standard dev.	1.7	0.8

Table 3-5 summarizes the discovery records for ten-year periods starting in 1939, two decades prior to opening of the Seaway, through 2003. The years 1989-1993 are not included since these were the transition years during which BWE was voluntary and resulted in only partial compliance with BWE procedures. In addition, a number of parasites and pathogens reported during 1994-2003 were the result of specifically targeted research focused on a small number of fish invaders, and therefore are also not counted. As seen in Table 3-5 the average number of new free-living ANS <u>attributed to shipping</u> per decade increased dramatically with the opening of the Seaway in 1959, and has varied within a small range since then, averaging 10 ± 0.8 (s.d.). Examination of the total record shows that about 2/3 of the free-living ANS discovered since the Seaway opened (1960-2006) are attributed to shipping, whereas for the equal period of time prior to the opening of the Seaway (1912-1958), only ~20% of the free-living ANS discovered in the Great Lakes were attributed to shipping.

Multiple environmental factors are suspected of contributing to successful invasions of aquatic ecosystems, including increased disturbance, increased opportunities for invasion, and facilitative interactions among nonindigenous species (Ricciardi 2001, Holeck et al. 2004). The opening of the St. Lawrence Seaway in 1959 permitted the influx of larger vessels carrying greater volumes of ballast water and sediments into the Great Lakes. Domestic vessels have provided a secondary vector that can spread these propagules between ports throughout the Great Lakes, thereby contributing to the potential for successful invasions by giving introduced organisms more opportunities to encounter suitable habitat. A simple proxy for potential propagule pressure exerted by the total shipping activity affecting the Great Lakes is the net cargo tonnage of ships visiting all Great Lakes ports. Ricciardi (2006) tested the relationship between the number of discovered invaders and shipping activity in the Great Lakes per decade by regression analysis of the net tonnage of cargo ships (both foreign and domestic vessels) averaged over each decade from 1900 to 1999 (Figure 3-8; shipping data were obtained from the Lake Carriers' Association (1999)). This relationship explains more than half of the variation in the number of invaders (algae, fishes and free-living-non-parasitic invertebrates) attributed to a ship vector over the past century.

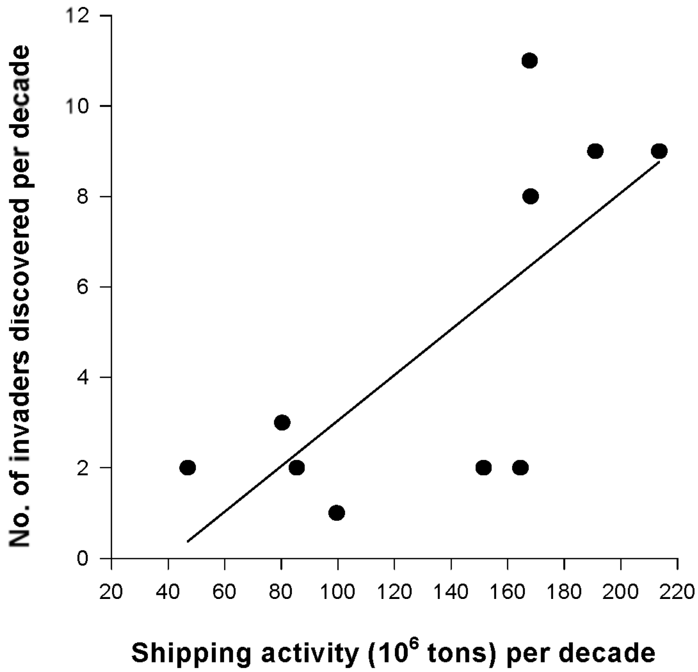

Figure 3-8: Number of free-living invaders presumed introduced by ships versus shipping activity in the Great Lakes. Shipping activity is measured in net tonnage of cargo ships (both foreign (overseas) and domestic vessels) averaged over all years within each decade. Line fitted by least-squares regression (r2=0.51, P<0.019). Shipping data are from Lake Carriers' Association (1999). After Ricciardi (2006).

3.7.2.2 Other Lines of Evidence

Records of introduced species that failed to invade

Since 1959, there have been multiple discoveries in the Great Lakes of benthic, brackish-water organisms that have failed to establish reproducing populations (i.e. failed to invade). These discoveries have continued even after ballast water regulations were implemented and include adult Chinese mitten crab *Eriocheir sinensis* in 1994, 1996, and in 2005 (Leach 2003; Vicki Lee, Ontario Ministry of Natural Resources, pers. comm.; P. Fuller, http://nas.er.usgs.gov/), European flounder *Platichthys flesus* in 1994, 1996, and 2000 (Leach 2003; A. Niimi, Canada Centre for Inland Waters, pers. comm.), and the Ponto-Caspian amphipod crustacean *Corophium mucronatum* in 1997 (Grigorovich and MacIsaac 1999). The most plausible vector responsible for the introduction of each of these species is ballast water release from overseas shipping. European flounder and Chinese mitten crab are incapable of establishing reproducing populations in fresh water (Gutt 1985, Anger 1991) and, indeed, no young-of-the-year individuals for either species have been reported from the Great Lakes. A European flounder collected from Lake Erie in the year 2000 was estimated to be approximately 7 years old (A. Niimi, pers. comm.), suggesting it was introduced at about the time BWE became mandatory. The lifespan of Chinese mitten crabs is <5 years (Jin et al. 2002, Rudnick et al. 2005), so at least some of these discoveries – such as in L. Erie in March 2005 and in L. Superior in December 2005 – are most likely the result of recent ballast water introductions rather than an extensive time lag between a pre-1993 introduction and subsequent detection.

Table 3-7 (page 87) lists the species discovered in the Great Lakes from 1994 through 2003. Figure 3-9 compares the composition of Great Lakes invaders with attributes hypothesized to affect their introduction under ballast-water regulation, for the periods 1960-1988, and 1994-2003. The composition appears to have changed after ballast water regulation, but the results should be interpreted with caution, given the relatively small number of invaders in the post-1993 comparison. Great Lakes invaders attributable to shipping after 1993 are more likely to be euryhaline organisms with benthic juvenile and adult lifestyles. There was no significant change in the proportion of species with resting stages. The resting stages (diapausing eggs) of several species of zooplankton are resistant to seawater exposure (Bailey et al. 2004, Gray 2005). Interestingly, Duggan et al. (2005) documented the predominance of benthic invertebrates in the residual ballast material of NOBOB ships and NOBOB ships became the dominant foreign trade into the lakes during the 1980s through the present (Figure 3-2, page 49).

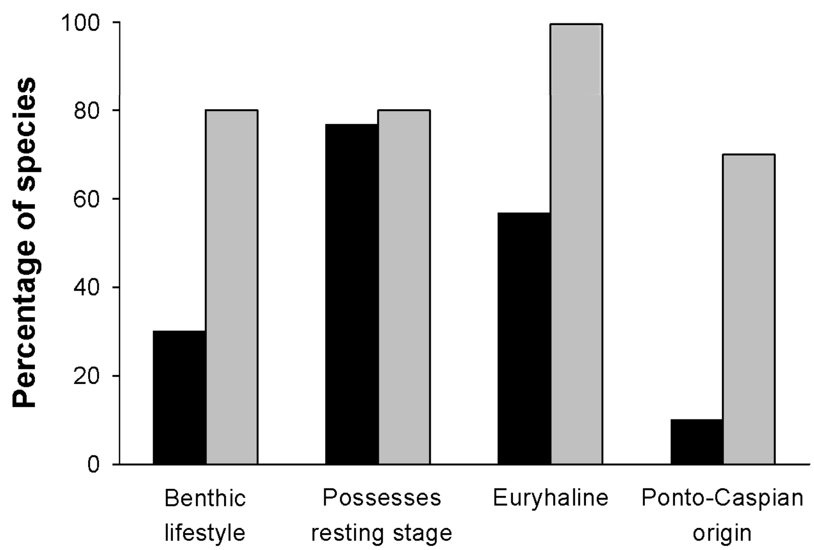

Figure 3-9: Proportions of Great Lakes invaders possessing attributes hypothesized to affect their introduction under ballast-water regulation. Results are shown for free-living species whose introduction is attributed to shipping from 1960 to 1988 (black bars) and from 1994 to 2003 (grey bars). Differences between time periods are significant for benthic species (Fisher 2-tailed test, p=0.009), euryhaline species (p=0.016) and Ponto-Caspian species (p=0.0006). After Ricciardi (2006).

3.7.2.3 The Ponto-Caspian Connection

Most of successful Great Lakes invaders recorded since the opening of the St. Lawrence Seaway are Eurasian in origin and over the past three decades, there have been increasing discoveries of invaders that are native to the Black and Caspian Seas ("Ponto-Caspian") region (Ricciardi and MacIsaac 2000, Grigorovich 2003, Pothoven et al. 2007). The establishment of these species in the Great Lakes coincides with the spread of Ponto-Caspian species into Western European ports, from which the Great Lakes receives the bulk of its shipping traffic (Figure 3-5).

Post-BWE invaders, including parasites and pathogens, are also more likely to be native to the Ponto-Caspian region of Eurasia (Figure 3-9), although those found in the Great Lakes are likely to have come by way of another invaded ecosystem, such as the Baltic Sea (Ricciardi and MacIsaac 2000, Ricciardi 2006), rather than directly from the Ponto-Caspian region. Ponto-Caspian organisms comprised ~10% of free-living non-parasitic invaders attributed to ballast-water and recorded between 1960 and 1988 and ~70% for 1994-2003. More Ponto-Caspian species have been discovered in the Great Lakes system since 1993 than in any other time period (Ricciardi 2006). The reason for this increase is unknown but appears coincidental with increasing colonization of European ports by these species (Ricciardi and MacIsaac 2000). The most recent Great Lakes aquatic invader, *Hemimysis anomala* (Pothoven et al. 2007) is also native to that region, and invaded the Baltic Sea in 1992. The predominance of Ponto-Caspian animals after 1993 may be linked, in part, to their evolved tolerance to broad salinities (Dumont 1998, Reid and Orlova 2002), which may allow them to survive an incomplete BWE or transport in low-salinity residual ballast of NOBOB vessels.

The apparent susceptibility of the Great Lakes to Ponto-Caspian species (Ricciardi and MacIsaac 2000) is significant because previous Ponto-Caspian invaders (such as the zebra mussel, quagga mussel, fish-hook waterflea, and round goby) have caused substantial ecological impacts in the Great Lakes and elsewhere (Vanderploeg et al. 2002). Dozens of Ponto-Caspian species continue to spread to and dominate biota in western European ports, from which they have multiple opportunities for transport to the Great Lakes via NOBOB ships (Ricciardi and Rasmussen 1998, Bij de Vaate et al. 2002, Johengen et al. 2005). Kolar and Lodge (2001) identified three Ponto-Caspian fish, and Ricciardi and Rasmussen (1998) identified 14 Ponto-Caspian invertebrates (including *H. anomala*) as likely future invaders to the Great Lakes - St, Lawrence River system. Moreover, the invasion history of several of these species in Europe suggests that they could exert strong ecological impacts if they become established in the Great Lakes (Ricciardi & Rasmussen 1998).

It should be noted that not a single nonindigenous species, <u>once established in the Great Lakes basin</u>, is known to have subsequently disappeared or been successfully eradicated. Thus, there has been an accumulation, rather than a turnover, of nonindigenous species over time. Because nonindigenous species can interact in ways that exacerbate each other's impacts (e.g. interactions between quagga mussels and round gobies have caused recurring outbreaks of avian botulism in Lake Erie; see Ricciardi 2001, Holeck et al. 2004), the continued accumulation of invaders may lead to a greater frequency of synergistic disruptions.

3.7.3 Summary and Conclusions

By examining the vessel traffic history and record of discovery of new aquatic nonindigenous species over time in the Great Lakes, we have found that

a) The opening of the St. Lawrence Seaway in 1959 permitted the influx of more and larger vessels carrying large volumes of ballast water and ballast sediments into the Great Lakes, and was associated with an increase in the discovery of new aquatic invaders consistent with ballast water being a significant vector.

b) Estimates of Great Lakes saltwater vessel traffic and changes in vessel and ballast characteristics pre- (1978-1988) and post- (1994-2004) BWE suggest a possible 76% reduction in the average total amount of ballast potentially carried into the Great Lakes.

c) For a scenario using ballast quantity as a simple coarse surrogate for propagule supply, and applying a 90% reduction of live organisms due to BWE, we estimated an average decrease in total potential ballast quantity (and therefore, potential propagule supply) between pre- and post-BWE periods of ~97%, equivalent to eliminating an average of ~3.3 millions t per year of unexchanged ballast water for the 11 years (1994-2004) after implementation of BWE regulations compared to an equal period prior to BWE (1978-1988).

d) Changes in economic factors that affected trade, changes in shipping practices, and implementation of BWE regulations all contributed to decreasing the propagule supply to the Great Lakes.

e) Even with increasingly strict enforcement of BWE requirements, resulting in high compliance rates for vessels arriving from overseas with pumpable ballast, there have been several gaps (NOBOBs and coastwise traffic) in the protection framework for which BWE is the centerpiece.

f) Although the magnitudes of the risks associated with NOBOB and coastwise vessels cannot be calculated for the Great Lakes, it is clear that regardless of how effective BWE may be in reducing coastal and freshwater organisms in ballast water when conducted according to guidelines, the overall Great Lakes ecosystem protection framework was weakened by the gaps in application of ballast management regulations represented by these vessels.

g) The average rate of ANS discovery in the Great Lakes ecosystem <u>attributable to all vectors</u> since 1960 through 2003 was 1.8 species per year, or one new successful invader discovered every 29 weeks. This discovery rate is higher than any other freshwater system for which long-term data exist and places the Great Lakes among the most highly invaded aquatic ecosystems in the world. However, discovery rate is not the same as invasion rate and the latter cannot be measured with existing methods.

h) About 2/3 of all Great Lakes ANS discovered since the opening of the Seaway are attributed to the shipping vector. After 1993 they are more likely to be euryhaline organisms with benthic adult and juvenile lifestyles, and are more likely to be natives of the Ponto-Caspian region of Eurasia. The establishment of these species in the Great Lakes coincides with their spread into western European ports from which the Great Lakes receives the bulk of its shipping traffic.

i) An important step forward in protecting the Great Lakes was the implementation in 2006 of Canadian requirements that all ballast water, including NOBOB residual water, be at salinity of 30 or greater. If these requirements prove equally effective as BWE, we would expect significant additional reductions in the propagule supply due to this vector.

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Table 3-6: Densities of Organisms Collected in Ballast Tanks

(From "Ships' Ballast Water and the Introduction of Exotic Organisms into the San Francisco Estuary: Current Status of the Problem and Options for Management" Andrew N. Cohen, San Francisco Estuary Institute. October 1998. Edited and with additions.)

Range, Maximum or Mean Density of Organisms (individuals per metric tonne)		Mesh Size of Collecting Device	Study
All organisms (except bacteria and viruses)			
	Range = 1300-14,000 Mean = 5700	80 µm	Ruiz & Hines 1997
	Range = 0 - 14,960 Mean = 750 in non-exchanged tanks: Mean = 35 in exchanged tanks	80 µm	Smith et al. 1996
Virus-like particles			
	70 trillion	??	Ruiz et al.2000
	10 trillion-1 quadrillion	NOBOB residual water	Johengen et al.2005
	10 trillion-100 quadrillion	NOBOB sediment pore water	Johengen et al.2005
Bacteria			
	830 billion	??	Ruiz et al.2000
	100 billion-1 quadrillion	NOBOB residual water	Johengen et al.2005
	10 billion – 100 trillion	NOBOB sediment pore water	Johengen et al.2005
	Bacteria & autotrophic plankton max = 2.2 trillion	sedimented wholewater samples	Subba Rao et al. 1994
Phytoplankton			
	≈1540 ≈10	80 µm on a 17 day voyage in cargo hold: ≈at start ≈at end	Wonham et al. 1996
	≈880 ≈0	80 µm on a 17 day voyage in deck tanks: ≈at start ≈at end	Wonham et al. 1996
Diatoms			
	max = 59,390	80 µm	Bio-Environmental Services 1981
	range = 0 to 1210 mean = 790	80 µm	Ruiz & Hines 1997
	max = 2.4 billion	sedimented wholewater samples	Subba Rao et al. 1994

Table 3-6 (continued): Densities of Organisms Collected in Ballast Tanks

	Range, Maximum or Mean Density of Organisms (individuals per metric tonne)	Mesh Size of Collecting Device	Study
Dinoflagellates			
	max = 350	80 µm	Bio-Environmental Services 1981
	range = 0 to 260 mean = 50	80 µm	Ruiz & Hines 1997
	max = 3.1 million	sedimented wholewater samples	Subba Rao et al. 1994
	Dinoflagellate cysts Range = 80 million-850 million	NOBOB sediments	Johengen et al.2005
	toxic dinoflagellate cysts max = 13 billion	20 µm in tank-bottom sediments:	Hallegraeff & Bolch 1992
	dinoflagellate cysts max = 19 billion	20 µm in tank-bottom sediments:	Hallegraeff & Bolch 1992
Other Algae (not Diatoms or Dinoflagellates)			
	max = 189,180	80 µm	Bio-Environmental Services 1981
All Animals			
	Mean = 1,300,000	Combined, NOBOB sediment	Johengen et al.2005
	Mean = 10,898	Combined, NOBOB residual water	Johengen et al.2005
Zooplankton			
	range = 11 to >57,190	41 µm	Locke et al. 1993
	≈6600 ≈70	80 µm on a 17 day voyage in cargo hold: ≈at start ≈at end	Wonham et al. 1996
	≈2200 ≈0.09	80 µm on a 17 day voyage in deck tanks: ≈at start ≈at end	Wonham et al. 1996
Flagellates			
	max = 13 billion	sedimented wholewater samples	Subba Rao et al. 1994
Ciliates			
	max = 1450	80 µm	Bio-Environmental Services 1981
	max = 8.6 million	sedimented wholewater samples	Subba Rao et al. 1994

Table 3-6 (continued): Densities of Organisms Collected in Ballast Tanks

	Range, Maximum or Mean Density of Organisms (individuals per metric tonne)	Mesh Size of Collecting Device	Study
Rotifers			
	max = 147,380	80 µm	Bio-Environmental Services 1981
	max = 43,990	41 µm	Locke et al. 1993
Cladocerans			
	max = 549,450	80 µm	Bio-Environmental Services 1981
	max = 28,600	41 µm	Locke et al. 1993
Copepods			
	max = 57,190	80 µm	Bio-Environmental Services 1981
	max = about 880	80 µm	Chu et al. 1997
	range = 11 to 8360 mean = 3080	80 µm	Ruiz & Hines 1997
	>1250	80 µm	Carlton & Geller 1993
	max =3960	153 µm	Carlton et al. 1982
	max = 17,600	41 µm	Locke et al. 1993
	max = 330,000	sedimented wholewater samples	Subba Rao et al. 1994
Invertebrate Resting Stages			
	Range = 40,000 – 91,000,000 Mean = 3.6 million	NOBOB sediment	Johengen et al.2005
Nematodes			
	max = 3080	80 µm	Bio-Environmental Services 1981
Annelids			
	max = 140	80 µm	Bio-Environmental Services 1981
	range = 0.4 to 1030 mean = 260	80 µm	Ruiz & Hines 1997
Polychaetes			
	max = 20	153 µm	Carlton et al. 1982
	>160	80 µm	Carlton & Geller 1993

Table 3-6 (continued): Densities of Organisms Collected in Ballast Tanks

	Range, Maximum or Mean Density of Organisms (individuals per metric tonne)	Mesh Size of Collecting Device	Study
Molluscs			
	max = 1010	80 µm	Bio-Environmental Services 1981
	>160	80 µm	Carlton & Geller 1993
	max = 9	153 µm	Carlton et al. 1982
	range = 1 to 3960 mean = 570	80 µm	Ruiz & Hines 1997
Barnacles			
	range = 10 to 3520 mean = 590	80 µm	Ruiz & Hines 1997
	>160	80 µm	Carlton & Geller 1993
	max = 680	80 µm	Bio-Environmental Services 1981
	max = 260	153 µm	Carlton et al. 1982
Crustaceans			
	range = 70 to 770	80 µm	Wang 1990

Table 3-7: Established nonindigenous species discovered in the Great Lakes, 1994-2003.

Species name	Common name	Year of discovery	Vector of introduction
Scolex pleuronectis	*cestode*	*1994*	*shipping*
Neoergasilus japonicus	*copepod*	*1994*	*unknown*
Megacyclops viridis	*cyclopoid copepod*	*1994*	*unknown*
Sphaeromyxa sevastopoli	*mixosporidian*	*1994*	*shipping*
Echinogammarus ischnus	*amphipod*	*1994*	*shipping*
Alosa aestivalis	*blueback herring*	*1995*	*canals*
Heteropsyllus nr. nunni	*harpacticoid copepod*	*1996*	*shipping*
Acineta nitocrae	*suctorian*	*1997*	*shipping*
Cercopagis pengoi	*fish-hook waterflea*	*1998*	*shipping*
Schizopera borutzkyi	*harpacticoid copepod*	*1998*	*shipping*
Nitocra incerta	*harpacticoid copepod*	*1999*	*shipping*
Daphnia lumholtzi	*waterflea*	*1999*	*unintentional release*
Heterosporis sp.	*microsporidian*	*2000*	*unknown*
Rhabdovirus carpio	*spring viraemia of carp*	*2001*	*unintentional release*
Gammarus tigrinus	*amphipod*	*2001*	*shipping*
Psammonobiotus communis	*testate amoeba*	*2001*	*shipping*
Psammonobiotus sp.	*testate amoeba*	*2002*	*shipping*
Psammonobiotus linearis	*testate amoeba*	*2002*	*shipping*
Piscirickettsia cf. salmonis	*muskie pox*	*2002*	*unknown*
Largemouth Bass Virus	*iridovirus*	*2002*	*unintentional release*
Enteromorpha flexuosa	*green alga*	*2003*	*shipping*
Novirhabdovirus sp.	*Viral Hemorrhagic Septicemia (VHS)*	*2003*	*unknown*

4 CHESAPEAKE BAY: CHANGES IN BALLAST WATER MANAGEMENT & DELIVERY

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4.1 Introduction

In the Chesapeake Bay region, both Maryland and Virginia have state laws concerning ballast water management. These primarily focus on reporting requirements to each state and do not require specific ballast water management. Thus, the regulations for ballast management in the Chesapeake are the federal regulations, which established voluntary guidelines following the passage of the National Invasive Species Act (1996), with mandatory regulations beginning in September 2004 (see Chapter 1).

In this section, we examine the temporal changes in ballast water management and delivery for the Chesapeake Bay during the years 1993 – 2004, using multiple overlapping data sets described below. We use several sources of information to estimate (a) the annual number of commercial ship arrivals from foreign versus domestic ports, (b) the percentage of ship arrivals carrying foreign and domestic ballast water, (c) the volume discharged by foreign arrivals according to ship type, (d) the percent of foreign arrivals reporting BWE, and (e) the concentrations of zooplankton associated with unexchanged versus exchanged ballast water of foreign arrivals.

4.2 Methods

A comprehensive picture of shipping and ballast water delivery to the Chesapeake Bay required the use of multiple overlapping data sets containing various information types. These datasets include information on vessel traffic (i.e., ship arrivals compiled by Marine Exchanges and MARAD), ballast water delivery and management (as derived from the NBIC database and SERC interviews), and ballast-borne biota (collected by SERC through direct ballast tank sampling). These data were collected independently over a 12 year period (1993-2004, Figure 4-1).

The first dataset represents the arrivals from 1994-2004 as reported by the two major port complexes in Chesapeake Bay, the Baltimore Maritime Exchange in Baltimore, Maryland and the Hampton Roads Maritime Exchange in Norfolk, Virginia, hereafter *Maritime Exchange data*. The data for 1997 were unavailable from the Hampton Roads Maritime Exchange, and thus 1997 was excluded from the Maritime Exchange dataset. The second dataset represents "entry records" (arrivals) from 1994-2004 as indicated by the U.S. Foreign Waterborne Transportation Statistics maintained by the Department of Transportation's Maritime Administration (MARAD), hereafter *MARAD data*. The third dataset, NBIC data, is composed of BW Reports submitted by vessels equipped with ballast tanks arriving to US ports and places of destination. Importantly, these data encompass the US Coast Guard's regulatory requirements for ships which have changed substantively over time. Beginning on July 1, 1999, voluntary ballast water management and mandatory reporting to the National Ballast Information Clearinghouse (NBIC) were required for all vessels which had operated outside the US EEZ (foreign arrivals) prior to arrival at a US port or place of destination. As of August 13, 2004, mandatory reporting was expanded to include domestic arrivals and monetary and civil penalties were imposed for non-compliance (Federal Register, 69 FR 32864). On September 27, 2004, mandatory Ballast Water management with penalties went into effect for all foreign arrivals (Federal Register, 69 FR 44952). Therefore, NBIC data from September 27 to December 31, 2004 are presented here as *post-penalty NBIC* data and provide the best available information on the current extent of ballast water reporting, discharge, and exchange for arrivals to the Chesapeake Bay. The fourth and final dataset was collected from 1993–2000 during vessel boardings by Smithsonian scientific staff in the ports of Baltimore and Norfolk, hereafter *SERC boardings*. These included a crew interview and zooplankton sampling of some ballast water tanks. Since bulkers are the dominant foreign arriving ship type (see Section 4.3.1) and they discharge the greatest volume of ballast water (see Section 4.3.2), they were the primary ship type sampled by SERC. Due to the multiple sources of these data, it was not possible to examine all aspects of ballast water management and delivery for all data sets over the entire time period, but a timeline is presented in Figure 4-1 to clarify these different datasets.

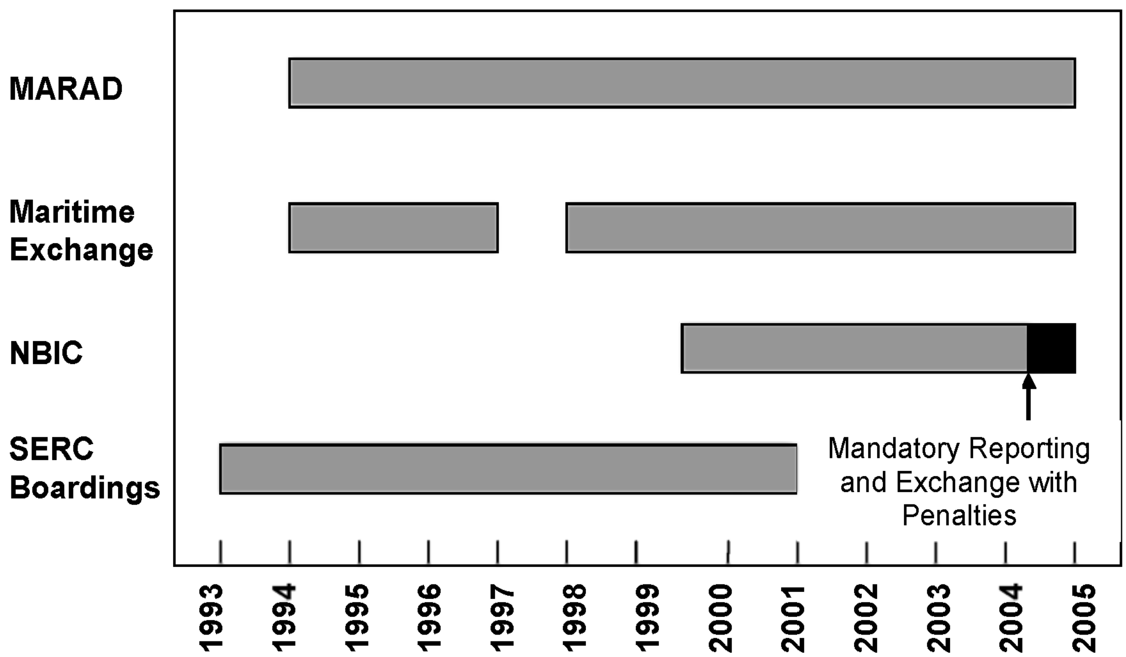

Figure 4-1: Timeline of the datasets used to analyze changes in ballast water management and delivery to Chesapeake Bay. The MARAD and Maritime Exchange datasets are comprised of arrival information. Maritime Exchange arrivals were unavailable in 1997. NBIC data collection began July 1, 1999 from ballast water reports.

4.2.1 Chesapeake Bay Vessel Traffic

The history of vessel traffic arriving in Chesapeake Bay was compiled for the time period 1994–2004 from the MARAD data and the Maritime Exchange Data (Figure 4-1). The number of yearly arrivals was compared with a paired t-test. Using the MARAD dataset, which indicates last port of call, the numbers of domestic and foreign arrivals to Chesapeake Bay were determined pursuant to Coast Guard regulations (i.e., arrivals to U.S. ports from Canada are considered as domestic arrivals and arrivals from Puerto Rico or the U.S. Virgin Islands are considered as foreign arrivals). The consistency in the composition of arrivals (i.e., domestic and foreign arrivals) between the two sources was tested using the chi-squared test of independence.

4.2.2 Ballast Water Delivery & Management for Chesapeake Bay

Ballast water discharge into Chesapeake Bay was characterized based upon reports submitted to the National Ballast Information Clearinghouse (NBIC) from 1999-2004. Reporting compliance to NBIC prior to the implementation of non-reporting penalties was approximately 34 ± 4.7% (± 1 s.d.) of foreign arrivals, while reporting compliance in Chesapeake Bay of both foreign and domestic arrivals was approximately 77% (1,000 NBIC total arrivals and 1,302 MARAD total arrivals) for the post-penalty time period,

We used the post-penalty NBIC data to estimate the percentage of both foreign and domestic arrivals to Chesapeake Bay carrying ballast water. We estimated the volume of foreign ballast water discharged into the Chesapeake from the NBIC dataset, 1999-2004. The mean volume of individual discharges and the total volume discharged were calculated for Bulk Carriers (Bulkers), Container Ships (Containers), and all other types of vessels, including tankers, RORO, Passenger vessels, general cargo carriers, etc.

Finally, we characterized changes in the management of ballast water for the period of 1993 – 2004. We estimated the annual percentage of bulkers discharging foreign ballast water that conducted some degree of BWE from both ship interviews (SERC boarding data, 1993-2000) and from the NBIC data for which there were complete years, 2000-2004 (Figure 4-1). This enabled us to examine temporal changes in ballast water treatment for this vessel type. To estimate the present effect of the U.S. Coast Guard regulations on mandatory BWE, the percentage of arrivals discharging foreign and domestic ballast water that underwent some degree of BWE was calculated for bulkers, containers, and other ships based on the post-penalty NBIC data.

4.2.3 SERC Ship Sampling in Chesapeake Bay

From 1993-2000 SERC staff boarded ships (n = 406) arriving in Norfolk, VA and Baltimore, MD to interview the crew to document the last port of call, the type of ship, ballast water source and management history (Figure 4-1). In addition, ballast tanks of 145 ships (113 unexchanged tanks, 52 exchanged tanks) were sampled to estimate zooplankton density. Ballast tanks were sampled with two net tows using 80 µm plankton nets, and the number of zooplankton per sample was determined using a stereo-microscope (see Smith et al. 1999 for discussion of methods). The two samples per tank were averaged to provide an estimate of the zooplankton density for each tank. The majority of this sampling effort was focused on bulk carriers, due to the relatively large volume of ballast water delivered per ship and cumulatively to the Chesapeake by this vessel type (Carlton et al. 1995, Smith et al. 1999; see results below).

The zooplankton densities of unexchanged ballast tanks represent the density of coastal or estuarine zooplankton surviving entrainment in the ballast tank and transport to Chesapeake Bay, while the zooplankton densities in exchanged ballast tanks represent the total zooplankton, of both coastal and oceanic origin. The effects of BWE and season when ballasted (i.e., warm: April – September; cold: October – March) were analyzed with a 2-way ANOVA. To estimate the effect of BWE, we assumed a 90% reduction from the observed zooplankton densities in unmanaged ballast tanks (see Chapter 2; Ruiz unpublished data; n >30 experimental voyages).

4.3 Results

4.3.1 Chesapeake Bay Vessel Traffic

The mean number of vessel arrivals to Chesapeake Bay remained fairly constant between 1994 and 2004 and averaged 4593 and 4726, as reported by the maritime exchanges and MARAD, respectively (Figure 4-2). The total yearly arrivals to the Chesapeake Bay were not significantly different between the Maritime Exchanges and MARAD data ($P = 0.396$). The majority of arrivals are domestic, meaning that the last port of call was another U.S. or Canadian port on the Atlantic Coast or the Gulf of Mexico. The proportion of foreign arrivals differed significantly across years ($P < 0.001$) and ranged between 23.5% and 29.5%.

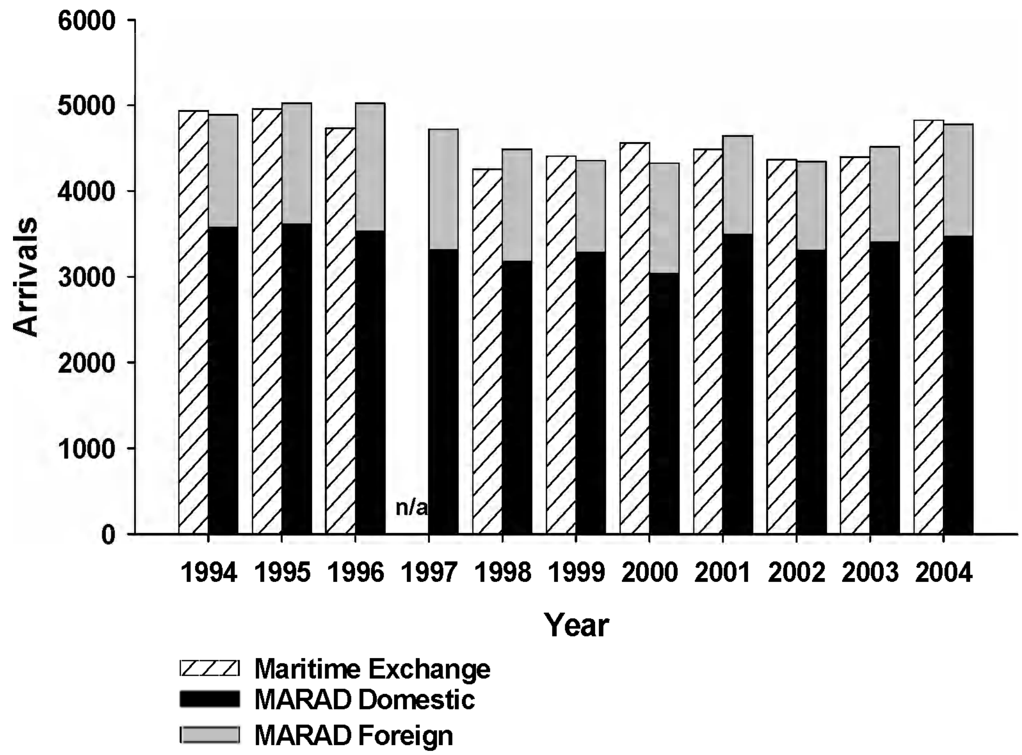

Figure 4-2: Arrivals to Chesapeake Bay based upon reports to the Baltimore and Hampton Roads Maritime Exchanges and to MARAD from 1994 – 2004. MARAD Arrivals were characterized as foreign or domestic arrivals based upon the last port of call. (Note: Arrival records from the Hampton Roads Maritime Exchange were unavailable in 1997).

Based upon the MARAD data from 1995-2004, the years with defined vessel types, there were clear differences in the type of vessels involved in the domestic vs. foreign shipping traffic (Figure 4-3). The domestic arrivals were dominated by container vessels, while bulkers were the largest individual type of vessel among foreign arrivals. The "Other" category included vessels of unspecified type, as well as, tankers, RORO, general cargo vessels, passenger vessels, etc. In 2001, there was a larger than normal number of arrivals in the MARAD data that were of unspecified vessel type, shown in Figure 4-3 as an increase in the "other" vessel type.

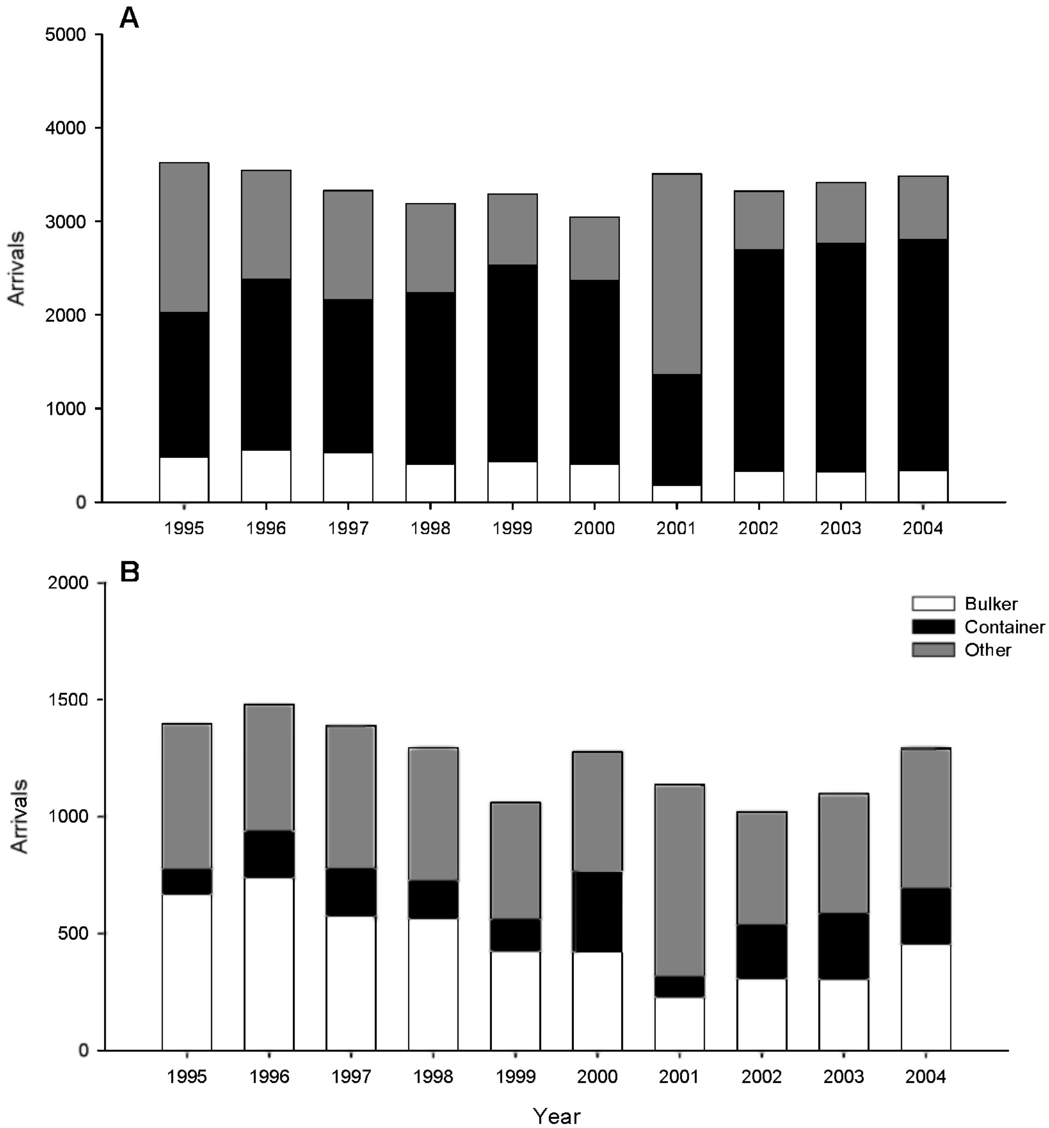

Figure 4-3: Arrivals to Chesapeake Bay by the type of vessel. A) Domestic arrivals and B) Foreign Arrivals based upon last port of call. Data from MARAD arrival reports 1995 – 2004. The other category includes tankers, ROROs, passenger vessels, general cargo vessels, etc.

4.3.2 Ballast Water Delivery and Management for Chesapeake Bay

The majority of all arrivals to Chesapeake Bay reported carrying ballast water, and nearly all container ships reported carrying ballast water (Figure 4-4). For both foreign and domestic arrivals (post-penalty NBIC data, September 27 - December 31, 2004), in excess of 70% of vessels were reported to be in ballast. It is important to note that the origin of these arrivals was based upon last port of call and not origin of the ballast water; consequently, some of the domestic arrivals were vessels that had made a previous portage in the U.S. and may ultimately have discharged ballast water that originated outside of the EEZ. As with all analyses of ballast water delivery and management in this section, the NBIC data that were used consist of self-reporting by ships, as required under existing regulations.

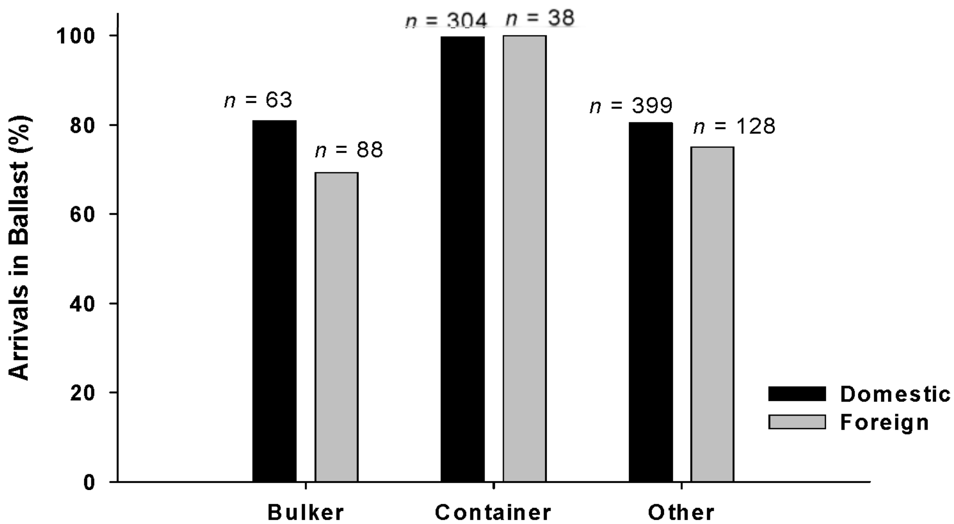

Figure 4-4: Percentage of arrivals to the Chesapeake Bay that report carrying ballast water as reported to NBIC from September 27, 2004 to December 31, 2004.

On average, bulkers discharged a much larger volume of foreign water per arrival than any of the other types of vessels (Figure 4-5). Of bulkers that discharged in the Chesapeake, they reported a mean discharge of 22,436 m^3 for foreign ballast water per arrival with a maximum discharge of approximately 88,500 m^3. Bulkers tend to arrive in ballast to the Chesapeake and carry outbound cargo (Carlton et al. 1995, Smith et al. 1999). Container ships, due to differences in their operational behavior, discharged on average 1,391 m^3 with maximum discharge reported as almost 12,000 m^3. All other vessel types combined discharged on average much less than did bulkers.

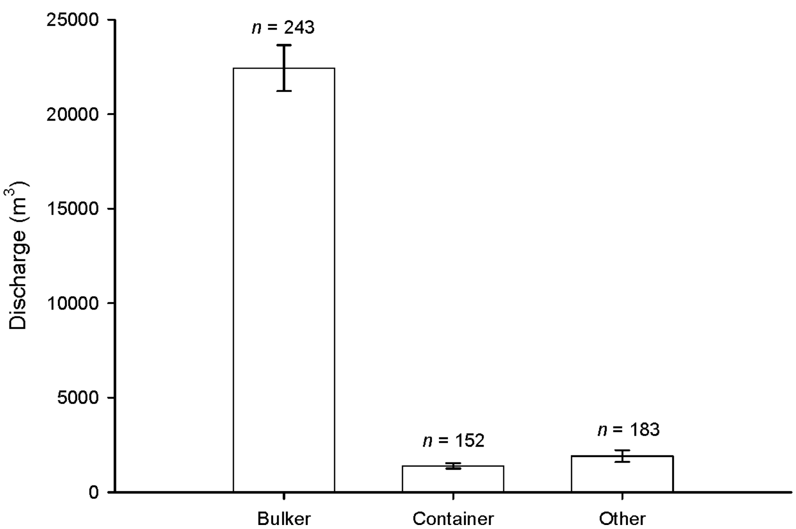

Figure 4-5: Mean (±1 s.e.m.) discharge of ballast water of foreign origin into Chesapeake Bay per arrival as reported to NBIC from July 1, 1999 to December 31, 2004.

Since the single largest group of foreign arrivals was bulkers, and they discharged the largest volumes, it is not surprising that they discharged the majority (i.e., 90%) of the foreign ballast water into the Chesapeake Bay (Figure 4-6).

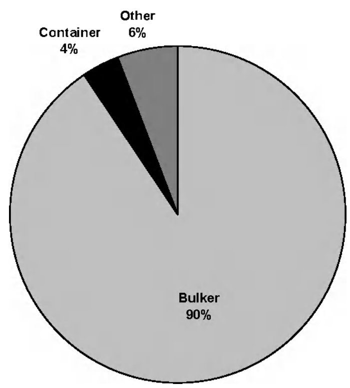

Figure 4-6: Percentage of the total ballast water of foreign origin discharged by bulkers (n = 243), containers (n = 152), and other ship types (n = 183) into Chesapeake Bay as reported to NBIC from July 1, 1999 – December 31, 2004.

Pursuant to federal laws and regulations, vessels discharging foreign ballast water in the Chesapeake Bay were asked to voluntarily undergo BWE beginning in 1996, and ballast water management, which includes BWE and any other Coast Guard approved treatment technology, became mandatory in September 2004. Since the vast majority of foreign ballast water was discharged by bulkers, and we had a significant amount of data from ship-based boarding interviews (see Methods), we examined changes in the frequency of BWE by this vessel type.

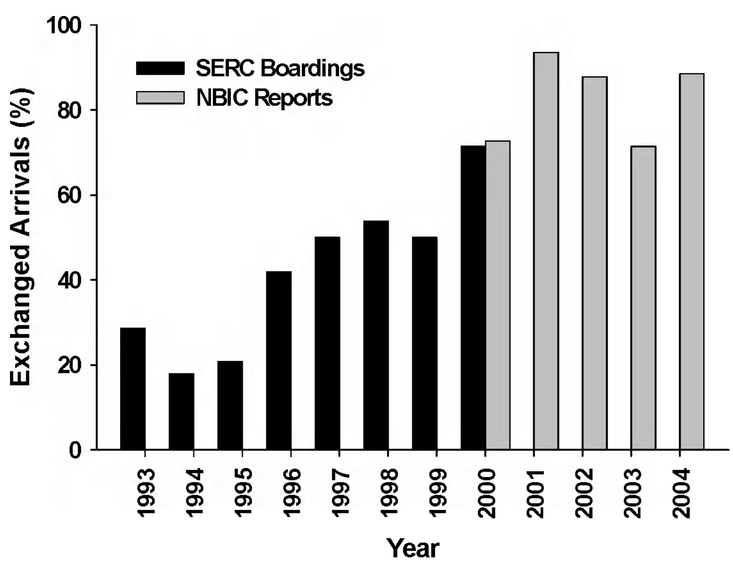

Figure 4-7: Percentage of foreign-arriving bulkers undergoing some degree of mid-ocean BWE. The data from 1993 –2000 were collected by SERC staff while boarding ships and interviewing the crew in the Baltimore, MD and Norfolk, VA. The data from 2000 – 2004 represent the percentage of bulkers that discharged ballast water in Chesapeake Bay that reported performing mid-ocean exchange. [Sample sizes by year: 1993 (21 ships), 1994 (28 ships), 1995 (29 ships), 1996 (31 ships), 1997 (6 ships), 1998 (26 ships), 1999 (28 ships), 2000 (14 ships boarded, 33 ships reporting), 2001 (31 ships reporting), 2002 (41 ships reporting), 2003 (28 ships reporting), and 2004 (87 ships reporting)]

There has been an increase in the percentage of foreign-arriving bulkers that underwent BWE as reported in both the SERC boardings and to NBIC (Figure 4-7). The frequency of BWE was in the range of 20-30% from 1993-1995, increased to 40-55% during 1996-1999, and by the time the mandatory BWE requirement was implemented in 2004, the percentage of bulkers discharging foreign water that conducted BWE (Figure 4-7 and Figure 4-8) was over 80%. During the post-penalty period, 85% of bulkers reported BWE, and for all vessels discharging ballast water of foreign origin, greater than 60% of arrivals by vessel type reported conducting BWE; in contrast, the percentage of vessels discharging exchanged domestic ballast water during this period was much lower (Figure 4-8).

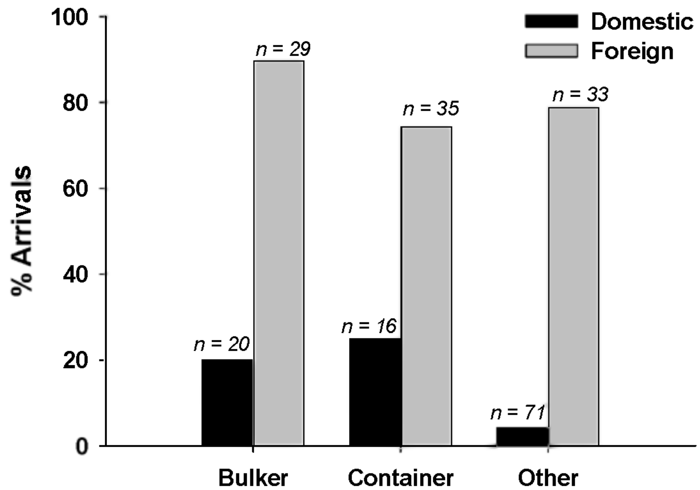

Figure 4-8: Percentage of the vessel arrivals to Chesapeake Bay that discharged ballast water and reported some degree of mid-ocean BWE as reported to NBIC from September 27, 2004 – December 31, 2004.

There has been an increase in the percentage of foreign-arriving bulkers that underwent BWE as reported in both the SERC boardings and to NBIC (Figure 4-7). The frequency of BWE was in the range of 20-30% from 1993-1995, increased to 40-55% during 1996-1999, and by the time the mandatory BWE requirement was implemented in 2004, the percentage of bulkers discharging foreign water that conducted BWE (Figure 4-7 and Figure 4-8) was over 80%. During the post-penalty period, 85% of bulkers reported BWE, and for all vessels discharging ballast water of foreign origin, greater than 60% of arrivals by vessel type reported conducting BWE; in contrast, the percentage of vessels discharging exchanged domestic ballast water during this period was much lower (Figure 4-8).

4.3.3 Zooplankton Density and the Effect of BWE

Zooplankton densities in ballast tanks were significantly lower when ballasted during the cold season (October – March) compared to the warm season (April – September) regardless of whether or not they conducted mid-ocean BWE ($F_{1,161}$ = 11.96, P = 0.0007; Figure 4-9). In the unexchanged ballast tanks sampled by SERC there were mean zooplankton densities of 3,223 organisms·m^{-3} and 778 organisms·m^{-3} during the warm and cold season, respectively, and in exchanged tanks there were mean total zooplankton densities of 1,089 organisms·m-3 and 182 organisms·m-3 in the warm and cold season, respectively (Figure 4-9). By either analysis, BWE significantly reduced the zooplankton densities in both seasons ($F_{1,161} = 4.05$, $P = 0.0457$; Figure 4-9). As discussed in Chapter 2, this comparison does not control for the effect of source region or time, and can therefore only provide a coarse measure of BWE effects on total zooplankton communities. Importantly, such a comparison underestimates the effect of BWE on coastal plankton, as samples from these ships include zooplankton of BOTH coastal and oceanic origin.

An alternative approach to estimating the effect of BWE on coastal zooplankton communities would be to reduce the density of zooplankton concentration of untreated ballast water by 90%, the estimated efficacy of BWE (see Chapter 2). This suggests zooplankton concentrations would decline from a mean of 3,223 organisms·m^{-3} and 778 organisms·m^{-3} in untreated water during the warm and cold seasons, respectively, to 322 and 78 organisms·m^{-3} in treated water (Figure 4-9).

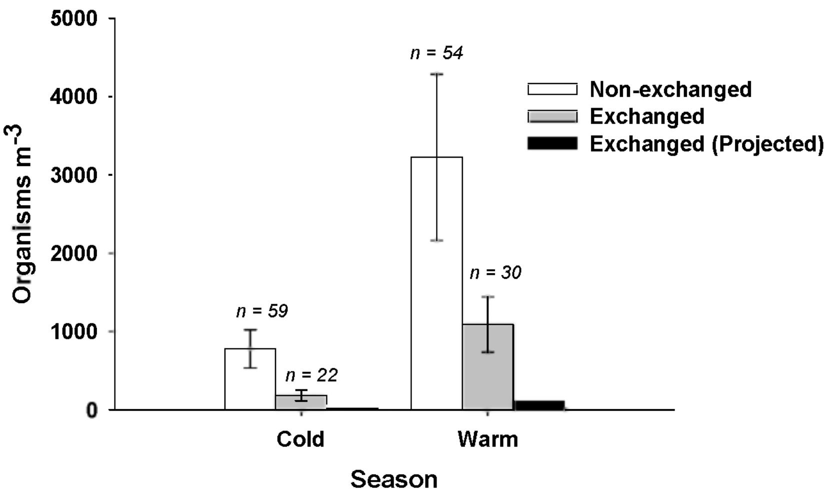

Figure 4-9: Mean zooplankton densities by season (± 1 s.e.m.) in unexchanged ballast tanks, ballast tanks that underwent mid-ocean exchange, and the projected density of coastal zooplankton following mid-ocean exchange (approximately 90% efficient).

4.4 Discussion & Conclusions

Our analyses indicate that there has been a substantial shift in the ballast management practices of ships arriving to the Chesapeake Bay from foreign ports. From 1994-2004, Chesapeake Bay received approximately 5,000 ship arrivals annually and 23-29% of these were from foreign ports. Of foreign arrivals, bulkers accounted for 90% of the ballast water discharge reported to the Chesapeake. Our data indicate that the frequency of BWE for bulker foreign arrivals has increased from 20% (1994) to 85% (September-December 2004).

Due to the increase in BWE, there has clearly been a large reduction in the concentration and total number of coastal organisms discharged to Chesapeake Bay by foreign arrivals over the last decade. Based upon measures for the efficacy of BWE (Chapter 2), we estimate that BWE reduces zooplankton concentrations by 90%, and most bulkers (85%) are now conducting BWE. Our direct measures support the conclusion that zooplankton concentrations have declined, although this underestimates the total decline (because oceanic organisms were entrained during exchange and included in the total counts).

We expect that, due to BWE, there have also been strong declines in concentration of other taxonomic groups delivered to Chesapeake Bay, such as diatoms, protists, and other microorganisms.

In general, smaller organisms in the water column are likely to be removed during BWE to the same or similar extent (~90%) as the original ballast water. Some of these small organisms can increase in population size following exchange (Gollasch 2000), although this does not appear to be common (Ruiz unpubl. data). In addition, organisms can occur on the bottom or internal surfaces of ballast tanks, sometimes as cysts or resting stages (Bailey et al. 2005, Drake et al. 2005, Mimura et al. 2005). The size of this reservoir or "seed bank" and the extent to which it contributes to subsequent discharge of organisms in ballast water remains undefined. It is important to note, however, that this reservoir is present with or without exchange.

The biological significance of BWE, in terms of reduction of invasion risk, is yet to be resolved. While there has been a strong reduction in the number of organisms transferred by ballast water to the Chesapeake Bay, some organisms (including non-native species) still arrive from other global regions. Our results suggest that the residual coastal organisms in ballast water may be roughly 10% of the expected concentration without BWE. Nonetheless, delivery of coastal organisms still occurs. For example, if one scales up to the mean dosage from a bulker, the mean discharge dosage (i.e., mean volume * mean density) from an unexchanged bulker during the summer would be 72,311,228 zooplankton per discharge, falling to 7,231,122.8 zooplankton per discharge following exchange. Although we expect this to greatly reduce the likelihood of future invasions, because establishment is density-dependent (i.e., the chance of colonization increases with increasing density), the amount of residual risk remains difficult to assess (see Ruiz and Carlton 2003 for discussion).

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5 CHESAPEAKE BAY: INVASION HISTORY AND THE ROLE OF SHIPPING AND BALLAST WATER EXCHANGE

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5.1 Introduction

In this chapter, we provide an overview of biological invasion patterns for the Chesapeake Bay, examining the role of shipping and ballast water. The Chesapeake is the largest marine estuary in the United States and one of the earliest sites of continuous European settlement in North America. Following the first European settlement at the mouth of the Chesapeake in 1608, the region experienced rapid and sustained growth in human population size, shipping, fishing, and agriculture. Today, the Chesapeake remains a major hub of human activity, and together the ports of Baltimore and Norfolk receive among the largest number of ship arrivals of ports in the U.S. (Carlton et al. 1995, Smith et al. 1999). This long history of modern human activities suggests the Chesapeake Bay region has been exposed to non-native biota delivered through many vectors. Here, we characterize the non-native species documented to occur in the Chesapeake Bay.

5.2 Methods

Our analysis of invasions focuses on the tidal waters and wetlands of the Chesapeake Bay and its tributaries, and the adjacent Atlantic waters of Virginia and Maryland, including the chain of coastal Atlantic bays north of the mouth of the Chesapeake, to the Maryland-Delaware border. We include shores, wetlands, up to the monthly mean high-tide line, and the head-of-tide of tributaries.

We compiled information on species in the Chesapeake Bay region from a variety of sources, including published literature, "gray literature", Internet datasets, and interviews with scientists. We also conducted intensive field surveys of sessile invertebrates in the lower Chesapeake Bay (for description see Ruiz and Hewitt 2002, NEMESIS 2005), providing additional information and several new species records for the region.

We classified each species into several categories, which describe invasion history and distribution in the Chesapeake Bay region. The detailed information, information sources, and classification for each nonindigenous species were incorporated into our database, the National Estuarine and Marine Exotic Species Information System (NEMESIS). NEMESIS was used to evaluate patterns of invasions presented by taxonomic group, time, transport mechanism (vector), and origin. Details for each species are available on-line at http://invasions.si.edu/nemesis/chesapeake.html.

5.2.1 Category definitions

Invasion status- [Introduced, Cryptogenic, Native.] We used criteria discussed and summarized by Carlton (1979) and Chapman and Carlton (1991, 1994) to distinguish species introduced by human activities from native and cryptogenic ones. We included some species which were native or cryptogenic in a portion of the Chesapeake Bay region (e.g., one river tributary), and also included two bird species which were historically present as winter migrants, but whose breeding populations resulted from human activities.

Population status- [Established, Extirpated, Failed, Unknown.] We considered nonindigenous species to have established populations if they had several records of collection in the region within the last 30 years, and if accounts of their local occurrence and biology were consistent with a reproducing population. With regard to unsuccessful introductions, we distinguished between species which were introduced without any evidence of reproduction (failed), and those which maintained populations for a time, but eventually disappeared (extirpated).

Residency- [Regular Resident, Boundary Resident, Unconfirmed.] Along the borders of tidal waters and wetlands of estuaries, many organisms can be collected which are commonly thought of as terrestrial or characteristic of non-tidal freshwater habitats such as upland streams or ponds. Based on habitat descriptions from the literature, we have divided nonindigenous species in the Chesapeake Bay region into "regular residents", typically aquatic and wetland species which maintain populations in tidal waters, and "boundary residents", primarily terrestrial or non-tidal freshwater species.

Native regions [Western Atlantic; Eastern Atlantic; Pacific; Unknown-Marine; North America; South America; Eurasia; East Asia; Africa.] We have divided nonindigenous species into marine forms, defined by ocean regions, and continental species (freshwater-terrestrial). Borderline cases include:

- Species capable of reproduction and growth in fresh, brackish, and marine environments in the Chesapeake region largely confined to estuaries (e.g., *Cordylophora caspia*) - classified as marine.
- Insects predominantly inhabiting marine intertidal shorelines (e.g., *Anisolabis maritime; Procanace dianneae*) - classified as marine.
- Parasites of catadromous eels (*Anguilla* spp.), which may best survive and reproduce in freshwater, but can infect eels at salinities of 20-30 PSU (e.g., *Anguillicola crassus*; *Pseudodactylogyrus anguillae*) (Koie 1991) - classified as marine.
- Vascular plants of upper marine intertidal and spray zones- classified as continental. (We consider plants of the marine subtidal (e.g. sea-grasses) and lower intertidal zones (e.g. *Spartina* spp.) to be marine, but no plants of these types are known to be introduced in the Chesapeake Bay region).
- Freshwater-spawning fishes with anadromous populations, and/or adults capable of dispersing through seawater (e.g., salmonids; *Dorosoma petenense*- Threadfin Shad) classified as continental.

Source Regions- We assigned probable source regions based on the dispersal history of the organism, proximity of other invading organisms, and likely mechanisms of transport. In cases where several source regions seemed equally possible, we listed the source region as "unknown". Source region and native region can differ, if a species is thought to colonize from an earlier site of introduction. In cases where species escaped locally from cultivation or captivity, we considered their source region to be identical with their native region.

Date of 1st Record- For dates of first record, we reported the date of first collection, sighting, or documented deliberate releases when available. If these could not be found, dates of writing or publication of records were reported. Some species of plants had isolated 17-18th century records, followed by a period of absence from Chesapeake floras for a century or more before regular occurrence was reported. These early specimens often appear to have been cultivated specimens, local garden escapees, or early failed introductions. In these cases, we used the arrival and regular occurrence of these species in uncultivated areas as the time of initial invasion. For most freshwater species, we used the first date when these species were reported from tidal waters and wetlands, rather than dates of introduction to the watershed. However, for boundary resident vascular plants, we used dates of first record from coastal locations, including farmland and settlements. In many cases, these were very early records, without ecological data. We assume that these species, most of them opportunistic and weedy, would have colonized disturbed tidal wetlands and shorelines soon after introduction.

Vectors of introduction [Broad Categories (subvectors); Shipping (ballast water, fouling, dry ballast, cargo, etc.); Fisheries (intentional, accidental-not oysters, oysters-accidental, discarded bait, bait-packing material); Ornamental (aquatic plant shipments, garden escape, pet release); Agriculture (weed/pest; agricultural packing material- e.g., rice straw)]; Biocontrol; Natural dispersal.] We evaluated plausible mechanisms of introduction for each introduction based upon time of arrival, life history, and a variety of ecological attributes. In many cases, the mode of introduction was well documented (e.g., intentional release of fishes), but often several mechanisms were possible, in which case multiple vectors were listed. “Natural dispersal” as a vector here means dispersal from other regions of North America or the northwestern Atlantic where a nonindigenous species has invaded.

5.3 Results

Since the onset of European colonization in 1608, at least 171 nonindigenous species (NIS) have become established in tidal waters and tidal wetlands of the Chesapeake Bay region. Major taxonomic groups of NIS include invertebrates (57 species), algae (8 species), vascular plants (68 species), fishes (27 species), and vertebrates other than fishes (10). Another 38 nonindigenous species have been recorded here, for which present population status is considered unknown, including 2 species of algae, 20 invertebrate species, 7 vertebrate species, and 7 species of vascular plants (NEMESIS 2005).

The discovery rate of NIS for Chesapeake Bay has increased greatly in the past 50 years, and this is unevenly distributed among taxonomic groups (Figure 5-1). The rate of discovery jumped from 15-22 species per 25-year interval (1855-1954) to 35 species per in each of the last two 25-year intervals (1955-2005), representing an increase of >59%. This increase is caused by a 4-5 fold increase in invertebrates and algae (combined), whereas the number of new plant discoveries have declined, and those for fishes show more variable temporal patterns without clear change in the recent time periods.

Our analysis indicates that shipping was a possible vector for the introduction of 55 (85%) of the 65 invertebrate/alga1 species, including both species attributed to shipping as a sole mechanism or one of multiple possible mechanisms (NEMESIS 2005). Figure 5-2 shows the remarkable acceleration in the rate of discovery of invertebrate/algal NIS in the later half of the 20th century, and the number of these species associated with shipping as a possible vector has increased in parallel, driving the overall rate of discovery. It is further noteworthy that none of the newly reported nonindigenous plants and fish in the past 50 years (Figure 5-1) were attributed to shipping.

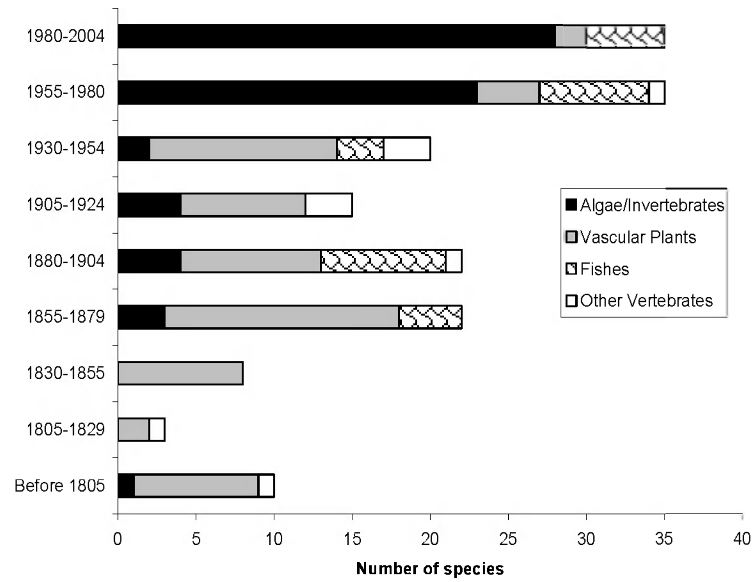

Figure 5-1: Changes in taxonomic composition of nonindigenous species established in the Chesapeake Bay region (n=171). Shown is the number of species newly discovered per 25-year interval, according to major taxonomic groups.

Across all time periods, ballast water and hull fouling have been the most important shipping modes of introduction for invertebrates and algae in the Chesapeake Bay region, but the relative importance of these two modes of shipping transport remains difficult to determine (Table 5-1: page 115); see also Fofonoff et al. 2003). Cumulatively, we considered ballast water to be the sole mode of introduction to the Chesapeake Bay region for 5 species, based on their life history and invasion history. Three of these species were first collected in Chesapeake Bay. Hull fouling was considered a sole mode of introduction transport for 13 species, all of which spend only very brief periods of their life cycle in the plankton (water column). For 15 species, both ballast water and fouling are possible vectors, since these organisms had both prolonged planktonic and attached phases in their life cycles. Another 9 species could have been transported by ballast water, or by various non-shipping vectors, including fisheries activities and the trade in ornamental aquatic plants (Table 5-1: page 115).

Other modes of shipping transport, including dry (solid) ballast and cargo, were limited primarily to organisms tolerant of air exposure. Transport in solid ballast of sailing ships was an important mode of shipping introductions, especially for vascular plants, from the 17th century to the early 20th century. It was a considered the sole vector for only 5 Chesapeake introductions before 1880, and 4 from 1880 to 1954 (Figure 5-1). Solid ballast was also considered a possible vector for 31 species that were attributed to multiple vectors in these periods, but only one of those discovered in 1955-2004. Most of the latter candidates for solid ballast transport are vascular plants, many of which could have also been introduced as agricultural weeds or as garden escapes.

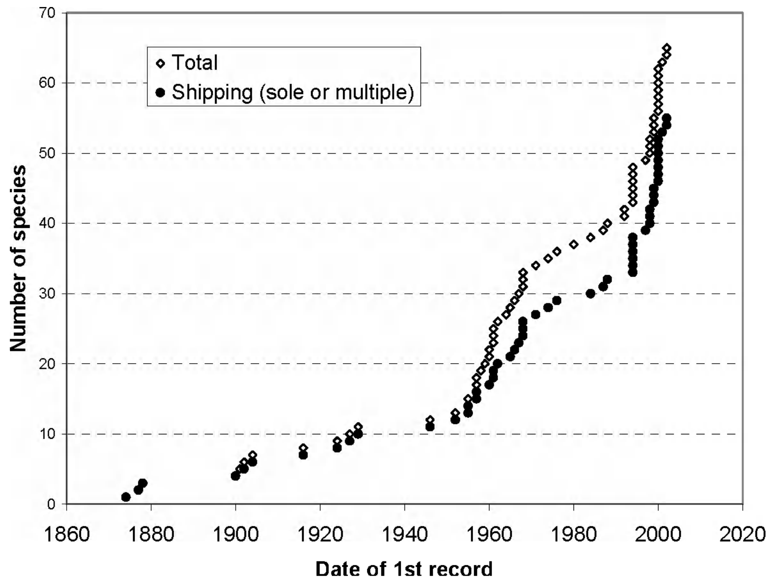

Figure 5-2: Cumulative numbers of aquatic nonindigenous invertebrates and algae established in the Chesapeake Bay region.

For invertebrate/algal introductions alone, historical transport in dry ballast was a possible vector for 4 animals of the upper intertidal zone. In addition, at least 8 recently discovered insects associated with wetland plants (with first records from 1955 to 2000) could have been transported in cargo, containers, or other out-of-the-water modes of shipping transport (Table 5-1: page 115).

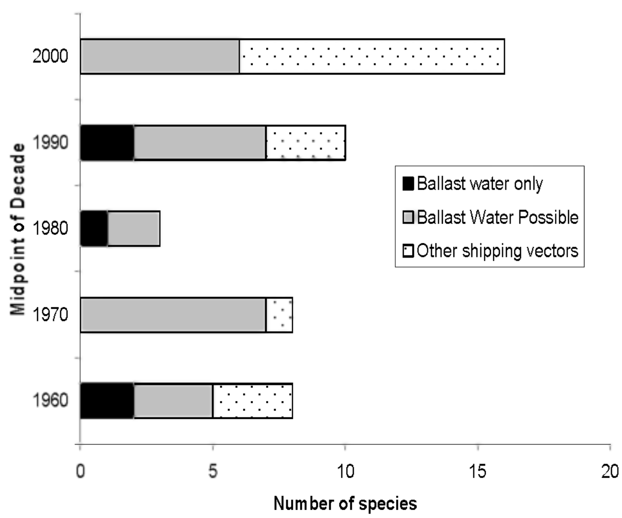

Figure 5-3: Shipping vectors for invertebrates and algae introduced to the Chesapeake Bay region, 1955-2004. The number of species newly discovered per 10-year interval is shown.

Figure 5-3 shows the relative importance of ballast water as a possible vector for invertebrate/algal invasions by decade over the last 50 years, the period of rapid discovery (see Figure 5-1 and Figure 5-2). Ballast water is a possible vector for 51% (28) of the 45 nonindigenous species discovered in this period, but most of these include hull fouling as a possible vector (Table 5-1: page 115). Only 11% (5 of 45 species) are attributed solely to ballast water, and ballast water does not appear to play any role in approximately half of all invasions during this period.

Another important aspect of Figure 5-3 is the fluctuation in discovery rate by decade for the shipping-related invasions by invertebrates and algae. Fluctuations in collection activity or in published reports seem to account for much of the variation in the number of reports over the decades, including the period from 1975 to 1984, which lay between some of the major collecting programs (see Discussion for further detail).

5.4 Discussion

Non-indigenous species are a conspicuous component of the Chesapeake Bay biota in terms of species richness, abundance, and function. We presently know of 171 nonindigenous species with established, self-sustaining populations in the tidal waters of the Chesapeake region, and these include a diverse range of taxa across 17 phyla. Another 38 nonindigenous species have been recorded here, for which present population status is considered unknown. Some of the established populations are relatively large and are known to have significant impacts as predators, competitors, pathogens, and physical structure (Carter and Rybicki 1994, Phelps 1994, Burreson et al. 2000; see also review by Ruiz et al. 1999). Although the direct and indirect impacts of most nonindigenous species in the Chesapeake remain unexplored, it is evident that invasions play a significant role in the ecology of Chesapeake Bay.

For the Chesapeake Bay, the nature of invasions exhibits many changes through time. One of the most striking changes is a strong increase in discovery rate in the past 50 years. Most of these recent arrivals were invertebrates and algae, and were attributed to shipping as a vector, underscoring the combined role of ballast water and hull-fouling. This represents a shift in invasion history, whereby invasions in previous time periods were dominated by plants and fishes, arriving by different vectors. There was also an associated shift in origin and habitat utilization associated with these changes (Fofonoff et al., in review, NEMESIS 2005).

5.4.1 Interpreting temporal patterns of invasion

While a dramatic increase in discovery rate exists for the Chesapeake and other estuaries, we urge caution in interpreting these temporal patterns of invasion. There are inherent biases in the underlying data, which Ruiz et al. (2000) noted derive from historical sampling efforts that are unevenly distributed among time intervals, taxonomic groups, and habitats. These data are essentially by-catch from a broad mix of prior studies, instead of a routine monitoring program designed to rigorously evaluate changes in species composition and abundance. Importantly, sampling effort was sparse in the first few centuries and episodic through time for many taxonomic groups (Fofonoff et al., in review), placing obvious constraints on the detection of new invasions in particular intervals and possibly inflating estimates of the overall rate increase.

More broadly, a lag-time in detection of new invaders may result from sampling efforts operating in combination with population dynamics and species-level attributes (Crooks and Soulé 1999). Given a fixed level of sampling effort (field surveys), the likelihood of detecting a species will depend upon its abundance and the observer's ability to recognize it as unique from native (or previously described) residents. Clearly, if an organism occurs in very low abundance in only one very small area, the likelihood of detection is relatively low compared to an organism that is common over a large area. Likewise, a nonindigenous species that is small in body size or not easily identified may avoid detection, and this may explain the relative paucity of microorganisms among marine invasions (Ruiz et al. 2000a, b). At the present time, it remains a significant challenge to predict the population dynamics of invasions (Carlton 1996, Kolar and Lodge 2002, Drake 2004), making estimates of actual date of colonization uncertain.

In Chesapeake Bay, these issues of detection are illustrated by our recent surveys of the sessile invertebrate community. Using substrate deployed as passive collectors in the lower Chesapeake Bay, we have detected 15 nonindigenous species since 1994 that were previously undescribed for the bay (NEMESIS 2005), representing a significant fraction of the 35 species newly reported in the past 25-year interval. Although many of these species appear to be recent arrivals, surveys of the Chesapeake's fouling community have been very limited in the past few decades (Calder 1971, Wass 1972, Thompson 1993, Wasson et al. 2000), creating uncertainty about the actual date of colonization. The pulsed nature of such surveys (search effort) has certainly contributed to the fluctuation rates of discovery shown in Figure 5-3, confounding efforts to estimate the time of invasion by year or even decade.

Despite the lack of precision, we have considerable confidence that the overall rate of invasions by marine invertebrates and algae have increased in the Chesapeake in the past 50 years. Many of the newly detected species are sufficiently conspicuous that they are unlikely to avoid detection for long (e.g., the whelk *Rapana venosa*, the rhizocephalan barnacle *Loxothylacus harrisii*, the serpulid polychaete *Ficopomatus enigmaticus*, the clam *Rangia cuneata*, the tunicate *Styela plicata*), or they have well documented patterns of spread (e.g., the shore crab *Hemigrapsus sanguineus*, the clam *Corbicula fluminea*, the alga *Codum fragile*) (see NEMESIS 2005 for details). In previous 25-year intervals, the number of newly reported invertebrates and algae never exceeded 4 species. Thus, given that the number of conspicuous or well-documented arrivals exceeds this number, we surmise a recent increase in invasion rate has indeed occurred in the past decades.

5.4.2 Interpreting the role of ships' ballast water

Our analysis indicates that the observed increase in invasion rate is driven by shipping as a vector. Chesapeake Bay is one of the largest port systems in the U.S., both in terms of number of ship arrivals and ballast water discharge (Carlton et al. 1995, Ruiz et al. 2001). In 1991, the Chesapeake received an estimated 12 million metric tons of ballast water from foreign arrivals, the second largest in the country, and Smith et al. (1999) have characterized the diverse taxa present in this ballast. The number and size of ships arriving to the Chesapeake has certainly increased greatly over the past century, resulting in an increasing transfer of organisms in ships' ballast water and outer surfaces (e.g., hull, rudder, propeller, etc.) to the region, but the magnitude of this change has not been quantified.

Although shipping is clearly an important vector for the Chesapeake, the relative importance of ballast water versus hull fouling is unresolved. We estimated that 51% of the recent invertebrate/algal invasions in the past 50 years may have arrived by ships' ballast water, but only a subset are attributed solely to ballast (Table 5-1: page 115). Many species could have arrived by ballast or hull fouling of ships, and a large fraction of these recent arrivals were attributed solely to hull fouling.

Numbers of ballast-water introductions in Chesapeake Bay are certainly underestimated, and lag-times in discovery of those species which are detected are potentially large. The five species that we consider to result from ballast water as a sole vector of introduction include two conspicuous benthic invertebrates (*Rapana venosa. Hemigrapsus sanguineus*) which were probably detected within a decade of their introduction. However, the other three species are diatoms (*Coscinodiscus wailesii; Odontella sinensis; Thalassiosira punctigera*). The introduced status of these diatoms in Chesapeake Bay and the Northwest Atlantic is based on their probable Pacific origin and their sudden appearance in European waters (*C. wailesii*-1977; *O. sinensis*-1903; *T. punctigera*-1978), where studies of the diatom flora date to the middle 19th century (Hasle 1983, Boalch 1984, Wyatt and Carlton 2002). In Northwest Atlantic phytoplankton studies, up to the 1960s, many diatoms including *Coscinodiscus* and *Thalassiosira* were often identified only to genus (e.g. Wolf et al. 1926, Paul Hargraves, personal communication). Consequently, the date of introduction of these three diatoms to Chesapeake Bay is not known. The first Chesapeake reports of *C. wailesii* and *O. sinensis* were in 1961; *T. punctigera* was first identified in the late 1980's (NEMESIS 1995). These species could have been introduced to the East Coast of North America and Chesapeake Bay anytime between the adoption of water ballast in the late 19th-early 20th centuries and the dates of their discovery. It is highly probable that many other species of phytoplankton, as well as many species of zooplankton, planktonic protists and bacteria have been introduced to the Chesapeake Bay region and the Northwest Atlantic. However, to our knowledge, these three diatoms, and the Eastern Atlantic mysid *Praunus flexuosus*, known from the Gulf of Maine to Long Island Sound (Wigley and Burns 1971, Pederson et al. 2005), are the only definitely identified introduced marine holoplanktonic organisms occurring in the Northwestern Atlantic.

Marine holoplanktonic organisms, including bacteria, flagellates, dinoflagellates, diatoms, protozoans, and copepods are numerically dominant organisms in ballast water (Carlton 1985, Carlton and Geller 1993, Smith et al. 1999, Smith et al. 2000, Choi et al. 2005). However, their invasion and establishment outside their native ranges are sometimes extremely difficult to detect, because of the high diversity of the native planktonic biota, the difficulty of taxonomic resolution, and the relatively recent history of plankton studies in most parts of the world (Wyatt and Carlton 2002). The planktonic biota of Chesapeake Bay's largest source region for ballast water, the Northeast Atlantic coast of Europe (Smith et al. 1999), is dominated by many species usually considered native on both sides of the Atlantic. Many other species, including the dominant genera of copepods, belong to widespread species complexes, whose European and North American species can only be separated by molecular methods or by painstaking morphological examinations (e.g. *Acartia clausi* and *A. margalefi* vs. *A. hudsonica*, Bradford 1976; members of the *Pseudocalanus* and *Eurytemora "affinis"* complexes, Frost 1989; Lee 2000). It is also possible that some morphologically distinct species are relegated to the "unidentified" category owing to lack of knowledge and time constraints. Consequently, it is probable that many planktonic invasions are overlooked by existing sampling programs.

5.4.3 Interpreting the effects of ballast water management on invasion patterns

It is premature to empirically assess the effects of ballast water management on the rate of invasions for Chesapeake Bay. Over the past 10 years, there has been an increase in the frequency of ballast water treatment for ships arriving to the Chesapeake that clearly reduces the density/number of nonindigenous organisms in arriving ballast (see Chapter 2). We do not see any evidence of a decline in the rate of new discoveries of nonindigenous species during this same timeframe. In fact, our data show an increase in new discoveries, due perhaps in large part to our increased sampling in this time period. However, it would be erroneous to conclude that ballast water treatment is having no effect. There are clearly confounding issues of search effort and lag-times in detection, making estimates of invasion rates much too coarse grained to evaluate the ballast management efforts --- that have only been implemented very recently.

Although we are confident that reduction in ballast-mediated propagule supply will reduce the risk of invasion, there are several reasons why a strong response may not be observed over a longer time period. First, it is not evident that ballast water is the most important contemporary vector for aquatic invasions in the Chesapeake. Most invertebrate/algal invasions are attributed to shipping, including both ballast water and hull fouling, and hull fouling may actually be the dominant vector (see 5.3 Results). Second, the expected magnitude of reduction in invasion risk to lower propagule supply is not known. The relationship between supply and invasion risk is not likely to be linear, exhibiting instead thresholds where there is a rapid change in probability of invasion. Whether the current ballast water management crosses such thresholds, greatly depressing invasion risk, remains unknown (see Ruiz and Carlton 2003 for discussion).

In addition, changes in local conditions in the Chesapeake may also play a role in the observed invasion patterns. As an urbanized estuary with a large and growing human population in the surrounding watershed, the bay has been subjected to many changes in hydrology, eutrophication, sediment loading, fishing pressure, and habitat alteration (Brush 2001, Kennedy and Mountford 2001). Major declines have occurred in the area occupied by submerged aquatic vegetation and native oyster reefs, the abundance of commercial shellfish and finfish, and the frequency of hypoxia events (Davison et al. 1997, Dauer et al. 2001, Paul 2001, Wennersten 2001). These changes represent major disturbance agents that may operate alone or in combination to affect susceptibility to invasion (Elton 1958, Cohen and Carlton 1995, Occhipinti-Ambrogi and Savini 2003, Jewett et al. 2005). To date, the relationship between these disturbances and invasion susceptibility is not well understood in estuaries (see Ruiz et al. 1999 and references therein).

To truly assess the response of invasion patterns to management strategies requires implementation of standardized, repeated sampling programs over time. A solid baseline is required to measure changes in the arrival and abundance of nonindigenous species. At the present time, no such program exists in the United States. Although there are clearly some existing data on invasions, which we summarize here, these derive from measures that were never designed or intended to track invasion patterns across space or time. As a result, there are many inherent biases and limitations in the quality and quantity of available data, limiting a robust understanding of invasion dynamics and conclusions about management effects (Carlton 1996, Ruiz et al. 2000, Ruiz and Hewitt 2002). We therefore recommend establishing a standardized sampling program at several key estuaries in the U.S., to provide the high-quality data necessary that measures invasion patterns in response to vector management and other key variables.

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Table 5-1: Algae and invertebrates introduced to the Chesapeake Bay region. Shown for each species is the date of first record, native region, and vector. Vector is hierarchical, with coarse vector followed by fine vector classification in parentheses. For example, shipping as a coarse vector can include ballast water, hull fouling, dry ballast, or cargo as a fine vector. Multiple vectors are possible for many species. Species discovered by the SERC Marine Invasions Laboratory fouling plate survey, and known to have established populations, are marked with an asterisk (*). For more detailed information see NEMESIS 2005.

Major taxa	Species	Common Name	1st Record	Native Region	Vector (mode)
Bacillariophyta	*Coscinodiscus wailesii*	diatom	1961	Amphi-Pacific	Shipping (Ballast Water)
Bacillariophyta	*Odontella sinensis*	diatom	1961	Western Pacific	Shipping (Ballast Water)
Bacillariophyta	*Thalassiosira punctigera*	diatom	1988	Amphi-Pacific	Shipping (Ballast Water); Natural Dispersal
Chlorophyta	*Codium fragile ssp. tomentosoides*	Dead-Man's Fingers	1976	Western Pacific	Shipping(Fouling, Ballast Water), Fisheries(Packing Material-Bait); Oysters-Accidental); Natural Dispersal
Phaeophyta	*Striaria attenuata*	brown alga	1968	Eastern Atlantic	Shipping (Fouling; Ballast Water); Natural Dispersal
Rhodophyta	*Bonnemaisonia hamifera*	red alga	1968	Western Pacific	Shipping (Fouling; Ballast Water); Natural Dispersal
Rhodophyta	*Gracilaria vermiculophylla*	red alga	1999	Western Pacific	Shipping (Fouling , Ballast Water); Fisheries (Fisheries-Accidental)
Rhodophyta	*Neosiphonia harveyi*	red alga	1957	Western Pacific	Shipping (Fouling, Ballast Water); Natural Dispersal
Haplosporidia	*Haplosporidium nelsoni*	MSX	1958	Western Pacific	Fisheries (Oysters-accidental)
Cnidaria (Hydrozoa)	*Blackfordia virginica*	hydromedusa and hydroid	1904	Eastern Atlantic	Shipping (Ballast Water, Fouling)

Table 5-1 (continued). Algae and invertebrates introduced to the Chesapeake Bay region.

Major taxa	Species	Common Name	1st Record	Native Region	Vector (mode)
Cnidaria (Hydrozoa)	*Cordylophora caspia*	Freshwater Hydroid	1877	Eastern Atlantic	Shipping (Fouling)
Cnidaria (Hydrozoa)	*Garveia franciscana*	Rope Grass Hydroid	1946	Unknown-Marine	Shipping (Fouling)
Cnidaria (Hydrozoa)	*Maeotias marginata*	hydromedusa and hydroid	1968	Eastern Atlantic	Shipping (Ballast Water, Fouling)
Cnidaria (Hydrozoa)	*Moerisia lyonsi*	hydromedusa and hydroid	1965	Eastern Atlantic	Shipping (Ballast Water, Fouling)
Cnidaria (Anthozoa)	*Diadumene lineata*	Striped Sea Anemone	1929	Western Pacific	Shipping (Fouling)
Platyhelminthes	*Gyrodactylus anguillae*	eel gill trematode	1999	Eastern Atlantic	Fisheries (Fisheries Accidental); Shipping (Ballast Water)
Platyhelminthes	*Pseudodactylogyrus anguillae*	eel gill trematode	1999	Western Pacific	Fisheries (Fisheries Accidental), Shipping (Ballast Water)
Nemata	*Anguillicola crassus*	Eel Swimbladder Nematode	1997	Western Pacific	Shipping (Ballast Water), Fisheries (Fisheries Accidental)
Annelida (Oligochaeta)	*Branchiura sowerbyi*	oligochaete	1957	East Asia	Shipping (Ballast Water), Ornamental (Aquatic Plant)
Annelida (Polychaeta)	**Ficopomatus enigmaticus*	serpulid tubeworm	1994	Unknown-Marine	Shipping (Ballast Water, Fouling), Fisheries (Oysters-Accidental)
Mollusca (Gastropoda)	*Bithynia tentaculata*	Faucet Snail	1927	Eurasia	Shipping (Dry Ballast), Ornamental (Aquatic Plant), Agriculture (Packing Material-Agricultural)

Table 5-1: (continued). Algae and invertebrates introduced to the Chesapeake Bay region.

Major taxa	Species	Common Name	1st Record	Native Region	Vector (mode)
Mollusca (Gastropoda)	*Cipangopaludina chinensis*	Chinese Mystery Snail	1960	East Asia	Ornamental (Aquatic Plant, Pet Release), Fisheries (Fisheries Accidental)
Mollusca (Gastropoda)	**Cuthona perca*	Lake Merrit Cuthona	1994	Unknown-Marine	Shipping (Ballast Water, Fouling)
Mollusca (Gastropoda)	*Littorina littorea*	Common Periwinkle	1959	Eastern Atlantic	Natural Dispersal
Mollusca (Gastropoda)	*Myosotella myosotis*	salt marsh snail	1900	Eastern Atlantic	Shipping (Dry Ballast)
Mollusca (Gastropoda)	*Rapana venosa*	Veined Rapa Whelk	1998	Western Pacific	Shipping (Ballast Water)
Mollusca (Gastropoda)	*Stramonita haemastoma*	Southern Oyster Drill	1955	Amphi-Atlantic	Fisheries (Oysters-accidental); Shipping (Dry Ballast; Fouling)
Mollusca (Gastropoda)	*Viviparus georgianus*	Banded Mystery Snail	1901	North America	Fisheries (Fisheries-Accidental),Ornamental (Pet Release, Aquatic Plant)
Mollusca (Bivalvia)	*Corbicula fluminea*	Asian Freshwater Clam	1971	East Asia	Shipping (Barge/Dredge, Ballast Water), Fisheries (Discarded Bait)
Mollusca (Bivalvia)	*Cyrenoida floridana*	Florida Marsh Clam	1952	Western Atlantic	Shipping (Dry Ballast, Barge/Dredge)
Mollusca (Bivalvia)	*Rangia cuneata*	Gulf Wedge Clam	1960	Western Atlantic	Shipping (Ballast Water, Barge/Dredge), Fisheries (Oysters-accidental)
Mollusca (Bivalvia)	*Teredo navalis*	Naval Shipworm	1878	Unknown-Marine	Shipping (Fouling)

Table 5-1: (continued). Algae and invertebrates introduced to the Chesapeake Bay region.

Major taxa	**Species**	**Common Name**	**1st Record**	**Native Region**	**Vector (mode)**
Arthropoda (Crustacea-Cirripedia)	*Balanus amphitrite*	Striped Barnacle	1967	Western Pacific	Shipping (Ballast Water, Fouling)
Arthropoda (Crustacea-Cirripedia)	*Loxothylacus panopaei*	Mud Crab Parasitic Barnacle	1964	Western Atlantic	Fisheries (Oysters-accidental)
Arthropoda (Crustacea-Cladocera)	*Daphnia lumholtzi*	water-flea	1998	Africa	Shipping (Ballast Water), Fisheries (Fisheries Accidental), Ornamental(Aquatic Plant), Natural Dispersal
Arthropoda (Crustacea-Cladocera)	*Ilyocryptus agilis*	water flea	1974	Eurasia	Shipping (Ballast Water), Ornamental (Aquatic Plant)
Arthropoda (Crustacea-Isopoda)	*Ligia exotica*	Sea Roach	1924	Western Pacific	Shipping (Fouling, Dry Ballast)
Arthropoda (Crustacea-Isopoda)	**Synidotea laevidorsalis*	isopod	2002	Western Pacfic	Shipping (Ballast Water, Fouling)
Arthropoda (Crustacea-Amphipoda)	**Gitanopsis sp.*	amphipod	1994	Unknown-Marine	Shipping (Ballast Water, Fouling), Fisheries (Oysters-Accidental)
Arthropoda (Crustacea-Decapoda)	*Carcinus maenas*	Green Crab	1874	Eastern Atlantic	Shipping (Fouling, Dry Ballast); Natural Dispersal
Arthropoda (Crustacea-Decapoda)	*Hemigrapsus sanguineus*	Japanese Shore Crab	1994	Western Pacific	Shipping (Ballast Water), Natural Dispersal
Arthropoda (Crustacea-Decapoda)	*Orconectes virilis*	Virile Crayfish	1957	North America	Fisheries (Discarded Bait)

Table 5-1: (continued). Algae and invertebrates introduced to the Chesapeake Bay region.

Major taxa	Species	Common Name	1st Record	Native Region	Vector (mode)
Arthropoda (Crustacea-Decapoda)	*Procambarus clarkii*	Red Swamp Crayfish	1980	North America	Fisheries (Fisheries Accidental, Discarded Bait), Ornamental (Pet Release)
Arthropoda (Hexapoda-Insecta)	*Anisolabis maritima*	Seaside Earwig	1916	Eastern Atlantic	Shipping(Dry Ballast; Unspecified)
Arthropoda (Hexapoda-Insecta)	*Brachydeutera longipes*	shore fly	1984	East Asia	Shipping (Ballast Water; unspecified), Ornamental(Aquatic Plant)
Arthropoda (Hexapoda-Insecta)	*Chaetococcus phragmitis*	*Phragmites* mealy-bug	2000	Eurasia	Shipping (unspecified), Ornamental (Aquatic Plant); Agriculture (Packing Material)
Arthropoda (Hexapoda-Insecta)	*Galerucella calmariensis*	Purple Loosestrife leaf beetle	1992	Eurasia	Biocontrol
Arthropoda (Hexapoda-Insecta)	*Galerucella pusilla*	Purple Loosestrife leaf beetle	1992	Eurasia	Biocontrol
Arthropoda (Hexapoda-Insecta)	*Holocranum saturejae*	cattail seed bug	1955	Eurasia	Shipping (unspecified); Ornamental (Aquatic Plants); Agriculture (Packing Material)
Arthropoda (Hexapoda-Insecta)	*Lasioptera hungarica*	*Phragmites* gall midge	2000	Eurasia	Shipping (Unspecified); Ornamental (Aquatic Plant); Agriculture(Packing Material)

Table 5-1: (continued). Algae and invertebrates introduced to the Chesapeake Bay region.

Major taxa	Species	Common Name	1st Record	Native Region	Vector (mode)
Arthropoda (Hexapoda-Insecta)	*Lipara rufitarsis*	*Phragmites* green-eyed fly	2000	Eurasia	Shipping(Unspecified); Ornamental(Aquatic Plant); Agriculture(Packing Material)
Arthropoda (Hexapoda-Insecta)	*Nacerdes melanura*	Wharf Borer (beetle)	1902	Eurasia	Shipping(Fouling; Unspecified); (Natural Dispersal)
Arthropoda (Hexapoda-Insecta)	*Procanace dianneae*	beach fly	1987	Unknown-Marine	Shipping(unspecified)
Arthropoda (Hexapoda-Insecta)	*Sclerocona acutella*	*Phragmites* moth	1998	Eurasia	Shipping(Unspecified); Ornamental(Aquatic Plant); Agriculture(Packing Material)
Arthropoda (Hexapoda-Insecta)	*Tetramesa phragmitis*	*Phragmites* wasp	2000	Eurasia	Shipping (Unspecified); Ornamental (Aquatic Plant); Agriculture (Packing Material)
Entoprocta	**Barentsia benedeni*	kamptozoan	1994	Unknown-Marine	Shipping (Fouling)
Entoprocta	**Loxosomatoides laevis*	kamptozoan	1994	Western Pacific	Shipping (Fouling)
Ectoprocta	**Bugula neritina*	marine bryozoan	2000	Unknown-Marine	Shipping (Fouling)
Ectoprocta	*Lophopodella carteri*	freshwater bryozoan	1961	East Asia	Ornamental (Aquatic Plant), Fisheries (Fisheries Accidental), Natural Dispersal
Chordata (Ascidiacea)	**Botrylloides violaceus*	colonial tunicate	2000	Western Pacific	Shipping (Fouling)

Table 5-1: (continued). Algae and invertebrates introduced to the Chesapeake Bay region.

Major taxa	Species	Common Name	1st Record	Native Region	Vector (mode)
Chordata (Ascidiacea)	**Botrylloides violaceus*	colonial tunicate	2000	Western Pacific	Shipping (Fouling)
Chordata (Ascidiacea)	*Botryllus schlosseri*	Golden Star Tunicate	1962	Unknown-Marine	Shipping (Fouling)
Chordata (Ascidiacea)	**Diplosoma listerianum*	colonial tunicate	2001	Unknown-Marine	Shipping (Fouling)
Chordata (Ascidiacea)	*Ecteinascidia turbinata*	Mangrove Tunicate	1966	Western Atlantic	Shipping (Fouling)
Chordata (Ascidiacea)	**Styela canopus*	Rough Sea Squirt	2000	Unknown-Marine	Shipping (Fouling)
Chordata (Ascidiacea)	**Styela plicata*	Pleated Sea Squirt	2002	Unknown-Marine	Shipping (Fouling)

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

We have attempted to evaluate the apparent efficacy of BWE in preventing or reducing ship-related aquatic invasions in two key U.S. coastal ecosystems, however, it is really much too soon to accurately assess the effects of ballast water management on the rate of invasions in any ecosystem. Interpretation of existing data is confounded by issues related to the intensity and quality of sampling efforts. Data records are unevenly distributed among time intervals, taxonomic groups, and habitats and there are significant uncertainties about lag-times in detection. Estimates of invasion rates are thus much too coarse to be used with great confidence for evaluating ballast management efforts that have only been implemented very recently.

6.1.1 Efficacy of Ballast Water Exchange

- The process of Ballast Waster Exchange, whether 100% empty-refill or 300% flow-through can be highly effective at replacing coastal ballast water with mid-ocean water (88-99% replacement of original water) and coastal planktonic organisms (80-95% reduction in concentration) across ship types, when conducted according to guidelines and regulations.

- The use of BWE by vessels has significantly reduced (a) the discharge of coastal organisms in ballast to the Great Lakes, Chesapeake Bay, and other U.S. estuaries and (b) associated risk of invasions.

- Salinity stress during BWE can be an important factor in reducing the risk for a freshwater ecosystem like the Great Lakes and for the low-salinity portions of estuaries. However, considerable variation exists in the response of organisms to salinity stress and some euryhaline organisms exhibit a wide salinity tolerance that could allow them to survive BWE.

- BWE does have several limitations. First, some coastal organisms remain even after BWE is completed according to guidelines. Second, to conduct BWE, a ship must have sufficient time in transit (i.e., between ports), acceptable sea state, and be a sufficient distance from shore. As a result, this treatment is often not applied to coastwise traffic between domestic ports, and this represents a sizeable loophole for the transfer and spread of nonindigenous species in U.S. waters.

- Regulations for BWE did not address potential risks associated with NOBOB vessels, and this deficiency represented a gap in the protection framework that established BWE regulations; however, this was of significance primarily for the Great Lakes, since the percentage of NOBOB vessels entering other ports is generally much lower, and has been the focus of additional regulation implemented in 2006 (see below).

6.1.2 Great Lakes:

- The opening of the St. Lawrence Seaway in 1959 permitted the influx of more and larger vessels carrying large volumes of ballast water and ballast sediments into the Great Lakes, and was associated with an increase in the discovery of new aquatic invaders consistent with ballast water being a significant vector.

- Estimates of Great Lakes saltwater vessel traffic and changes in vessel and ballast characteristics pre- (1978-1988) and post- (1994-2004) BWE suggest a possible 76% reduction in the average total amount of ballast potentially carried into the Great Lakes.

- It appears reasonably certain that there was a significant decrease in the overall propagule supply to the Great Lakes between the pre-BWE and post-BWE periods, part of which can be attributed to ballast management regulations and, in particular, BWE. For a scenario using ballast quantity as a simple coarse surrogate for propagule supply, and applying a 90% reduction of live organisms due to BWE, we estimated an average decrease in total potential ballast quantity (and therefore, potential propagule supply) between pre- and post-BWE periods of ~97%, equivalent to eliminating an average of ~3.3 millions t per year of unexchanged ballast water for the 11 years (1994-2004) after implementation of BWE regulations compared to an equal period prior to BWE (1978-1988).

- Changes in economic factors that affected trade, changes in shipping practices, and implementation of BWE regulations all contributed to decreasing the propagule supply to the Great Lakes.

- Even with increasingly strict enforcement of BWE requirements, resulting in high compliance rates for vessels arriving from overseas with pumpable ballast, there have been several gaps (NOBOBs and coastwise traffic) in the protection framework for which BWE is the centerpiece.

- Although the magnitudes of the risks associated with NOBOB and coastwise vessels cannot be calculated for the Great Lakes, it is clear that regardless of how effective BWE may be in reducing coastal and freshwater organisms in ballast water when conducted according to guidelines, the overall Great Lakes ecosystem protection framework was weakened by the gaps in application of ballast management regulations represented by these vessels.

- The average rate of ANS discovery in the Great Lakes ecosystem <u>attributable to all vectors</u> since 1960 through 2003 was 1.8 species per year, or one new successful invader discovered every 29 weeks. This discovery rate is higher than any other freshwater system for which long-term data exist and places the Great Lakes among the most highly invaded aquatic ecosystems in the world. However, discovery rate is not the same as invasion rate and the latter cannot be measured with existing methods.

- About 2/3 of all Great Lakes ANS discovered since the opening of the Seaway are attributed to the shipping vector. After 1993 they are more likely to be euryhaline organisms with benthic adult and juvenile lifestyles, and are more likely to be natives of the Ponto-Caspian region of Eurasia. The establishment of these species in the Great Lakes coincides with their spread into western European ports from which the Great Lakes receives the bulk of its shipping traffic.

- An important step forward in protecting the Great Lakes was the implementation in 2006 of Canadian requirements that all ballast water, including NOBOB residual water, be at salinity of 30 or greater. If these requirements prove equally effective as BWE, we would expect significant additional reductions in the propagule supply due to this vector.

6.1.3 Chesapeake Bay

- There has been a significant increase in the discovery rate of invasions to the Chesapeake Bay over the last 50 years, particularly for invertebrates and algae. Many of these are conspicuous species not easily overlooked in earlier surveys, providing considerable confidence that a real upsurge in invasions has occurred in the Chesapeake Bay during the last half century.

- There has been a substantial shift in the ballast management practices of ships arriving to the Chesapeake Bay from foreign ports, with the frequency of use of BWE having increased significantly from 1994 to 2004.

- Empirical and theoretical measures for the Chesapeake indicate a significant reduction in coastal organisms being discharged in ballast water has occurred since 1993.

- Shipping is implicated as the predominant source of aquatic invasions, but the relative contribution of ballast water discharge versus hull fouling is unresolved.

- The discovery rate of invasions for the Chesapeake has not declined in the past decade, during which time BWE has increased. However, it is premature to estimate the effect of BWE on invasion rate for such a short time interval, given the same issues (including especially lagtime and sampling effort) as discussed above for the Great Lakes.

- To assess the response of invasion patterns and rates to ballast management strategies with any significant and defensible confidence requires implementation of standardized, repeated sampling programs over time. A solid baseline is required to measure changes in the arrival and abundance of nonindigenous species to key coastal ecosystems. At the present time, no such program exists in the United States.

6.2 Recommendations

Based on this synthesis and analyses, we make the following recommendations.

1. BWE should be considered a useful and beneficial ballast management practice to reduce species transfers and invasion risk. It is a valuable measure, especially because it is available now for immediate use on many vessels and shipping routes, in the absence of proven alternative treatment methods.

2. Research and development to produce alternative ballast treatment methods and technology-based ballast treatment systems should continue as a high priority, in order to improve the efficacy of treatment and expand application of treatment to most vessels and routes.

3. The use of high-salinity water to flush NOBOB ballast tanks should be considered a useful and beneficial management practice to reduce species transfers and invasion risks as-

sociated with NOBOB ships entering the Great Lakes. In the absence of proven alternatives, this practice provides some level of protection against some adult and larval life stages, but probably not against resting eggs and spores of zooplankton and phytoplankton.

4. A quantitative, empirical assessment of the actual release of propagules from NOBOB vessels in the Great Lakes is needed for a better risk assessment to guide management and policy in this area.

5. The effects of salinity stress on a broad range of estuarine and freshwater organisms should be further explored and assessed with respect to ballast treatment, focusing especially on the use of high-salinity water to (a) flush NOBOB ballast tanks and (b) treat low salinity ballast water moved by coastwise shipping.

6. A standardized sampling program targeting key coastal ecosystems in the U.S. is needed to provide the high-quality data necessary to delineate and measure the performance of different vector management actions.

7. A significant effort should be devoted to understanding the relationship between propagule supply (dosage) and invasion risk. The quantitative relationship between propagule pressure and invasion establishment remains a fundamental gap in knowledge, yet it is at the core of defining management goals (such as ballast discharge standards) and predicting the effectiveness in preventing future invasions.

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