SCIENCE ADVICE FROM THE RISK ASSESSMENT FOR SHIP-MEDIATED INTRODUCTIONS OF AQUATIC NONINDIGENOUS SPECIES TO THE GREAT LAKES AND FRESHWATER ST. LAWRENCE RIVER

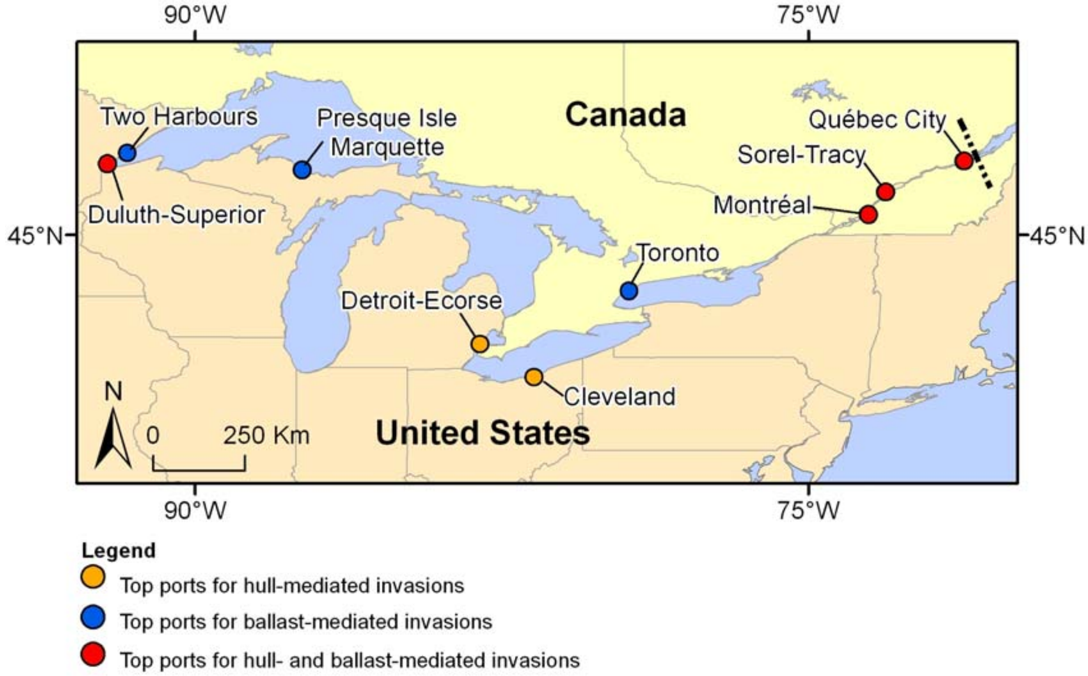

Figure 1. Locations of top Great Lakes/St. Lawrence River (GLSLR) ports based on the number of vessel arrivals or volume of ballast water discharged.

Context :

Transport Canada (Marine Safety) is tasked with managing a regulatory program that sets shipping procedures in order to reduce the risk of ship-mediated transfer of invasive species. Current ballast water regulations are being revised and Transport Canada has submitted a formal request to Fisheries and Oceans Canada (DFO) for science advice on the level of risk posed by the commercial shipping vector to Canadian waters. DFO's Centre of Expertise for Aquatic Risk Assessment (CEARA) has established guidelines for assessing biological risk of aquatic invasive species in Canada.

The objective of the current advisory process is to assess the level of risk posed by ships transiting to, or from freshwater ports in the Great Lakes/St. Lawrence River (GLSLR) for the introduction of aquatic invasive species to Canadian waters and the level of risk posed by domestic shipping activities.

This Science Advisory Report is from the Fisheries and Oceans Canada, Canadian Science Advisory Secretariat national meeting held March 1-2, 2011 in Burlington ON to assess the risk of ship-mediated introduction of nonindigenous species. Additional publications from this process will be posted as they become available on the DFO Science Advisory Schedule at http://www.dfo-mpo.gc.ca/csas-sccs/index-eng.htm.

SUMMARY

- Freshwater ports of the Great Lakes and St. Lawrence River (GLSLR) are utilized by international and domestic ships, resulting in potential for species transfers between connected ports *via* hull fouling and ballast water discharge vectors.
- Introduction of nonindigenous species (NIS) can potentially cause great ecological, social and economic harm to an area.
- This study ranks relative risk posed by ship-mediated introduction of NIS to GLSLR ports based on 2005-2007 shipping data and recent environmental data.
- Montréal, QC, Québec City, QC and Duluth-Superior, MN-WI are identified as GLSLR ports with the highest relative risk of environmental consequences due to introduction of NIS *via* hull fouling.
- Duluth-Superior, MN-WI is the GLSLR port with the highest relative risk of environmental consequences due to introduction of NIS *via* ballast water discharge while Québec City, QC and Montréal, QC are at an intermediate level of relative risk.
- Biological sampling of ship vectors should be conducted to further quantify/calibrate invasion risk with attention to species-specific and site-specific characteristics.
- Future research and/or monitoring activities in the GLSLR should be prioritized at the top ports identified as higher risk by this assessment.
- If shipping traffic patterns or climate conditions in the GLSLR change, a re-assessment may be required.

INTRODUCTION

It is now common to hear of negative impacts to natural ecosystems caused by nonindigenous species (NIS). NIS are the second greatest cause of extinction globally and the greatest threat to biodiversity in freshwater ecosystems. Long-term economic consequences of NIS have cost industry and society (directly and indirectly) an estimated $13.3 to $34.5 billion/year in Canada.

Founding individuals, called propagules, must arrive at a new location and must be able to survive the environmental conditions of the new area. They must survive long enough and in great enough numbers to reproduce and become established in an area. They may then spread from the localized area of establishment by various means to become widespread in a region. Shipping has been identified as a major vector in the transport of aquatic NIS around the world.

Ballast water is pumped into ballast tanks of a ship to control trim and stability, and to prevent hull stress. Diverse communities of plankton present in the water are inadvertently pumped into ballast tanks as the water is loaded. At port, sediments and their associated organisms can be re-suspended by shipping activities and also taken in with ballast water. Ballast water may then be transported to a new port and discharged, providing opportunity for release of NIS.

Vessel type, size and trade patterns influence the invasion risk associated with a particular vessel. Merchant vessels such as bulk carriers and tankers are higher risk for ballast-mediated transport of NIS, while ships that do not regularly discharge ballast such as tugboats and passenger ships are less important for introductions *via* ballast. Trans-oceanic vessels have been considered the primary pathway for NIS introductions since they connect distant ports, but domestic or coastal vessels contribute to secondary spread of established NIS within a region.

Hull fouling is another means by which shipping activities can transport NIS around the world. Sessile organisms such as algae, hydroids, bryozoans, barnacles and other bivalves can form dense colonies on external underwater surfaces that may provide structural habitat and protection for crustaceans and other mobile taxa. Fouling taxa can become detached or release reproductive propagules anywhere along the shipping route.

As with ballast water, operational characteristics of the vessel and its trading patterns influence invasion risk. Invasion risk increases with increased mooring time and time elapsed since last application of antifouling coating system. Risk decreases as vessel speed increases, producing shear forces that can remove or kill organisms attached to the hull. In addition, trade route can influence risk: ships which pass through highly variable environments, such as moving from low salinity coastal waters to euhaline ocean waters, pose lower risk than ships operating within a more continuous environment.

Ballast Water Management Regulations

Ballast water exchange (BWE) is a process by which a ship exchanges ballast water loaded at port with water from the open ocean. It is hypothesized that any open-ocean taxa released with exchanged ballast water will not thrive in coastal and freshwater port environments and will be low-risk for invasion. In 2000, Canada established ballast water management regulations which require all vessels at least 50 m in length and having at least eight m^3 ballast capacity, that enter and operate in Canadian waters, to conduct BWE at sea. There are the following exceptions:

(i) Ships that operate exclusively in Canadian waters;

(ii) Vessels used in government non-commercial service;

(iii) Ships that carry only permanent ballast in sealed tanks.

In order to maximize BWE efficiency, ballast tanks that are exchanged by the empty-refill method must replace at least 95% of their ballast water while vessels conducting flow-through exchange must pump a minimum of three tank volumes through each ballast tank. The exchanged ballast water must have a final salinity of ≥ 30‰. BWE must be conducted at least 200 nautical miles from land at ≥ 2000 m depth. If a vessel does not pass through an appropriate exchange area, Canada will accept exchange in an alternate exchange zone (≥ 50 miles offshore and ≥ 500 m depth).

In 2006, additional regulations were implemented to reduce the risk of invasion posed by organisms in residual water or sediment in ballast tanks considered empty by industry standards. These tanks must now be flushed with open ocean water to achieve a final salinity of ≥ 30‰. Ballast sediment must now be monitored and should be disposed of at a reception facility.

Studies indicate that BWE physically removes 80-100% of coastal planktonic organisms, and further reduces the risk of freshwater or low salinity NIS by causing salinity shock. However, in accordance with proposed international standards, BWE is to be phased out and replaced by shipboard ballast water treatment systems, such as filtration, biocides and/or chlorination, by 2016.

Specific Issues of Concern

The Great Lakes region is one of the most ecologically diverse areas in North America, containing a variety of unique habitats with over 150 fish species and 50 native plant communities. The St. Lawrence River, which contains freshwater, brackish-water and marine regions, connects the Great Lakes to the Atlantic Ocean. Natural barriers prevented large ocean-going ships from traversing the entire passage until 1959, when a series of locks and canals were constructed and the St. Lawrence Seaway was opened. The establishment of aquatic NIS is the greatest environmental problem threatening the Great Lakes. At least 182 aquatic NIS are established in the GLSLR, making the system one of the most highly invaded ecosystems globally. Invasion patterns have changed over time with the evolution of the Seaway and changes in the shipping vector; approximately 55–70% of established aquatic NIS introduced after the Seaway opened are attributed to ballast water release.

While a number of established aquatic NIS are foreign species attributed to international vessels, nine species native to rivers of the North American east coast have established in the Great Lakes. In addition, 13 species first introduced to the St. Lawrence River have since invaded the Great Lakes, indicating domestic ship traffic may also be an important pathway for new introductions and/or secondary spread of NIS. Domestic shipping operations account for ~95% of ballast water discharges in the GLSLR (68 million tonnes). Domestic ports may act as a source of new NIS if species native to the source port are not native to the recipient port or they may serve as ‘stepping stone’ ports if NIS initially introduced (by any vector) establish at those ports.

In the GLSLR there has been little attention paid to hull fouling since it has been a viable vector for less than 3% of established aquatic NIS; however, a ban on the very effective, but very toxic, tributyl tin-based anti-fouling paint in 2008 may result in increased risk. A recent study suggested that hull fouling is unimportant for new introductions of NIS due to the fact that international vessels must pass though high salinity marine water *en route* to the Great Lakes. Nonindigenous freshwater taxa would be killed, while coastal and marine organisms more likely to survive the voyage would not survive in the fresh water of the GLSLR. Hull fouling may be an important vector for secondary spread of established freshwater NIS within the GLSLR *via* domestic ships which do not cross high salinity waters.

RISK ASSESSMENT

For this analysis the GLSLR was defined as all freshwater ports in the five Great Lakes (Superior, Michigan, Huron, Erie and Ontario) and the St. Lawrence River, west of and including Québec City. Shipping activities during 2005-2007 (or at least a twelve month subset of that data) were used to assess risk for species transported by ballast water and hull fouling. Information on vessel type, ballast water status and discharge volume at specific GLSLR ports was combined with data on environmental conditions at Canadian and international ports directly connected to top GLSLR ports to estimate relative probabilities of introduction. Data on the number of high impact NIS at connected ports was used to determine the potential consequences of introduction. The probability of NIS introduction and magnitude of consequences were subsequently combined to determine the final relative invasion risk at top GLSLR ports.

Information Sources and Ship Categorization

Several data sources were utilized, including the Canadian Coast Guard's Information System on Marine Navigation, Transport Canada's Ballast Water Database, the U.S. National Ballast Information Clearinghouse, the U.S. Coast Guard's National Vessel Movement Centre and Rup et al. (2010), to obtain records of arrival and departure events, and cargo and ballast operations in port, for all commercial vessels operating at Canadian and American ports in the GLSLR. Because the U.S. data was available only for merchant vessels, this analysis does not include non-merchant vessels. Shipping data was organized by port, month of arrival, and operational region (Laker, Coastal Domestic and International) (Table 1).

Table 1. Vessel classification system based on operational region and ship type with corresponding definitions and examples.

Vessel classification	Definition/Example
Operational region	
Laker	Vessels that operated exclusively within the GLSLR region during the study period and are not required to conduct ballast exchange/flushing
Coastal domestic	Vessels that operated exclusively within the Canadian Exclusive Economic Zone (EEZ) during the study period and are not required to conduct ballast exchange/flushing
International	Vessels that operated outside of the Canadian EEZ for at least part of the study period and are required to conduct ballast exchange/flushing prior to entering the Canadian EEZ; some vessels will move domestic ballast water (not required to exchange/flush) on subsequent voyages within the EEZ
Ship type	
Merchant	Bulk carriers, tankers, general cargo, and roll on/roll off vessels

The Nature Conservancy's Marine Invasive Database (Molnar *et al*. 2008) contains a list of invasive species and classifies them by geographic region, potential pathway of spread (i.e., hull fouling or ballast water) and expected impact on an invaded ecosystem. High impact NIS were defined as those that disrupt multiple species, ecosystem function and/or keystone or threatened species. The Marine Invasive Database is limited to coastal ecoregions, therefore we created an inland GLSLR ecoregion by applying the same criteria as Molnar et al. (2008) against the 182 established NIS listed in the Great Lakes Aquatic Nonindigenous Species Information System (available at http://www.glerl.noaa.gov/res/Programs/ glansis/glansis.html).

Determination of Hull Fouling-Mediated Invasion Risk

Relative risk of invasion *via* hull fouling was estimated using the following steps.

1. PROBABILITY OF ARRIVAL: The number of vessel arrivals was used as a coarse proxy for number of propagules introduced to a port by hull fouling, recognizing that factors such as voyage history and anti-fouling management practices can have strong influence on arrival probability but are much more difficult to assess; this estimate therefore has moderate uncertainty. Due to the large number of ports in the region and limited time and resources available to complete the risk assessment, the top three ports in each vessel category were prioritized for further assessment.
2. PROBABILITY OF SURVIVAL: Given that global research indicates that hull fouling is an important vector for coastal marine ports but not freshwater ports, the probability of survival of propagules at potential recipient GLSLR ports was estimated to be lowest if the recipient port was freshwater and highest if the recipient port was brackish or saline; however, the probability of survival was set at highest for ships operating exclusively in the GLSLR because any fouling organisms would be freshwater and would not be exposed to salt water. This estimate carries a moderate level of uncertainty since salinity can vary both spatially and temporally with a single port and because other physical variables such as pH, dissolved oxygen or depth, and biological factors such as species interactions influence survival but could not be addressed considering the wide array of requirements by different species in a pathway risk assessment.
3. PROBABILITY OF INTRODUCTION: The probabilities of arrival and survival were combined to determine the probability of introduction. Since both arrival and survival must occur for NIS establishment, the lowest probability was retained as the probability of introduction. The highest level of uncertainty was retained for this estimate.
4. MAGNITUDE OF POTENTIAL CONSEQUENCES: A list of high impact fouling NIS established in all connected source ports was used to estimate the magnitude of potential consequences, assuming that a greater number of high impact NIS with potential for introduction would result in a greater overall impact on that port. Since data for high impact species was available for ecoregions rather than specific ports and it is difficult to predict effects of NIS introduced to new locations, the level of uncertainty associated with this estimate is moderate.
5. RELATIVE RISK: The probability of introduction was combined with the magnitude of potential consequences using a risk matrix (Table 2) to determine the overall level of risk posed to individual ports by the hull fouling vector. The highest level of uncertainty associated with the two input components was retained.

Table 2 The mixed rounding symmetrical approach used to combine probability of introduction and magnitude of potential impact ratings to determine final invasion risk at each GLSLR top port for each ship category. Five levels of probability and impact ratings ranging from lowest (blue) to highest (red) are combined into a final invasion risk ranging from lower (green) to higher (orange).

Magnitude of potential impact	Probability of introduction: Lowest	Lower	Intermediate	Higher	Highest
Highest					
Higher					
Intermediate					
Lower					
Lowest					

6. SECONDARY SPREAD: An additional measure, called ship-mediated spread potential, was determined to rank a port's potential to facilitate stepping-stone, or inter-regional, invasions *via* hull fouling. Assuming that each domestic vessel that arrived at a GLSLR port would subsequently depart to a different Canadian port, the number of domestic vessel arrivals was used to estimate potential for secondary spread. Since this estimate considers only one of many potential vectors of secondary spread and measures risk nationally rather than for a specific port, it was not included in the calculation of relative risk.

Determination of Ballast-Mediated Invasion Risk

Relative risk to GLSLR ports via ballast water was assessed using the following steps.

1. PROBABILITY OF ARRIVAL: The volume of ballast water discharged was used to estimate the number of propagules introduced to a port by ballast water, recognizing that volume of ballast water discharged is not a direct measurement of the probability of arrival. Correction factors were applied to account for the decreased number of propagules in exchanged ballast water. The last port of call was assumed to be the ballast source when records were not available. This estimate was considered to have low uncertainty. Due to the large number of ports in the region and limited time and resources available to complete the risk assessment, the top three ports in each vessel category were prioritized for further assessment.
2. PROBABILITY OF SURVIVAL: The fundamental physical factors affecting survival and reproduction of aquatic organisms are temperature and salinity. These factors were used to calculate an environmental similarity (ES) ranking for each source-recipient port- pair. The average ES of all ports directly connected to each top GLSLR port was used as a measure of probability of survival at each port. This estimate had a moderate degree of uncertainty because other physical variables, such as pH, dissolved oxygen or depth, and biological factors, such as species interactions, influence survival but could not be addressed considering the wide array of requirements by different species in a pathway risk assessment.
3. PROBABILITY OF INTRODUCTION: The probabilities of arrival and survival were combined to determine the probability of introduction. Since both arrival and survival

must occur for NIS establishment, the lowest probability was retained as the probability of introduction. The highest level of uncertainty was retained for this estimate.

4. MAGNITUDE OF POTENTIAL CONSEQUENCES: A list of high impact ballast-mediated NIS established in all connected source ports was used to estimate the magnitude of potential consequences, assuming that a greater number of high impact NIS with potential for introduction would result in a greater overall impact on that port. Since data for high impact species was available for ecoregions rather than specific ports and it is difficult to predict effects of NIS introduced to new locations, the level of uncertainty associated with this estimate is moderate.
5. RELATIVE RISK: The probability of introduction was combined with the magnitude of potential consequences using a risk matrix (Table 2) to determine the overall level of risk posed to individual ports by NIS transported in ballast water. The highest level of uncertainty associated with the two input components was retained.
6. SECONDARY SPREAD: An additional measure, called ship-mediated spread potential, was determined to rank a port's potential to facilitate stepping-stone, or inter-regional, invasions *via* ballast water. Assuming that each domestic vessel that loaded ballast water at a GLSLR port would subsequently discharge that ballast at a different Canadian port, the number of ballast uptakes was used to estimate potential for secondary spread. Since this estimate considers only one of many potential vectors of spread, and applies to the region rather than a port, it was not included in the calculation of relative risk.

Results

The results of the risk assessment indicating relative invasion risk posed to, and the potential spread from, top GLSLR ports by hull fouling are presented in tables 3 and 4. The results of the ballast water mediated risk assessment for the top GLSLR ports are presented in tables 5 and 6.

Table 3. Relative invasion risk to top GLSLR ports by hull fouling NIS, by vessel category, with level of uncertainty indicated in brackets below each column heading.

	P(Introduction) (moderate)	**Magnitude of consequence** (moderate)	**Invasion risk** (moderate)
Top ports for international merchant arrivals			
Montréal, QC	Lowest	Highest	Intermediate
Québec City, QC	Lowest	Higher	Intermediate
Sorel-Tracy, QC	Lowest	Intermediate	Lower
Top ports for coastal domestic merchant arrivals			
Montréal, QC	Lowest	Lowest	Lower
Québec City, QC	Lowest	Lowest	Lower
Sorel-Tracy, QC	Lowest	Lowest	Lower
Top ports for Laker merchant arrivals			
Duluth-Superior, MN-WI	Higher	Lowest	Intermediate
Detroit-Ecorse, MI	Intermediate	Lowest	Lower
Cleveland, OH	Lower	Lower	Lower

Table 4. Departure statistics for coastal domestic and Laker vessels from top GLSLR ports as a measure of potential for hull-mediated secondary spread.

	Annual number of departures	P(Spread)
Top ports for international merchant vessels		
Montréal, QC	291	Lower
Québec City, QC	278	Lower
Sorel-Tracy, QC	145	Lowest
Top ports for coastal domestic merchant vessels		
Montréal, QC	291	Lower
Québec City, QC	278	Lower
Sorel-Tracy, QC	145	Lowest
Top ports for Laker merchant vessels		
Duluth-Superior, MN-WI	749	Highest
Detroit-Ecorse, MI	512	Higher
Cleveland, OH	369	Intermediate

Table 5. Relative invasion risk to top GLSLR ports by ballast-mediated NIS, by vessel category, with level of uncertainty indicated in brackets below each column heading.

	P(Introduction) (moderate)	**Magnitude of consequence** (moderate)	**Invasion risk** (moderate)
Top ports for international merchant ballast water discharges			
Québec City, QC	Lowest	Higher	Intermediate
Sorel-Tracy, QC	Lowest	Intermediate	Lower
Montréal, QC	Lowest	Highest	Intermediate
Top ports for coastal domestic merchant ballast water discharges			
Québec City, QC	Lowest	Lowest	Lower
Montréal, QC	Lowest	Lowest	Lower
Toronto, ON	Lowest	Lowest	Lower
Top ports for Laker merchant ballast water discharges			
Duluth-Superior, MN-WI	Highest	Intermediate	Higher
Two Harbors, MN	Lower	Lower	Lower
Presque Isle-Marquette, MI	Lowest	Lower	Lower

Table 6. Ballast water uptake statistics for coastal domestic merchant and Laker vessels at top GLSLR ports as a measure of potential for ballast-mediated secondary spread.

	Annual number of ballast water uptake events	P(Spread)
Top ports for international merchant vessels		
Québec City, QC	138	Higher
Sorel-Tracy, QC	119	Intermediate
Montréal, QC*	212	Highest
Top ports for coastal domestic merchant vessels		
Québec City, QC	138	Higher
Montréal, QC	212	Highest
Toronto, ON	93	Intermediate
Top ports for Laker merchant vessels		
Duluth-Superior, MN-WI	44	Lower
Two Harbors, MN	1	Lowest
Presque Isle-Marquette, MI	27	Lowest

Sources of Uncertainty

Pathway risk assessments must consider a large variety of species transported across time, many of which are unknown. As a result, there is a reliance on more generalized methods, which have an inherent level of uncertainty.

The number of ship arrivals and volume of ballast water discharged were used as proxy measures of probability of arrival. While these measures are commonly used in the literature, they are not direct measures of propagule supply, and their use adds a level of uncertainty to the assessment.

Port-specific attributes, including environmental conditions (temperature and salinity) and species composition vary both temporally and spatially, and are not well-documented globally, providing another key source of uncertainty.

Five equal categories were used in this risk assessment to rank probabilities and risk levels, based on the assumption of a linear relationship, which is consistent with invasion theory but not quantified.

CONCLUSIONS

Freshwater ports of the Great Lakes and St. Lawrence River (GLSLR) are connected to international and coastal domestic ports, resulting in potential for species transfers *via* hull fouling and/or ballast water discharge.

More than 90% of ship arrivals and ballast water discharge originated from domestic ports, making domestic vessels the most important mechanism for movement (secondary spread) of nonindigenous species (NIS) in the GLSLR region.

Montréal, QC, Québec City, QC and Duluth-Superior, MN-WI are identified as GLSLR ports with the highest relative risk of environmental consequences due to introduction of NIS *via* hull fouling. Duluth-Superior, MN-WI is the GLSLR port with the highest relative risk of environmental consequences due to introduction of NIS *via* ballast water discharge while Québec City, QC and Montréal, QC are at an intermediate level of relative risk.

Burns Harbour, IN; Nanticoke, ON; and St. Clair, MI are potentially important sources of ballast-mediated NIS for Duluth-Superior due to relatively high propagule supply and environmental similarity.

The authors recommend biological sampling of ship vectors and recipient port habitats to quantify/calibrate invasion risk with consideration of species-specific and site-specific characteristics. Future research should be prioritized at the ports identified as higher risk by this assessment.

OTHER CONSIDERATIONS

This pathway risk assessment was based on 2005-2007 shipping data and recent environmental data, representing only a snapshot in time. If shipping traffic patterns in the GLSLR or global climate conditions change significantly, a re-assessment may be required.

The ranking system used in this risk assessment is relative, allowing prioritization of GLSLR ports. Ports identified as higher risk in this study may not be high risk in a national scale considering, for example, the relatively low international shipping traffic in the region. Furthermore, delineating an acceptable level of risk is a decision to be made by risk managers and/or stakeholders.

SOURCES OF INFORMATION

This Science Advisory Report is from the Fisheries and Oceans Canada, Canadian Science Advisory Secretariat, national advisory meeting of March 1-2, 2011 on Risk Assessment for ship-mediated introductions of aquatic nonindigenous species to the Great Lakes and the Canadian Arctic. Additional publications from this process will be posted as they become available on the DFO Science Advisory Schedule at http://www.dfo-mpo.gc.ca/csas-sccs/index-eng.htm.

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Internet address: www.dfo-mpo.gc.ca/csas

ISSN 1919-5079 (Print)
ISSN 1919-5087 (Online)

La version française est disponible à l’adresse ci-dessus.

CORRECT CITATION FOR THIS PUBLICATION

DFO. 2012. Science advice from the risk assessment for ship-mediated introductions of aquatic nonindigenous species to the Great Lakes and freshwater St. Lawrence River. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2011/066.