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Quantification of risks of alien species introductions associated with ballast water discharge in the Gulf of St. Lawrence

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Abstract

Canada has one of the longest navigable coastlines in the world, bordering the Atlantic, Arctic and Pacific Oceans, as well as the Great Lakes. Shipping is important to the Canadian national and international trade. Our coastal waters receive yearly over 52 million tonnes of ballast water from foreign ports around the world [Gauthier and Steel (1966) Canadian Manuscript Report of Fisheries and Aquatic Sciences 2380: 1–57]. Millions of tonnes of ballast water are discharged into the estuary of the St. Lawrences River and into the Gulf of St. Lawrence each year [Bourgeois et al. (2001) Rapp. Tech. Can. Sci. Halient Aquat. 2338; viii +34p]. Ballast water has been identified as one of the pathways by which alien aquatic species are introduced outside of their normal range. Under the current Canadian voluntary guidelines, all ships entering Canadian waters are expected to exchange ballast water outside of the Exclusive Economic Zone (EEZ). The 2001 Transport Canada survey showed that 77% of all ships entering the Gulf of St. Lawrence have exchanged ballast water in mid-ocean. Of the remainder, 8.5% were ships that traveled up the North American coastline and declared themselves exempt from the need to exchange. An additional 13% did not have a clear reason for not exchanging and may in fact also be part of the coastal trade. Less then 1% of all ships surveyed declared safety as a reason for not doing the exchange. The current guidelines make provisions for ballast water exchange in 'back-up areas' if, for safety reasons, exchange is not feasible offshore. Incoming foreign ships may exchange their ballast water within the Gulf of St. Lawrence and in the Laurentian Channel southeast of Anticosti Island, where the depth exceeds 300 m. The magnitude of the risk such ballast water exchanges pose, compared to risk from ballast water discharge in other areas of the Gulf of St. Lawrence, was evaluated using a probabilistic risk assessment (PRA) model. The risk was measured in terms of quantity of alien species introduced into various parts of the Gulf, including the Laurentian Channel, given current shipping patterns and practices. The relative risk to the Laurentian Channel is 0.5% of the quantity of alien species introduced in the Gulf and Estuary as a whole (including the Laurentian Channel). As the model also calculates the quantity of alien species introduced into other discreet areas of the Gulf of St. Lawrence and the freshwater estuary, it shows that under current shipping patterns and practices other areas of the Gulf of St. Lawrence are at vastly greater risk of alien species introductions through ballast water discharge. The model also shows that the greatest potential for introductions comes from the North American Atlantic Coast (FAO Region A), followed by FAO Region B, which includes the European and Scandinavian coast of the North Atlantic. To date there is no evidence, or official reports of successful ballast-water-mediated introductions of nonindigenous species to the Estuary or the Gulf of St. Lawrence. At this time, the model is restricted to predicting the risk of introductions. It does not incorporate the potential for survival of the alien species introduced. This refinement should be added if

additional data can be obtained. Further, the possibility of introducing alien species into the Gulf of St. Lawrence on the hulls of incoming ships represents an additional risk to the one estimated by the model. In order to obtain a complete picture of the possibility of alien species introductions by shipping, this component of the risk must be quantified.

Introduction

Canada has one of the longest navigable coastlines in the world, bordering the Atlantic, Arctic and Pacific Oceans, as well as the Great Lakes. Shipping plays an important role in Canadian national and international trade. Our coastal waters receive yearly over 52 million tonnes of ballast water from foreign ports around the world, compared to the 121 Mt, 69 Mt, >43 Mt, and 5 Mt received respectively by Australia, the United States, the United Kingdom, and New Zealand (Gauthier and Steel 1966). In addition to this, domestic and coastal shipping are responsible for the translocation of additional quantities of ballast water.

Numerous authors and organizations have recognized aquatic alien species invasions through ballast water discharges as a serious problem threatening global biological diversity and human health worldwide. On November 27, 1997, the International Maritime Organization (IMO) Marine Environmental Protection Committee (MEPC) adopted Resolution A.868(20), "Guidelines for the Control and Management of Ships' Ballast Water to Minimize the Transfer of Harmful Aquatic Organisms and Pathogens". This international initiative was preceeded in Canada, by Voluntary Guidelines introduced in May 1989 for the control of ballast water discharges from ships entering the Great Lakes and St. Lawrence Seaway. These guidelines were in turn prompted by a number of highly visible introductions of non-native fish, other aquatic species and pathogens, which have caused extensive environmental harm and economic hardship. On September 1, 2000, the guidelines introduced for the Great Lakes were extended as national guidelines for all waters in Canada. In February 2004, an IMO convention was put in place that allows the continued use of ballast exchange as a ballast water management technique until specific ballast discharge standards come into force.

Currently, all ships entering Canadian waters are expected to exchange ballast water outside of the Exclusive Economic Zone (EEZ). Despite the presence of clear national guidelines, ships coming up the North American coastline frequently consider themselves exempted from the need to exchange. The current guidelines make provisions for ballast water exchange in 'back-up areas', if ballast water exchange is not feasible offshore for safety reasons. The suitability of these areas for ballast water exchange has yet to be fully assessed. Incoming foreign ships may exchange their ballast waters within the Gulf of St. Lawrence and in the Laurentian Channel southeast of Anticosti Island where the depth exceeds 300 m (located east of 63° W longitude) (Figure 1). This situation changes the risk for ballast water-mediated introductions in this ecosystem. The magnitude of the risk such ballast water exchanges pose, compared to the risk from ballast water discharge in other areas of the Gulf of St. Lawrence was evaluated in this study using the method of probabilistic risk assessment (PRA).

Background

To date there is no evidence, or official reports of successful ballast water-mediated introductions of nonindigenous species to the Estuary or the Gulf of St. Lawrence (Gilbert 2002, pers. comm.). Furthermore up to 2002, no nonindigenous species has been reported which would have environmental or socio-economic impacts comparable to those observed in the Great Lakes or elsewhere in the world. The apparent absence of successful ballast water-mediated introductions in the Estuary and Gulf may be a reflection of the

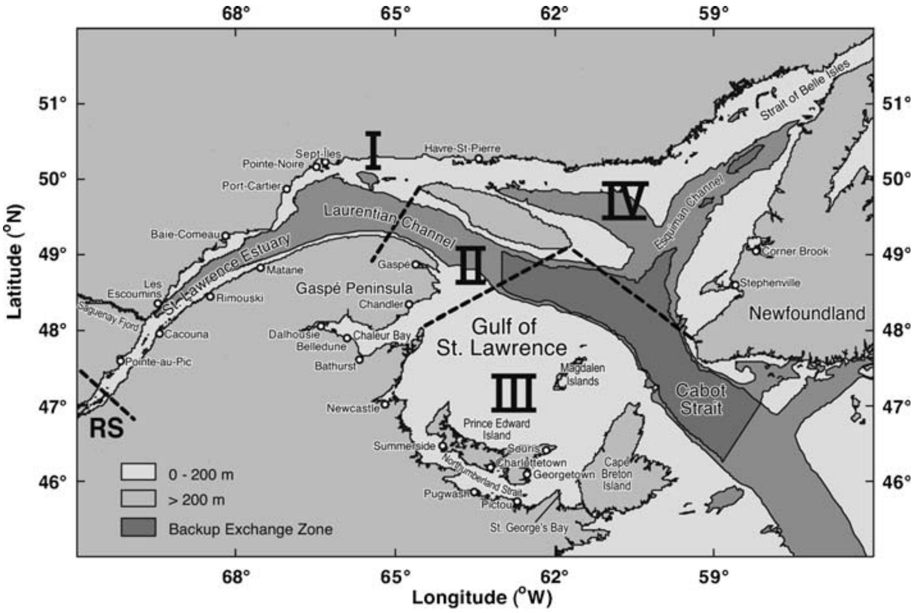

Figure 1. Current alternate ballast water exchange zone east of 63° W longitude for ships proceeding up the St. Lawrence Seaway and Great Lakes and the regions of the Gulf used in the model.

harsh marine climate in this region, or of the sparse biological monitoring in the last decade.

Available reports and databases were reviewed for data that could be used to construct the model. A number of personal interviews were conducted with leading scientists in the region.

In summary, although millions of tonnes of ballast water are discharged into the Estuary and into the Gulf each year (Gauthier and Steel 1996; Bourgeois et al. 2001), the precise volume of discharge is difficult to establish for two main reasons:

1. The data acquisition system to document the origins and volumes of the ballast water relies on the voluntary response of ships' officers. There is no verification.
2. The database of information from ballast water declaration forms collected following the September 2000 extension of the voluntary guidelines has only been in existence since June 2001.

The 2001 Transport Canada survey showed that 77% of all ships entering the Gulf of St. Lawrence have exchanged ballast water in mid-ocean. Of the remainder, 8.5% were ships that traveled up the North American coastline and declared themselves exempt from the need to exchange. An additional 13% did not have a clear reason for not exchanging and may in fact also be part of the coastal trade. Less then 1% of all ships surveyed declared safety as a reason for not doing the exchange. (M. Balaban, pers. comm.)

The study found that the only vessels that could be confirmed to have exchanged ballast water in the Laurentian Channel were those proceeding to the Great Lakes. Details of those ships were obtained from the United States Coast Guard office in Massena, New York. Dominique Tapin, Director of Marine Administration and Technology, for the Shipping Federation of Canada was contacted, as were other shipping representatives, and Transport Canada. No additional ships were identified as having conducted ballast water exchange in the Laurentian Channel until March 2002.

In mid-March 2002, Transport Canada forwarded an analysis of the Eastern Canada Region – Vessel Traffic Service (ECAREG) database developed by G. Herbert of the Department of Fisheries and Oceans, Canada. Data collected show 56 ships using the Laurentian Channel for ballast water adjustment or discharge in 1997 and 43 ships in 2000. Comparing the data collected for year 2000 with the data received from the US Coast Guard in Massena show an overlap of only three ships. The other nine vessels reported by Massena are not captured by the ECAREG database. Further examination of the year 2000 ECAREG data show some ships claiming to have no ballast on board (NOBOB), some which show partial ballast water discharge, and some registering their intention to exchange but with no confirmation that they have done so. Given the uncertainty of the data, a decision was made to base the PRA model on the verified information from the US Coast Guard. The possibility of additional ships using the Laurentian Channel and the impact it would have on the relative risk of introducing alien species in this region were incorporated into a sensitivity analysis (Appendix B).

What percentage of water is actually exchanged when ships report 'full' mid-ocean exchange is the subject of much discussion. Harvey et al. (1999) document that the percentage exchanged varied from 0 to 100% in a sample of 61 ships. The US Coast Guard considers 'full' exchange to mean that 80% of the ballast water was exchanged. In the absence of definitive data, this was the value used in the PRA model.

All relevant reports that were examined indicated high densities of live phytoplankton and zooplankton present in the ballast water being discharged in the Gulf of St. Lawrence. All studies found species in the ballast water not currently present in the Gulf. Encysted life forms were found in the sediments of ballast water tanks.

Taxonomy and population density information is sparse (Locke et al. 1991, 1993; Subba Rao et al. 1994; Harvey et al. 1999; Mallet 2001). The origin of ballast water will influence the number of individuals present and the species composition. However, ballast water remnants and sediment are present in the ballast water tanks as ships travel from port to port. Therefore, the biota of the last port of call does not necessarily correspond entirely to the species present in the ballast water tank. The result is that no two ships, even if arriving from the same point of departure, have the same species composition or densities of individuals. The available data were not extensive enough to incorporate into the PRA model in a meaningful way.

Smith and Kerr (1992) documented concerns about introductions of species transported in ships' ballast waters, and the risk these species posed to Canada's marine resources.

Very little information is available on the possible presence and density of pathogens. However, the threat of introduction of toxic phytoplankton to local mussel farming industries prompted the Canadian Coast Guard (CCG) in 1982 to issue the Notice to Mariners #995. This yearly renewed notice prohibits ships bound for the Mines Seleine's pier, situated in the Grande Entrée Lagoon of the Illes-de-la-Madeleine, Gulf of St. Lawrence, from discharging their ballast water within 10 nautical miles of the islands unless the water was taken on in a well-defined area off Canada's east coast, at a distance of five miles or greater from the shoreline (Gosselin et al. 1995).

The length of the voyage may affect the number of individuals present in the ballast water. The longer the voyage, the fewer species and individuals (M. Gilbert 2002, pers. comm.; J. Martin 2002, pers. comm.; Mallet 2001; MacIsaac et al. 2002). Not enough information is available to correlate the length of voyage with an exact decrease in population density of various taxa, but there is a significant decrease in both the number of species and a number of individual after five days in the ballast water tanks. After 10 days a 75% decrease was observed (Gilbert 2002, pers. comm.).

PRA model

The objective of the risk assessment undertaken was 2-fold:

1. To estimate the risk to the Gulf of St. Lawrence and Estuary, which includes the Laurentian Channel, from exchange and discharge of ballast water therein. The risk is measured in terms of the quantity of alien species introduced. The quantity is expressed as a fraction, in percentage, of the quantity of any alien spe-

cies present in the ballast at origin. By definition, all alien species are considered undesirable. The introduction alone was considered; survival post-introduction was beyond the scope of this model.
2. To estimate the relative risk to the Laurentian Channel. This is estimated as a fraction, expressed in percentage, of the risk to the Gulf of St. Lawrence and Estuary including the Laurentian Channel.

Assumptions

The following assumptions were made either because of paucity of data available or to streamline the model:

1. Due to paucity of data, there is no distinction made between different types of alien species. Consequently, all alien species, once introduced, are considered to have the same potential for adverse effect. Only the quantity of alien species introduced is considered as a measure of risk.
2. The effects of differences in salinity in the ballast water at the point of origin and the point of discharge in the Gulf are not considered due to a lack of data. The difference affects survival once introduced, but not the actual introduction.
3. The effects of the season when the exchange or discharge in the Gulf and Estuary takes place are not considered. This factor affects survival, not the actual introduction, and it was not pursued at this stage of the model.
4. The duration of a ship's voyage has an effect on the mortality of the alien species contained in the ballast water. The longer the voyage, the higher the mortality rate. Based on the limited data available, it is considered that any transit time that is less than five days has no mitigation effect, i.e., mortality rate in the ballast water tank is zero. The mortality rate for any transit time that is greater than five days is assumed to be 50%. This means, an exchange or discharge of ballast water from a ship with a transit time of more than five days would introduce only 50% of the amount of alien species that were present at origin. This assumption allows the model to take into account the transit time and its effects, while keeping the model relatively simple. There is a wide range of transit times recorded for ships coming into the Gulf of St. Lawrence.
5. Ports of origin and destinations are of significance only in terms of transit time. The differences in climate and salinity are not considered.
6. It is assumed that ships that exchange ballast either in mid-ocean or in the Laurentian Channel do a 'full' exchange. In practical terms this means that on average a mid-ocean exchange replaces 80% of the ballast water taken on in the port of origin. Therefore, the fraction of alien species remaining in the ballast water after a mid-ocean exchange is 20% of the amount that was present at origin. This does assume that the distribution of species throughout the tank is uniform during the exchange. We also assume that no mid-ocean species taken on during the exchange poses a threat to the coastal areas of the Gulf and, therefore, it is not considered in this model.
7. An exchange in the Laurentian Channel is considered to replace 80% of the ballast water taken on in the port of origin. That is, the fraction of alien species remaining in the ballast after the exchange is 20% of the amount that was present at origin, again assuming that the distribution within the tank is uniform.
8. No distinction is made between different taxa. All species in all taxa are considered to pose an equal threat.
9. On average only 13 ships bound for the Great Lakes exchange ballast water in the Laurentian Channel. It is assumed that the remaining ships bound for the Great Lakes either exchanged in mid-ocean or are NOBOB ships.

Model description

Using the assumptions made, the PRA model was developed to calculate the risk to the Gulf of St. Lawrence and Estuary (including the Laurentian Channel) and to calculate the relative risk to the Laurentian Channel alone.

Briefly, the steps involved in the development of the model were as follows:

(a) Enumerate the possible ways by which a discharge at ports in the Gulf of St. Lawrence and Estuary can occur.
(b) Enumerate the possible ways by which an exchange in the Laurentian Channel can occur.
(c) Determine for each possible way and thus in total, the quantity of alien species discharged at port, as a fraction of the quantity of alien species present at origin. This is the risk from discharge at port.
(d) Determine for each possible way and thus in total, the quantity of alien species discharged in the Laurentian Channel, as a fraction of the quantity of alien species present at origin. This is the risk from exchange in the Laurentian Channel.
(e) Determine also for each possible way and thus in total, the quantity of alien species discharged at port, as a fraction of the quantity of alien species present at origin in all ships from all FAO regions traveling to the Gulf and Estuary. This is the risk from discharge at port.
(f) Determine for each possible way and thus in total, the quantity of alien species exchanged in the Laurentian Channel, as a fraction of the quantity of alien species present at origin in all ships from all FAO regions traveling to the Gulf and Estuary. This is the risk from exchange in the Laurentian Channel.
(g) Using the above information, determine the total risk to the Gulf and Estuary and the relative risk to the Laurentian Channel.

The possible means of discharge or exchange is developed for a typical ship from the originating region 'i' to destination 'j'. For the purposes of this study, the originating regions are the FAO regions of origin A, B, C, G and all other regions that are collectively referred to herein as region O (Figure 2). The destination zones in the Gulf of St. Lawrence and Estuary are categorized as I, II, III, IV, RS (River Stretch), FWE (Freshwater Estuary), and GL-LC. Destination GL-LC, which represents the Laurentian Channel, is not really a destination zone but is considered as one for modeling purposes (Figure 1).

The many ways in which a discharge or an exchange can occur is enumerated using a method known as the Event Tree method. This method involves identifying the possible ways in which the amount of alien species introduced into the Gulf and Estuary (including the Laurentian Channel) could be mitigated. Then for

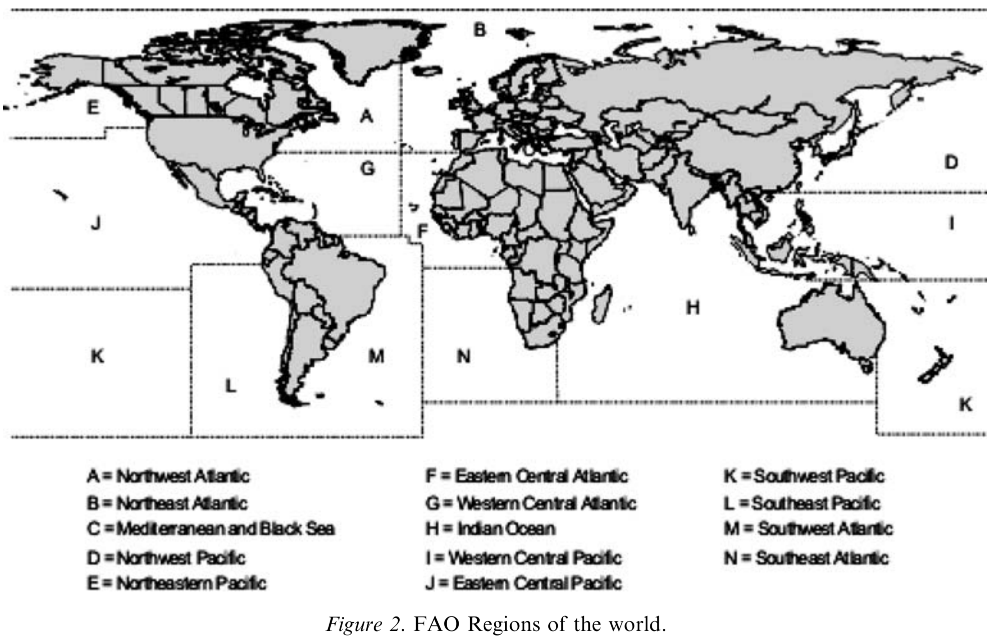

Figure 2. FAO Regions of the world.

a typical ship going from region ‘i’ to destination ‘j’, considering the applicability and success and failures of each mitigation, the different paths or sequences are developed such that each path culminates in an introduction of alien species.

In this study, there are three possible mitigating processes with respect to discharge in port for each ship. These are: the transit time being greater than five days, mid-ocean exchange, and Laurentian Channel exchange. With respect to discharge in the Laurentian Channel, only the transit time is a possible mitigating process. This is because, only ships that did not exchange ballast in mid-ocean would possibly exchange in the Laurentian Channel.

Each mitigation process or system is modeled using a binary model for outcome i.e., each is considered either to be a success or a failure. So, if all combinations of N mitigation processes were possible, then there would be 2^N sequences. Given that we are considering three possible mitigation processes, the maximum number of sequences possible would be $2^3 = 8$. However, as only ships that did not exchange in mid-ocean might exchange in the Laurentian Channel the possible sequences reduce to a total of six. This process is illustrated in the following figure (Figure 3), which represents the event tree for a ship going from region ‘i’ to destination ‘j’.

Top line	
OI-DJ	Ship from region ‘i’ going to destination ‘j’
T > 5 days	Transit time of the ship is greater than five days
ME	Mitigation through mid-ocean exchange
CE	Mitigation through exchange in the Laurentian Channel
Right column	
IJ N	Sequence number N for a ship from origin “i” going to destination “j”

As described above, each mitigation process has two possible outcomes; corresponding to each mitigating process. Success is depicted by the top horizontal branch and failure by the bottom branch. The six sequences depict the following possibilities:

Sequence number	Transit time > 5 days?	Mid-ocean exchange	Channel exchange
IJ 1	Yes	Yes	Not done
IJ 2	Yes	No	Yes
IJ 3	Yes	No	No
IJ 4	No	Yes	Not done
IJ 5	No	No	Yes
IJ 6	No	No	No

Sequence IJ 1 represents the possibility that the transit time is greater than five days and the

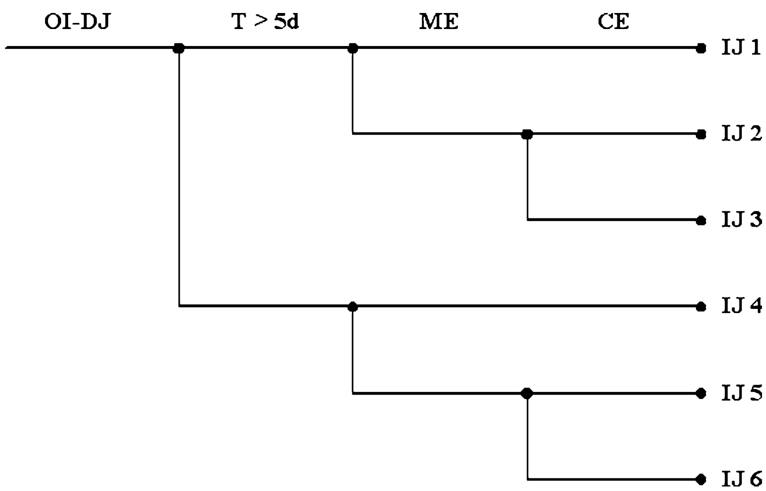

Figure 3. Event tree for region I and destination J – discharge in port.

ship exchanges ballast in mid-ocean. Therefore, it will not exchange ballast in the Laurentian Channel. Similarly, sequence IJ 6 can be interpreted to represent the possibility that the transit time is no more than five days and the ship does not exchange ballast either in mid-ocean or in the Laurentian Channel. Figure 3 depicts the model for risk from discharge at the ports. The same model with some modification can be used to obtain the risk from exchange in the

Table 1. Average number of ships discharging or exchanging in the Gulf of St. Lawrence per year (after Bourgeois et al. 2001).

From origin	Arriving at destination						
	I	II	III	IV	RS	FWE	GL-LC
A	62.0	22.0	9.0	12.0	35.0	47.0	11.0
B	267.0	21.0	20.0	25.0	446.0	93.0	0.3
C	54.0	4.0	5.0	2.0	88.0	27.0	0.3
G	40.0	35.0	32.0	32.0	145.0	41.0	1.0
O	9.0	5.0	1.0	1.0	72.0	23.0	0.3

Table 2. Average volume of ballast, tones per ship (after Bourgeois et al. 2001).

From origin	Arriving at destination						
	I	II	III	IV	RS	FWE	GL-LC
A	14.40	0.70	0.20	0.30	7.3	3.5	2.30
B	14.40	0.70	0.20	0.30	7.3	3.5	2.30
C	14.40	0.70	0.20	0.30	7.3	3.5	2.30
G	14.40	0.70	0.20	0.30	7.3	3.5	2.30
O	14.40	0.70	0.20	0.30	7.3	3.5	2.30

Table 3. Probability of ballast exchange or treatment.

From origin	Arriving at destination						
	I	II	III	IV	RS	FWE	GL-LC
(a) Probability of average transit time > 5 days, $p_{T, ij}$							
A	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C	1.00	1.00	1.00	1.00	1.00	1.00	1.00
G	0.50	0.50	0.50	0.50	0.50	0.50	0.50
O	1.00	1.00	1.00	1.00	1.00	1.00	1.00
(b) Probability of mid-ocean exchange, $p_{ME, ij}$							
A	0.15	0.15	0.15	0.15	0.15	0.15	0.15
B	0.90	0.90	0.90	0.90	0.90	0.90	0.90
C	0.90	0.90	0.90	0.90	0.90	0.90	0.90
G	0.60	0.60	0.60	0.60	0.60	0.60	0.60
O	0.90	0.90	0.90	0.90	0.90	0.90	0.90
(c) Probability of Channel exchange (given no mid-ocean exchange), $p_{CE, ij}$ (%)							
A	0.00	0.00	0.00	0.00	0.00	0.00	1.00
B	0.00	0.00	0.00	0.00	0.00	0.00	1.00
C	0.00	0.00	0.00	0.00	0.00	0.00	1.00
G	0.00	0.00	0.00	0.00	0.00	0.00	1.00
O	0.00	0.00	0.00	0.00	0.00	0.00	1.00

Table 4. Mitigation effectiveness.

From Origin	Arriving at destination						
	I	II	III	IV	RS	FWE	GL-LC
(a) Mitigation effectiveness of transit Time > 5 days – residual fraction							
A	0.50	0.50	0.50	0.50	0.50	0.50	0.50
B	0.50	0.50	0.50	0.50	0.50	0.50	0.50
C	0.50	0.50	0.50	0.50	0.50	0.50	0.50
G	0.50	0.50	0.50	0.50	0.50	0.50	0.50
O	0.50	0.50	0.50	0.50	0.50	0.50	0.50
(b) Mid-ocean exchange effectiveness – residual fraction							
A	0.20	0.20	0.20	0.20	0.20	0.20	0.20
B	0.20	0.20	0.20	0.20	0.20	0.20	0.20
C	0.20	0.20	0.20	0.20	0.20	0.20	0.20
G	0.20	0.20	0.20	0.20	0.20	0.20	0.20
O	0.20	0.20	0.20	0.20	0.20	0.20	0.20
(c) Channel exchange mitigation effectiveness – residual fraction							
A	0.20	0.20	0.20	0.20	0.20	0.20	0.20
B	0.20	0.20	0.20	0.20	0.20	0.20	0.20
C	0.20	0.20	0.20	0.20	0.20	0.20	0.20
G	0.20	0.20	0.20	0.20	0.20	0.20	0.20
O	0.20	0.20	0.20	0.20	0.20	0.20	0.20

Laurentian Channel. Only two of the six sequences, viz., sequences IJ 2 and IJ 5, represent the possibility of exchange in the Laurentian Channel. Based on this fact the quantity of alien species introduced in the Laurentian Channel can be calculated.

Appendix A details the mathematical model that was used for calculating the risk estimates. An uncertainty analysis is usually performed to quantify uncertainties in the input data and hence the results, which are point estimates. Due to resource constraints, only mean estimates are provided, and an uncertainty analysis was not performed.

Where input data vary and could be considered to be random variables, their true values can only be estimated to a degree of certainty that depends on the sample used for estimation. The input data are usually mean values, and therefore the results are also mean values. Quantifying the uncertainty will provide limits for the mean value. The limits are called confidence limits, as it can be stated with a defined level of confidence that the true mean value of the result would fall within these limits.

Appendix B describes the sensitivity analyses that were done as a means of verifying the logic of the model.

Input data

The input data on which the risk estimates are based, are given in Tables 1–4.

Table 1 gives the average number of ships from different FAO regions (Figure 2) to the different parts of the Gulf. The data used are from Bourgeois et al. (2001). Their report covers the period 1978–1996. Although there are a total of 13 FAO regions, those regions other than A, B, C, and G are combined together to form the so-called region 'O' (for other) in their report. The average annual traffic from the different regions of the Gulf was also based on Bourgeois et al. (2001).

Of the average 13 ships bound for the Great Lakes, 11 are assumed to come from FAO region A, one from region G, and the rest are equally distributed among regions B, C and O (hence the noninteger values of 0.3 in the table). The Laurentian Channel is treated as a virtual port and is designated as GL-LC.

Table 2 gives the average ballast capacity of ships.

Table 3 gives the likelihood of average transit time being greater than five days, the likelihood of mid-ocean exchange and the conditional likelihood of an exchange in the Laurentian Channel given there was no mid-ocean exchange. Ships from region A have an average transit time that is less than five days (D. Tapin 2002, pers. comm.). Based on the distances, it is considered that all ships from regions B, C and O have an average transit time greater then five days. Again, based on distances, half of the ships from region G are considered to have an average transit time greater than five days. Recently communicated information indicates that on the whole about 78% of the ships that travel to the Gulf of St. Lawrence exchange ballast in mid-ocean (Appendix D). For simplicity, 75% average was used. Only a small percentage of ships from FAO region A exchange in mid-ocean. It is considered reasonable to expect that a much greater percentage of ships from FAO region G would exchange ballast in mid-ocean. Thus, allowing for the possibility that a small percentage of ships from FAO regions B, C and O might not exchange ballast in mid-ocean, a 90% probability of exchange in mid-ocean is assigned to these ships. The probability of mid-ocean exchange for ships from FAO regions A and G were derived assuming that the likelihood for ships from region G is four times that of ships from region A. This leads to probabilities of 15% and 60%, respectively for ships from regions A and G.

Currently, only ships that are bound for the Great Lakes exchange in the Laurentian Channel if they carry ballast and did not already exchange in mid-ocean. This means that the conditional probability of a ballast exchange in the Laurentian Channel is 1 for these ships bound for the Great Lakes (destination GL-LC in Table 3) and 0 for all other ships.

Table 4 gives the effectiveness of mitigation resulting from transit time being greater than five days, and exchange of ballast in mid-ocean and the Laurentian Channel. While not much data are available on the effect of transit time, there is evidence to suggest a 50% mortality rate for ship with a transit time greater than five days. The effectiveness of exchange in both mid-ocean and the Laurentian Channel is assumed to be 80%. That is, the quantity of alien species remaining in the ballast after an exchange is 20% of the quantity that was present in the ballast before the exchange. For the purposes of the model this is called the residual fraction.

Results

The results corresponding to the current situation where the only ships exchanging in the Laurentian Channel are those bound to the Great Lakes are provided in Tables 5 and 6. Both tables provide results for each possible combination of region of origin and destination zone, as well as marginal aggregates and the total aggregate.

Table 5a provides risk of introduction at port, Table 5b provides risk of introduction in the Laurentian Channel, and Table 5c and Table 5d provide total risk of introduction in the Gulf and Estuary including the Laurentian Channel. Table 5c provides the risk from region 'i' to zone 'j' as well as the marginal risk from each of region 'i' and at each of zone 'j'. The risk from region 'i' to zone 'j' is given as a fraction of the ballast from region 'i' that is exchanged or discharged in zone 'j'. The marginal aggregate risk is given as a fraction of ballast that is exchanged or discharged from region 'i' or at zone 'j'. Table 5d provides the risk from region 'i' to zone 'j', the marginal aggregate risk from each of region 'i' and zone 'j', and the total risk to the Gulf and Estuary including the Laurentian Channel, all as a fraction of all the ballast from all regions that is exchanged or discharged in the Gulf and Estuary.

Referring to Table 5a, the results in the table are to be interpreted as follows. They provide an estimate of risk of introduction resulting from discharge of ballast at port. For example, the risk estimate for ships originating in region A with destination in zone II, is 88%. What this means is that the ballast discharged in zone II by a ship from region A would contain 88% of the quantity of alien species that were present in the ballast at the point of origin. Similarly, the ballast discharged in zone IV by a ship from region C would contain 14% of the quantity of alien species that were present in the ballast at the point of origin. Of course, GL-LC being the Channel and only a virtual port, the figures under the column GL-LC are all zero.

The estimate of marginal aggregate risk from ships originating in region A, is 86.4%. (See Appendix A for method of calculation for marginal risk from origin.) This means that the sum

Table 5. Risk of introduction – current scenario.

From origin	Arriving at destination							Risk from origin, %
	I	II	III	IV	RS	FWE	GL-LC	
(a) Risk of introduction at port – fraction of quantity in ballast at origin								
A	88.0	88.0	88.0	88.0	88.0	88.0	0.0	86.4
B	14.0	14.0	14.0	14.0	14.0	14.0	0.0	14.0
C	14.0	14.0	14.0	14.0	14.0	14.0	0.0	14.0
G	39.0	39.0	39.0	39.0	39.0	39.0	0.0	39.0
O	14.0	14.0	14.0	14.0	14.0	14.0	0.0	14.0
Risk at destination, %	26.9	42.8	35.9	37.4	21.9	33.5	0.0	
(b) Risk of introduction in Laurentian Channel – fraction of quantity in ballast at origin								
A	0.0	0.0	0.0	0.0	0.0	0.0	68.0	1.27
B	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.00
C	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.00
G	0.0	0.0	0.0	0.0	0.0	0.0	24.0	0.03
O	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.00
Risk from ships to destination, %	0.0	0.0	0.0	0.0	0.0	0.0	59.7	
(c) Total risk of introduction in Gulf and Estuary – fraction of quantity in ballast at origin								
A	88.0	88.0	88.0	88.0	88.0	88.0	68.0	87.6
B	14.0	14.0	14.0	14.0	14.0	14.0	4.0	14.0
C	14.0	14.0	14.0	14.0	14.0	14.0	4.0	14.0
G	39.0	39.0	39.0	39.0	39.0	39.0	24.0	39.0
O	14.0	14.0	14.0	14.0	14.0	14.0	4.0	14.0
Risk from ships to destination, %	26.9	42.8	35.9	37.4	21.9	33.5	59.7	
(d) Total risk of introduction in Gulf and Estuary – fraction of total quantity in ballast from all origins								
A	6.09	0.11	0.01	0.02	1.74	1.12	0.13	9.24
B	4.17	0.02	0.00	0.01	3.54	0.35	0.00	8.09
C	0.84	0.00	0.00	0.00	0.70	0.10	0.00	1.65
G	1.74	0.07	0.02	0.03	3.20	0.43	0.00	5.51
O	0.14	0.00	0.00	0.00	0.57	0.09	0.00	0.80
Risk at destination	13.00	0.20	0.04	0.06	9.75	2.10	0.14	25.29

Table 6. Relative risk of introduction in the Laurentian Channel.

From origin	Arriving at destination							Risk from origin, %
	I	II	III	IV	RS	FWE	GL-LC	
Relative risk of introduction in Laurentian Channel, fraction of total risk of introduction in Gulf and Estuary								
A	0.0	0.0	0.0	0.0	0.0	0.0	100.0	1.4
B	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0
C	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0
G	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.1
O	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0
Risk from ships to destination, %	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.5

total of the ballast discharged at ports in the Gulf and the Estuary by ships from region A would contain 86.4% of the quantity of alien species that were contained in the ballast of all the ships from region A at origin. The estimate of marginal aggregate risk from ships originating in region B is, 14.0%, the same as the risk estimate at individual zones (except GL-LC).

Similarly, the estimate of marginal aggregate risk in a destination, say zone II, is 42.8%. (See Appendix A for method of calculation for marginal risk at destination.) This means that the sum total of the ballast discharged at ports in zone II by ships from all the FAO regions would contain 42.8% of the quantity of alien species that were contained in the ballast of all the ships traveling to zone II from all the FAO regions.

Table 5b shows the risk of introduction in the Laurentian Channel. The results in this table are also to be interpreted in the same way as those in Table 5a. For example, the ballast discharged in the Laurentian Channel by a ship from region A would contain 68% of the quantity of alien species that were contained in the ballast at origin. As mentioned previously, only ships that are bound for the Great Lakes currently exchange in the Laurentian Channel if they carry ballast and did not already exchange in mid-ocean. Thus, nonzero values are shown only under the column GL-LC. That is, only ships that are bound to the Great Lakes and that exchange in the Laurentian Channel are included here.

Table 5c shows the total risk to different parts of the Gulf and Estuary including the Laurentian Channel. As mentioned previously, this table provides the risk from region 'i' to zone 'j' as well as the marginal risk from each of region "i" and at each of zone 'j'. The risk from region 'i' to zone 'j' is given as a fraction of the quantity of alien species present at origin in the ballast of ships from region 'i' that is exchanged or discharged in zone "j". The marginal aggregate risk for region 'i' is the quantity of alien species discharged in the Gulf and Estuary, given as a fraction of the quantity of alien species present at origin in the ballast of ships from region 'i'. Similarly, marginal aggregate risk for zone 'j' is the quantity of alien species discharged in zone 'j', given as a fraction of the quantity of alien species present at origin in the ballast of all ships from all FAO regions traveling to zone 'j'. The results in this table are also to be interpreted in the same way as those in Table 5a. For example, the ballast discharged in the Gulf and Estuary including the Laurentian Channel by a ship from region B is estimated to contain 14% of the quantity of alien species contained in the ballast at origin. Similarly, the ballast discharged in zone II is estimated to contain 42.8% of the quantity of alien species contained in the ballast of all the ships traveling to zone II from all the FAO regions. Other results are to be similarly interpreted.

Table 5d shows the total risk to the Gulf and Estuary including the Laurentian Channel but as a fraction of all the ballast from all regions that is exchanged or discharged in the Gulf and Estuary. In addition to providing the risk from region 'i' to zone 'j' and the marginal aggregate risk from each of region 'i' and zone 'j', it provides the total risk to the Gulf and Estuary including the Laurentian Channel. The marginal risk can be obtained by a summation of the appropriate row or column, and the total risk can be obtained by a summation of either the row or column of marginal aggregate risk. The results in this table are to be interpreted in the same way as those in Table 5a. For example, the quantity of alien species discharged in the Gulf and Estuary by a ship from region B would be 8.09% of the quantity of alien species contained in the ballast of all the ships from all FAO regions at origin. Similarly, the quantity of alien species discharged in the Gulf and Estuary by a ship arriving in zone I would be 13% of the quantity of alien species that were contained in the ballast of all the ships from all FAO regions at origin. Other results are to be similarly interpreted.

Table 6 provides risk of introduction in the Laurentian Channel (0.5%) relative to the total introduction in the Gulf and Estuary including the Laurentian Channel. This means that the quantity of alien species introduced in the Laurentian Channel is 0.5% of the quantity that is introduced in the Gulf and Estuary as whole, including the Laurentian Channel.

Discussion of results

In Table 5a, the estimate of marginal aggregate risk from ships originating in region A is 86.4%. This means that the sum total of the ballast discharged at port by ships from region A would contain 86.4% of the quantity of alien species that were present at origin. It is slightly less than the 88% risk at individual zones (except GL-LC) because the aggregate is based on all ships originating from region A, which includes ships from region A that are bound for the Great Lakes and that exchange in the Laurentian Channel. The estimate of marginal aggregate risk from ships originating in region B is 14.0%, the same as the risk estimate at individual zones (except GL-LC). This is because, very few ships from region B exchange in the Laurentian Channel, and therefore, do not significantly affect the aggregate estimate. Similar reasoning applies to other regions.

The estimate of marginal aggregate risk at zone II is 42.8%. Risk here is expressed as a fraction of the quantity of alien species present in the ballast at origin of all ships arriving in zone II. This estimate is influenced by the distribution of ships arriving in the zone from different regions. Referring to Table 1, a vast majority of ships arriving in zone I are from region B, which have a transit time greater than five days, and 90% of these ships exchange ballast in mid-ocean. On the other hand, a vast majority of ships arriving in zone II are from regions A and G, and the transit time of all the ships from region A and 50% of the ships from region G are less than five days. Also, only 15% of the ships from region A and 60% of ships from region G would exchange in mid-ocean. This explains why the marginal aggregate risk in zone II is significantly higher than that in zone I. Similar reasoning explains the results for other zones.

From Table 5b, the risk of introduction into the Laurentian Channel is the greatest from ships originating in region A and G. Again, risk here is expressed as a fraction of the quantity of alien species present in the ballast at origin of all ships exchanging in the Laurentian Channel. This is because, most of the ships that exchange in the Laurentian Channel come from these regions. Also, as mentioned above, the transit time of all the ships from region A and 50% of the ships from region G are less than five days; and, only 15% of ships from region A and 60% of ships from region G are considered to exchange ballast in mid-ocean. The marginal aggregate risk in the Laurentian Channel is 59.7%, i.e., the quantity of alien species discharged into the Laurentian Channel is estimated as 59.7% of the quantity of alien species contained in the ballast of the 13 ships that exchange in the Laurentian Channel in a year. However, as explained below, the total risk to the Laurentian Channel is two orders of magnitude less than this.

From Table 5c, ships that originate in region B are estimated to introduce 14% of the quantity of alien species contained in their ballast at origin. This low value is to be expected as their transit time is greater than five days and 90% of them exchange ballast in mid-ocean, both of which are significant mitigating factors. Ships that discharge in zone II introduces 42.8% of the quantity of alien species contained in the ballast of ships from all FAO regions at their origin. Again, risk here is expressed as a fraction of the quantity of alien species present in the ballast at origin. As mentioned in the previous paragraph, the ships that exchange in the Laurentian Channel introduce 59.7% of the quantity of alien species present in these (13) ships at origin. However, as the total ballast carried by these ships is very small compared to the total ballast of all other ships destined to a port in the Gulf and Estuary, the risk from exchange in the Channel is much smaller than what the 59.7% estimate might suggest. This is seen in Table 6, which shows that the relative risk of introduction in the Laurentian Channel is 0.5%. This in itself is an overestimate of the true risk, as the model does not take into account the effect of survival on introductions. From Appendix B it appears that about 50% of ships exchanging in the Laurentian Channel have fresh water or brackish ballast, making the survival of any introduced species unlikely. Further, Gilbert and Saucier (2000) have shown that any particle discharged in the Laurentian Channel is either flushed out or takes days before it impinges on shore. This situation is likely to mitigate the threat species discharged in this area may pose to coastal regions.

In Table 5d, the total risk to the Gulf and Estuary including the Laurentian Channel is estimated to be 25.3%. That is, the quantity of alien species introduced into the Gulf and Estuary is estimated as 25.3% of the quantity of alien species contained in the ballast of the ships from all FAO regions at their origin. Ships from region A going to zone I constitute the single highest risk at 6.1% or about 25% of the total risk. The ships from region B going to zone II constitute the second highest risk at 4.2% or about 20% of the total risk. This is explained as follows. A vast majority of ships from region A do not exchange ballast in mid-ocean and about 30% of these ships discharge their ballast in zone I. About 40% of the ships from region B discharge their ballast in zone I, although a significant number of these ships exchange their ballast in mid-ocean. Ships arriving in zone I carry the most ballast on the average – 14.4 tonnes per ship.

The marginal aggregate total risk at zone I is the highest at 13%, or 50% of the total risk to the Gulf and the Estuary. The reason for this is as explained above. The second highest is the risk to the River Stretch at 9.8% or 38% of the total risk to the Gulf and Estuary. This stems from the fact that 54% of all the ships entering the Gulf travel to the River Stretch ports and they carry an average 7.3 tonnes of ballast per ship. The marginal aggregate risk in the Laurentian Channel is 0.14%, which is only 0.55% of the total risk to Gulf and Estuary including the Laurentian Channel (see below).

The marginal aggregate total risk from ships from region A is the highest at 9.2% followed closely by ships from region B at 8.1%. This is explained by the reasons given above.

In Table 6, the risk of introduction in the Laurentian Channel comes only from those ships that are bound for the Great Lakes. The model considers that only ships that are bound for the Great Lakes exchange in the Laurentian Channel if they carry ballast and did not already exchange in mid-ocean. However, the marginal aggregate risk from each region is very small or nil. The quantity of alien species introduced in the Laurentian Channel is 0.5% of the quantity that is introduced in the Gulf and Estuary including the Laurentian Channel. This means that the quantity that is introduced at port is 99.5% of the quantity that is introduced in the Gulf and Estuary including the Laurentian Channel.

As there is a possibility that additional ships may be using the Laurentian Channel for ballast water exchange, sensitivity analysis was performed to examine the possible impact of this situation. The sensitivity analysis involved increasing the number of ships that discharge in the Laurentian Channel. The relative proportion of ships from different origins was kept the same as in Table 3, but the total number was increased to 43. This number was chosen based on information obtained in mid-March 2002, which indicated that in the recent past as many as 43 ships on the average might have exchanged ballast in the Laurentian Channel. The results from this sensitivity analysis showed that:

- Risk of introduction at port = 25.0%
- Risk of introduction in the Laurentian Channel = 0.46%
- Total risk = 25.5%
- Relative risk of introduction in the Laurentian Channel = 1.79%

Compared to the current situation, the risk at port is slightly less because, while the quantity discharged at port remains the same, there are more ships exchanging in the Laurentian Channel and hence the total amount discharged or exchanged in the Gulf and Estuary increases. As ships that exchange ballast in the Laurentian Channel carry smaller amounts of ballast water, this increase is small.

As can be expected, the risk of introduction in the Laurentian Channel increases. This increase is proportional to the increase in the number of ships exchanging in the Laurentian Channel and is still very small compared to the risks in other parts of the Gulf. In addition, the model is a simplified representation of reality in that it does not account for factors such as survival, dispersal and differences in seasons and salinity.

The results in Tables 5 and 6 provide estimates of the average risk. This is the outcome of using average values for the input data. An uncertainty analysis has not been performed at this time. It is not uncommon to perform uncertainty analyses, and it is recommended that it be part of any future analysis. As explained previously, an uncertainty analysis is usually performed to quantify uncertainties in the input data and hence the results, which are point estimates. Quantifying the uncertainty will provide limits for the mean value. The limits are called confidence limits, as it can be stated with a defined level confidence that the true mean value of the result would fall within these limits.

Conclusion

The risk of alien species introductions from discharge and exchange of ballast water in the various regions of the Gulf of St. Lawrence and

Estuary was estimated using a probabilistic risk assessment model. The overall risk to the Gulf and Estuary including the Laurentian Channel, as measured in this study, is estimated at 25.3%. The relative risk to the Laurentian Channel is estimated as 0.5%, i.e., the quantity of alien species introduced in the Laurentian Channel is 0.5% of the quantity of alien species introduced in the Gulf and Estuary as a whole (including the Laurentian Channel). Ships from region A going to zone I constitute the single highest risk at 6.1% or about 25% of the total risk. The ships from region B going to zone II constitute the second highest risk at 4.2% or about 20% of the total risk. The marginal aggregate total risk at zone I is the highest at 13%, or 50% of the total risk to the Gulf and the Estuary, followed by a risk of 9.8% or 38% at the River Stretch. The marginal aggregate total risk from ships from region A is the highest at 9.2% followed closely by ships from region B at 8.1%.

Due to paucity of data and resource limitations, the PRA model that was developed was simplified and does not account for such factors as survival, migration, and differences in salinity and season. The model was verified through a sensitivity analysis, but the verification is limited to the model logic and not the input data. Risk is measured in terms of the quantity of alien species introduced, expressed as a fraction of the quantity present in the ballast water at origin. This does not account for the actual quantity of ballast discharged or exchanged, or distinguish between the taxa of alien species. Survival and transport of introduced species was not taken into account. While these factors lead to a conservative estimate, they should be addressed in future studies.

Despite the limitations of the current model, it does provide consistent methodology for evaluating risks of alien introductions from ballast water discharges. It shows that the greatest danger to the Gulf of St. Lawrence is posed by coastal shipping from Region A discharging in the ports of Zone I. Therefore, remedying this situation first would provide the greatest return on investment in terms of the environmental health of the Gulf.

Appendix A

Ballast water risk – mathematical model

The following describes the method of calculating risk. Refer to Figure 3 for the different sequences.

Let, for a ship originating in region ‘i’ and destined for zone ‘j’:

$n$ij = number of ships per year
pT, ij = probability of transit time greater than 5 days
pME, ij = probability of mid-ocean exchange
pCE, ij = probability of channel exchange given no mid-ocean exchange
qT, ij = residual after being in transit for greater than 5 days as a fraction of the quantity in the ballast at origin, a measure of voyage mitigation effectiveness
qME, ij = residual after mid-ocean exchange
qCE, ij = residual after Channel exchange as a fraction of the quantity in the ballast prior to exchange, a measure of Channel exchange mitigation effectiveness

The various possibilities are represented in Figure 3.

Ships bound for the Great Lakes only pass through the Gulf and do not discharge at ports in the Gulf and Estuary. With the exception of NOBOB ships, these ships would exchange ballast in the Laurentian Channel if they had not already exchanged ballast in mid-ocean. The amount of alien species introduced in the Gulf and Estuary including the Laurentian Channel, therefore, is the sum of the amount introduced at ports in the Gulf and Estuary and the amount introduced in the Laurentian Channel. Thus, the risk to the Gulf and Estuary including the Laurentian Channel, as it is measured in this study, is the sum of the risk from discharge at ports and risk from exchange in the Laurentian Channel.

Discharge at port

The expected frequency of each sequence weighted by associated mitigation effectiveness is estimated as follows:

$$f\mathrm{ij},1 = (n\mathrm{ij}) \times (p\mathrm{T}\ ,\mathrm{ij}\ q\mathrm{T},\ \mathrm{ij}) \times (p\mathrm{ME},\mathrm{ij}\ q\mathrm{ME},\mathrm{ij})$$

$$f\mathrm{ij},2 = (n\mathrm{ij}) \times (p\mathrm{T},\ \mathrm{ij}\ q\mathrm{T},\ \mathrm{ij}) \times [(1-p\mathrm{ME},\ \mathrm{ij})p\mathrm{CE},\ \mathrm{ij}\ q\mathrm{CE},\ \mathrm{ij}]$$

$$f\mathrm{ij},3 = (n\mathrm{ij}) \times (p\mathrm{T},\ \mathrm{ij}\ q\mathrm{T},\ \mathrm{ij}) \times [(1-p\mathrm{ME},\ \mathrm{ij})(1-p\mathrm{CE},\ \mathrm{ij})]$$

$$f\mathrm{ij},4 = (n\mathrm{ij}) \times (1-p\mathrm{T},\ \mathrm{ij}) \times (p\mathrm{ME},\ \mathrm{ij}\ q\mathrm{ME},\mathrm{ij})$$

$$f\mathrm{ij},5 = (n\mathrm{ij}) \times (1-pT,ij) \times [(1-p\mathrm{ME},\ \mathrm{ij})\ p\mathrm{CE},\ \mathrm{ij}\ q\ \mathrm{CE},\ \mathrm{ij}]$$

$$f\mathrm{ij},6 = (n\mathrm{ij}) \times (1-p\mathrm{T},\ \mathrm{ij}) \times [(1-p\mathrm{ME},\ \mathrm{ij}) \times (1-p\mathrm{CE},\ \mathrm{ij})]$$

Then, in terms of the expected number of ships weighted by mitigation effectiveness, the risk of introduction at port from a ship originating in region 'i' and destined to zone 'j' is given by:

$$s\mathrm{ij} = \Sigma f\mathrm{ij},\ k \quad \text{introductions per year},\ \mathrm{k} = 1,6$$

Risk of introduction at port from ships originating from region 'i' is estimated as:

$$s\mathrm{i} = \Sigma s\mathrm{ij} \text{ introductions per year (summation over 'j') } [\mathrm{i} = \mathrm{A, B, C, G\ \&\ O};\ \mathrm{j} = \mathrm{I\ to\ FWE}]$$

Risk of introduction at port from ships arriving at zone "j" is estimated as:

$$s\mathrm{j} = \Sigma s\mathrm{ij} \text{ introductions per year (summation over 'i') } [\mathrm{i} = \mathrm{A, B, C, G\ \&\ O};\ \mathrm{j} = \mathrm{I\ to\ FWE}]$$

The total risk of introduction at port in the Gulf and Estuary is estimated as:

$$s = \Sigma \mathrm{si} = \Sigma s\mathrm{j} \text{ introductions per year}$$

Let $w\mathrm{ij}$ = the average quantity of ballast in a ship from origin 'i' to destination 'j'.

Then, in terms of the fraction of the quantity of alien species contained in the ballast at origin, the risk of introduction at port from ships originating from origin 'i' and destined to region 'j' is given by:

$$S\mathrm{ij} = (s\mathrm{ij}\ w\mathrm{ij})/(n\mathrm{ij}\ w\mathrm{ij}) = s\mathrm{ij}/n\mathrm{ij}$$

Risk of introduction at port from ships originating from origin 'i' is estimated as:

$$S\mathrm{i} = (\Sigma s\mathrm{ij}\ \mathrm{wij})/(\Sigma n\mathrm{ij}\ w\mathrm{ij}) \quad \text{(summation over j)} \quad [\mathrm{i} = \mathrm{A, B, C, G\&O};\ \mathrm{j} = \mathrm{I\ to\ FWE}]$$

Risk of introduction at port from ships arriving at zone 'j' is estimated as:

$$Sj = (\Sigma s\mathrm{ij}\ \mathrm{wij})/(\Sigma n\mathrm{ij}\ w\mathrm{ij}) \text{ (summation over 'i') } [\mathrm{i} = \mathrm{A, B, C, G\ O};\ \mathrm{j} = \mathrm{I\ to\ FWE}]$$

Risk of introduction at port from all ships exchanging or discharging in the Gulf and Estuary is estimated as:

$$S = (\Sigma s\mathrm{ij}\ w\mathrm{ij})/(\Sigma n\mathrm{ij}\ w\mathrm{ij}) \text{ (summation over 'i' and 'j') } (\mathrm{i} = \mathrm{A, B, C, G\ \&\ O};\ \mathrm{j} = \mathrm{I\ to\ FWE})$$

Exchange in the Channel

Referring to Figure 3, for a ship from origin 'i' destined to region 'j', there are two sequences that would discharge in the Channel. These are sequences IJ2 and IJ5.

$$h\mathrm{ij},2 = (n\mathrm{ij}) \times (p\mathrm{T},\ \mathrm{ij}\ q\mathrm{T},\ \mathrm{ij}) \times [(1-p\mathrm{ME},\ \mathrm{ij})p\mathrm{CE},\ \mathrm{ij}(1-q\mathrm{CE},\ \mathrm{ij})]$$

$$h\mathrm{ij},5 = (n\mathrm{ij}) \times (1-p\mathrm{T},\ \mathrm{ij}) \times [(1-p\mathrm{ME},\ \mathrm{ij})p\mathrm{CE},\ \mathrm{ij}\ (1-q\mathrm{CE},\ \mathrm{ij})]$$

Then, in terms of the expected number of ships weighted by mitigation effectiveness, the risk of introduction in the Channel from a ship originating in region 'i' and destined to zone 'j' is given by:

$$c\mathrm{ij} = h\mathrm{ij},2 + h\mathrm{ij},5 \quad \text{introductions per year}$$

Risk of introduction at port from ships originating from region 'i' is estimated as:

$$c\mathrm{i} = \Sigma c\mathrm{ij} \text{ introductions per year}$$
(summation over 'j')
[i = A, B, C, G & O; j = I to GL-LC]

Risk of introduction in the Channel from ships arriving at zone 'j' is estimated as:

$$c\mathrm{j} = \Sigma c\mathrm{ij} \text{ introductions per year}$$
(summation over 'i')
[i = A, B, C, G & O; j = I-to-GL-LC]

The total risk of introduction in the Channel is estimated as:

$$c = \Sigma c\mathrm{i} = \Sigma c\mathrm{j} \text{ introductions per year}$$

Let $w\mathrm{ij}$ = the average quantity of ballast in a ship from origin 'i' to destination 'j'.

Then, in terms of the fraction of the quantity of alien species contained in the ballast at origin, the risk of introduction in the Channel from ships originating from origin 'i' and destined to region 'j' is given by:

$$C\mathrm{ij} = (c\mathrm{ij}\ w\mathrm{ij})/(n\mathrm{ij}\ w\mathrm{ij}) = c\mathrm{ij}/n\mathrm{ij}$$

The marginal aggregate risk of introduction in the Channel from ships originating from origin 'i' is estimated as:

$$C\mathrm{i} = (\Sigma c\mathrm{ij}\ w\mathrm{ij})/(\Sigma n\mathrm{ij}\ w\mathrm{ij}) \text{ (summation over j)}$$
[i = A, B, C, G & O; j = I to GL-LC]

The marginal aggregate risk of introduction in the Channel from ships arriving at zone 'j' is estimated as:

$$C\mathrm{j} = (\Sigma c\mathrm{ij}\ w\mathrm{ij})/(\Sigma n\mathrm{ij}\ w\mathrm{ij}) \text{(summation over 'i')}$$
(i = A, B, C, G & O; j = I to GL-LC)

Risk of introduction in the Channel from all ships exchanging or discharging in the Gulf and Estuary is estimated as:

$$C = (\Sigma c\mathrm{ij}\ w\mathrm{ij})/(\Sigma n\mathrm{ij}\ w\mathrm{ij})$$
(summation over 'i' and 'j')
(i = A, B, C, G & O; j = I to GL-LC)

Total risk

The total risk to the Gulf and Estuary, in terms of the fraction of the quantity of alien species contained in the ballast at origin, from a ship from origin 'i' destined to region 'j' is given by:

$$g\mathrm{ij} = (s\mathrm{ij}\ w\mathrm{ij} + c\mathrm{ij}\ w\mathrm{ij})/n\mathrm{ij}\ w\mathrm{ij} = (s\mathrm{ij} + c\mathrm{ij})/n\mathrm{ij}$$

The marginal aggregate risk to the Gulf and Estuary from ships originating from origin 'i' is estimated as:

$$G\mathrm{i} = (\Sigma(s\mathrm{ij}\ w\mathrm{ij} + c\mathrm{ij}\ w\mathrm{ij}))/(\Sigma n\mathrm{ij}\ w\mathrm{ij})$$
(summation over j)
(i = A, B, C, G & O; j = I to GL-LC)

The marginal aggregate risk to the Gulf and Estuary from ships arriving at zone 'j' is estimated as:

$$G\mathrm{j} = (\Sigma(s\mathrm{ij}\ w\mathrm{ij} + c\mathrm{ij}\ w\mathrm{ij}))/(\Sigma n\mathrm{ij}\ w\mathrm{ij})$$
(summation over 'i')
(i = A, B, C, G & O; j = I to GL-LC)

The total risk of introduction in the Channel from all ships exchanging or discharging in the Gulf and Estuary is estimated as:

$$G = (\Sigma(s\mathrm{ij}\ w\mathrm{ij} + c\mathrm{ij}\ w\mathrm{ij}))/(\Sigma n\mathrm{ij}\ w\mathrm{ij})$$
(summation over 'i' and 'j')
(i = A, B, C, G & O; j = I to FEW)

The total risk to the Gulf and the Estuary may also be estimated in terms of the fraction of the quantity of alien species contained in the ballast of all ships at origin traveling from all FAO regions to the Gulf and Estuary. This is calculated as follows:

$$\text{Let}, Q = (\Sigma n\text{ij } w\text{ij})(\text{summation over 'i' and 'j'})$$
$$(\text{i} = \text{A, B, C, G \& O; j} = \text{I to GL-LC})$$

Risk from ships from region 'i' traveling to zone 'j' is estimated as:

$$g'ij = (s\text{ij } w\text{ij} + c\text{ij } w\text{ij})/Q$$

The marginal aggregate risk from all ships from region 'i' is estimated as:

$$G'\text{i} = (\Sigma(s\text{ij } w\text{ij} + c\text{ij } w\text{ij}))/Q \text{ (summation over j)}$$
$$(\text{i} = \text{A, B, C, G \& O; j} = \text{I to GL-LC})$$

The marginal aggregate risk from all ships traveling to zone "j" is estimated as:

$$G'\text{j} = (\Sigma(s\text{ij } w\text{ij} + c\text{ij } w\text{ij}))/Q$$
$$(\text{summation over j})$$
$$(\text{i} = \text{A, B, C, G \& O; j} = \text{I to GL-LC})$$

The total risk of introduction in the Channel from all ships exchanging or discharging in the Gulf and Estuary is estimated as:

$$G = \Sigma G'\text{i}$$
$$(\text{summation over i} = \text{A, B, C, G \& O})$$
$$= \Sigma G'\text{j (summation over j} = \text{I to FEW)}$$

Relative risk to the Channel

The risk to the Channel from exchanges in the Channel can be expressed relative to the total risk to the Gulf and Estuary from all ships. This is the so-called relative risk and is estimated for a ship from origin 'i' and destined to region 'j' as:

$$r\text{ij} = c\text{ij}/(s\text{ij} + c\text{ij})$$

The total relative risk to the Channel from ships originating from origin 'i' is estimated as:

$$R\text{i} = (\Sigma c\text{ij } w\text{ij})/(\Sigma(s\text{ij } w\text{ij} + c\text{ij } w\text{ij}))$$
$$(\text{summation over j})$$
$$(\text{i} = \text{A, B, C, G \& O; j} = \text{I to GL-LC})$$

The total relative risk to the channel from ships arriving at zone 'j' is estimated as:

$$R\text{j} = (\Sigma c\text{ij } w\text{ij})/(\Sigma(s\text{ij } w\text{ij} + c\text{ij } w\text{ij}))$$
$$(\text{summation over j})$$
$$(\text{i} = \text{A, B, C, G \& O; j} = \text{I to GL-LC})$$

The total relative risk to the channel from all ships exchanging or discharging in the Gulf and Estuary is estimated as:

$$R = (\Sigma c\text{ij } w\text{ij})/(\Sigma(s\text{ij } w\text{ij} + c\text{ij } w\text{ij}))$$
$$(\text{summation over 'i' and 'j'})$$
$$(\text{i} = \text{A, B, C, G \& O; j} = \text{I to GL-LC})$$

Appendix B

Risk model verification

In order to verify the risk model, sensitivity analysis was performed. This was done by changing some of the variables one at a time while keeping the rest at their values shown in Tables 3–6. The variable selected were mitigation effectiveness of the transit time, mid-ocean exchange and exchange in the Laurentian Channel. The results are presented in Table B-1. The highlighted rows are the results from Tables 1 and 2. A discussion follows.

Transit time

As the residual fraction increases, i.e., as the impact of the transit time on mortality decreases, the risk at port increases. This is to be expected, as the ballast water discharged at port will contain a greater percentage of the alien species that were present at origin.

The risk of introduction in the Laurentian Channel changes negligibly because the risk stems mostly from ships from region A, which has a transit time of less than five days, and also the size of their ballast is small.

Table B-1. Sensitivity analysis.

Variable	Mitigation effectiveness – residual fraction	Risk at port, %	Risk in channel, %	Total risk, %	Channel – relative risk, %
Transit time	0.00	12.8	0.14	12.9	1.06
	0.25	19.0	0.14	19.1	0.72
	0.50	**25.1**	**0.14**	**25.3**	**0.55**
	0.75	31.3	0.14	31.5	0.44
	1.00	37.5	0.14	37.7	0.37
Mid-ocean exchange	0.00	16.8	0.14	16.9	0.82
	0.20	**25.1**	**0.14**	**25.3**	**0.55**
	0.40	33.5	0.14	33.6	0.41
	0.60	41.9	0.14	42.0	0.33
	0.80	50.2	0.14	50.4	0.27
	1.00	58.6	0.14	58.7	0.24
Channel exchange	0.00	25.1	0.17	25.3	0.68
	0.20	**25.1**	**0.14**	**25.3**	**0.55**
	0.40	25.1	0.10	25.3	0.41
	0.60	25.1	0.07	25.2	0.27
	0.80	25.1	0.03	25.2	0.14
	1.00	25.1	0.00	25.1	0.00

Note: Mitigation effectiveness is expressed in terms of fraction of residual alien species in the ballast after the exchange. For example, an effectiveness of 0.6 means that after an exchange the ballast would contain 60% of the quantity it had prior to the exchange.

As the risk at port increases and the change in the risk to the Laurentian Channel is negligible, the relative risk of introduction in the Channel decreases as the residual fraction increases. This result is as expected.

Mid-ocean exchange

As the portion of ballast water exchanged in mid-ocean decreases, i.e., the residual fraction increases, the risk at port increases. Again, as in the case of transit time, this is an expected result.

The risk of introduction in the Laurentian Channel changes negligibly because, as in the previous case, the risk stems mostly from ships from region A, which has a transit time of less than five days, and also the size of their ballast is small.

As the risk at port increases and the change in the risk to the Laurentian Channel is negligible, the relative risk of introduction in the Channel decreases as the residual fraction increases. This result is also as expected.

Laurentian Channel exchange

As the portion of ballast water exchanged in Laurentian Channel decreases, i.e., the residual fraction of original ballast water increases, and the risk of introduction at port does not change. This is because, currently ships that discharge at port do not exchange in the Laurentian Channel. This is an expected result.

The risk of introduction in the Laurentian Channel decreases as the portion of ballast water exchanged in Laurentian Channel decreases, i.e., the residual fraction increases. At first glance, this might seem counter intuitive. What this means, however, is that as the residual fraction increases an exchange introduces a smaller proportion of alien species and retains in the ballast a higher proportion of the alien species that was present at origin.

As there is no impact on risk at port and the risk to the Laurentian Channel decreases, the relative risk of introduction in the Channel decreases as the portion of ballast water exchanged in Laurentian Channel decreases, i.e., the residual fraction increases. This result is also as expected.

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