Dispersion of discharged ship ballast water in Vancouver Harbour, Juan De Fuca Strait, and offshore of the Washington Coast

Max R. Larson, Michael G.G. Foreman, Colin D. Levings, and Michael R. Tarbotton

Abstract: The dispersion of harmful nonindigenous biological organisms that may be present in discharged ship ballast water is an issue of international interest. The present paper examines this issue as it applies to Vancouver Harbour and Juan de Fuca Strait, British Columbia, and the adjacent U.S. waters. The objective is to determine whether potential mechanisms exist to transport viable organisms that might be present in discharged ballast water to favourable reproductive habitats within British Columbian coastal waters. The study applied three-dimensional harmonic finite element models to generate representative tidal, atmospheric, and density-driven flow fields. Particle-tracking techniques were used to simulate representative trajectories of passive and active ballast water organisms discharged at existing deballasting sites. It was determined that the safest deballasting sites are off the west coast. Under normal conditions, organisms move southward (summer) or northward (winter) in the Shelf Break Current and only under strong eastward or northward winds are they transported to the Washington or Vancouver Island shorelines.

Key words: ship ballast water, discharge, microorganism, trajectory, Vancouver Harbour, West Coast.

Résumé : La dispersion d’organismes biologiques nuisibles et non indigènes qui peuvent être présents dans l’eau de ballast éliminée des navires est une question d’intérêt international. Cet article examine la question par rapport au Port de Vancouver et au détroit Juan de Fuca, en Colombie-Britannique, et aux eaux américaines voisines. L’objectif est de déterminer s’il existe des mécanismes potentiels de transporter des organismes viables qui pourraient être présents dans l’eau de ballast déchargée dans des habitats favorables à la reproduction dans les eaux côtières de la Colombie-Britannique. L’étude applique des modèles d’éléments finis harmoniques à trois dimensions pour générer des champs tidaux, atmosphériques et de courant géré par la densité. Des techniques de suivi des particules ont été utilisées pour simuler les trajectoires représentatives des organismes passifs et actifs dans l’eau de ballast déchargée à des sites de vidange existants. Il a été déterminé que les sites de vidange les plus sécuritaires sont au large de la côte Ouest. En condition normale, les organismes se déplacent vers le sud (été) ou le nord (hiver) dans le courant en bordure de la plate-forme continentale et ils sont transportés vers les rives de Washington ou de l’Île de Vancouver uniquement sous de forts vents vers l’est ou vers le nord.

Mots clés : eaux de ballast de navires, décharge, micro-organismes, trajectoire, Port de Vancouver, côte Ouest.

[Traduit par la Rédaction]

Introduction

Ballast water is used to compensate for the variation of payload weight as ships travel from one port of call to another. Many nonindigenous species have been transported to remote marine waters, where they would not normally exist, through discharge of ballast water. International regulations for these marine operations are not well developed. The International Maritime Organization (IMO) adopted voluntary procedures to minimize the introduction of unwanted aquatic organisms from ballast water in 1993, and adopted the IMO guideline for management of ballast water of ships in 1997. The United Nations Convention on the Law of the Sea also requires signatory nations to “take all measures necessary to prevent, reduce and control the intentional or accidental introduction of species, alien or new, to any part of the marine environment, which may cause significant or harmful changes thereto.” Despite these guidelines, there continues to be a significant potential for nonindigenous species (NIS) to be present in ballast water discharges and associated muds in coastal waters (Piercey et al. 2000; Barry and Levings 2002) and the fate of these organisms, once discharged, continues to be an international concern.

Organisms continue to arrive in British Columbia (B.C.) via ballast water of ships as shown by surveys on the west coast

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of Canada conducted between 1995 and 1997 (Levings et al. 1998; Piercey et al. 2000). Other studies have shown that algae can be grown from water and mud in the bottom of ballast tanks of ships in B.C. harbours (Waters et al. 2001). The recent arrival of the European green crab (*Carcinus maenas*) (Jamieson et al. 2002) in 1999 confirms that B.C. waters continue to be vulnerable to invasion by alien species. The green crab is thought to be a potential predator on endemic clam species and other indigenous invertebrate species (Grosholz et al. 2000). Although ballast water has not been confirmed as the vector for the green crab, it has been mentioned as a possibility (Jamieson et al. 2002). The varnish clam (*Nuttallia obscurata*) is an exotic clam species that is thought to have arrived in ballast water (Merilees and Gillispie 1995). This species has spread widely in the Strait of Georgia in the past five years and is now being considered for commercial harvest. The consequences of the arrival of this species has not been studied so ecosystem effects are not known (Levings et al. 2002).

This paper describes ballast water dispersion studies in two distinct regions of the west coast of North America where ballast water discharge is of concern; the boundaries of the two regions are indicated by the heavy lines shown in Fig. 1. The large more-westerly region includes the waters of Juan de Fuca Strait, northwest Washington State, and the continental shelf and slope off the western and northern coasts of Vancouver Island (Fig. 2); the second smaller region includes Vancouver Harbour and English Bay (Fig. 3). Most ships arriving in B.C. have conducted mid-ocean exchange (MOE) in accordance with Vancouver Port Authority (VPA) ballast water management plans (VPA 1998). The VPA management plan, described in detail on their website (h t t p://www.portvancouver.com/the_port/docs/harbour_manual.pdf) follows the management concept that ballast water management requires MOE. The VPA (and more recently Nanaimo and New Westminster Harbour Authorities) require that, if a ship has not completed MOE, officials can request that the vessel go back out to sea to do an exchange at an “alternate” site. These locations are the focus of the present paper. In the United States, vessels heading into Washington State ports do not have to do MOE and hence no U.S. “alternate” sites are defined. However, Beeton et al. (1998) wrote a report on the assumption that U.S. alternate sites would be mandated in the near future. Ships that enter VPA (or Nanaimo or New Westminster) waters are allowed to deballast anywhere as they are assumed to have completed MOE; ships bound for any other coastal port in B.C. are allowed to deballast without restriction.

It is important to recognize that the MOE process is relatively inefficient and that all deballasted water is likely to have a few organisms that are potential colonizers of B.C. waters. Ballast water discharge locations are not known precisely. Some vessels, such as large bulk carriers, likely begin to deballast when entering sheltered waters such as inner Juan de Fuca Strait. Ships in Vancouver harbour are not allowed to deballast before officials check for compliance with MOE. Theoretically, a ship that has not complied with MOE can be sent back out to sea to exchange water at a back-up location.

The goal of the present investigation was to determine whether potential mechanisms exist for the transport of viable biological organisms present in discharged ballast water to favourable reproductive habitats within the sheltered B.C. coastal waters in the Straits of Georgia and Juan de Fuca. It is far beyond the intent of this paper to provide statistical estimates of the fate of all organisms that might be discharged from ballast water into West Coast coastal waters as this would require an exhaustive study with different modelling techniques than have been employed here. Rather, the objective of this paper is to demonstrate whether the presently recommended alternate deballasting locations could result in undesirable particle transport during typical conditions. Due to the wide range of parameters affecting the transport of organisms (e.g., discharge location, tidal and seasonal conditions, organism properties, etc.), it is not feasible to investigate this issue with field techniques, and numerical simulation is the only practical approach to the problem. The remainder of the paper describes the simulation assumptions and procedures as well as the conclusions resulting from this work.

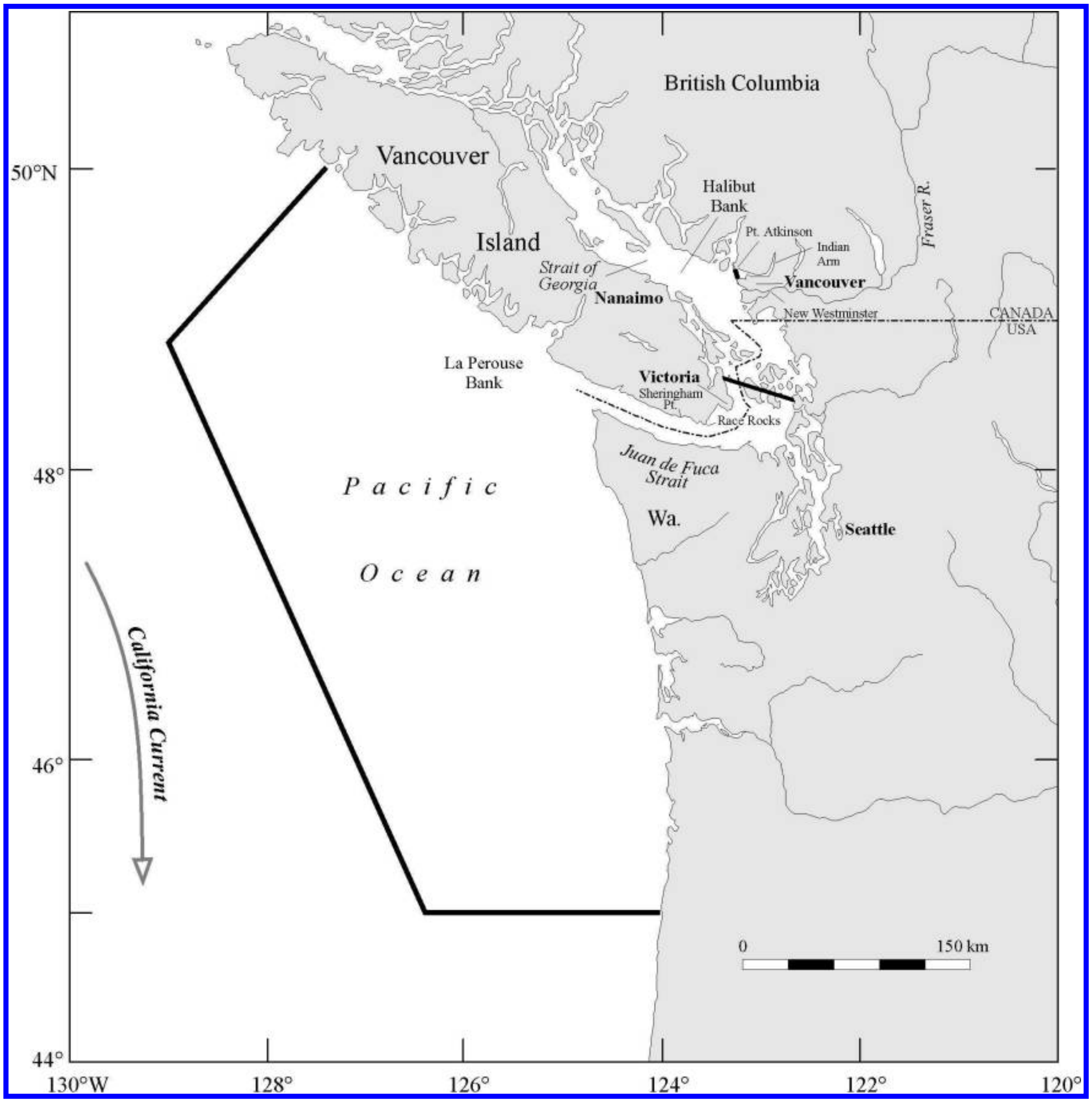
Model description

Three-dimensional baroclinic finite element model

Velocity fields in the Juan de Fuca region were calculated using the three-dimensional, diagnostic, baroclinic, finite element model FUNDY5, (Lynch and Werner 1987; Lynch et al. 1992; Foreman et al. 2000) while those for Vancouver Harbour were computed with a similar computational method developed by Walters (1987, 1992). The velocities are assumed to arise from a combination of tidal, wind, and buoyancy forcing and both models compute height and current constituents in the frequency domain. The tidal components have their distinct frequencies while both the wind and buoyancy components have zero frequency; that is, they are time invariant. Velocity fields are computed at 11 terrain-following surfaces in the vertical and a spatially-varying node density in the horizontal. A total of 13 119 horizontal nodes were used in the Juan de Fuca model and 16 491 nodes in the Vancouver Harbour model. Both grids were constructed to have fine resolution in regions having important circulation features and both models employ quadratic bottom friction and a vertical eddy viscosity that varies with the root mean square tidal velocity. Though the Juan de Fuca grid extends further eastward and southward but less northward than the grid employed in Foreman et al. (2000), a comparison of model tidal ellipse parameters with values obtained through the harmonic analysis of current meter time series revealed comparable accuracy to that described in Foreman et al. (1995, 2000). The Juan de Fuca grid is a modification of those used in Foreman et al. (2000) and Foreman and Thomson (1997) and has a similar resolution of approximately 1 km within Juan de Fuca Strait (see Fig. 3 in Foreman and Thomson (1997)).

Water levels and currents due to the effects of buoyancy forcing and surface wind-stress were also included in the simulations. Hydraulic conditions on the Strait of Georgia bound-

Fig. 1. Study area.



aries of the Vancouver Harbour model were interpolated from wind-driven simulations with a modified version of the model described in Foreman et al. (1995). Radiation conditions and iterative adjustments to boundary elevations were used to avoid spurious reflections of the wind- and buoyancy driven flows along offshore boundaries of the Juan de Fuca model.

Particle tracking

The fate of discharge organisms was computed through simulation of tracer particles that are assumed to represent the fate of a typical organism within the discharged ballast water. The trajectories of tracer particles were computed using the program Drog3D which was obtained from the QUODDY user's group website at http://www.opnml.unc.edu/Particle _Tracking/part_track.html. Implementation of Drog3D for this study involved porting the mainframe code to a PC, recoding to use double precision to accommodate the UTM horizontal grid coordinates, and development of graphical routines to plot the resulting trajectories. The Drog3D particle tracking routines were further modified to simulate active (swimming) organisms in addition to the default passive behaviour. A detailed description of the assumed organism behaviour is described in the next section.

Test program

The modelling system described previously was used to simulate the range of parameters summarized in Table 1; the following paragraphs describe the tabulated parameters. For each simulation run, tracer particles were discharged into the model domains under a variety of marine environmental conditions and each was tracked to determine its locations over a three-week period. This simulation duration was chosen to represent the

Fig. 2. Juan de Fuca domain — ballast water discharge locations.

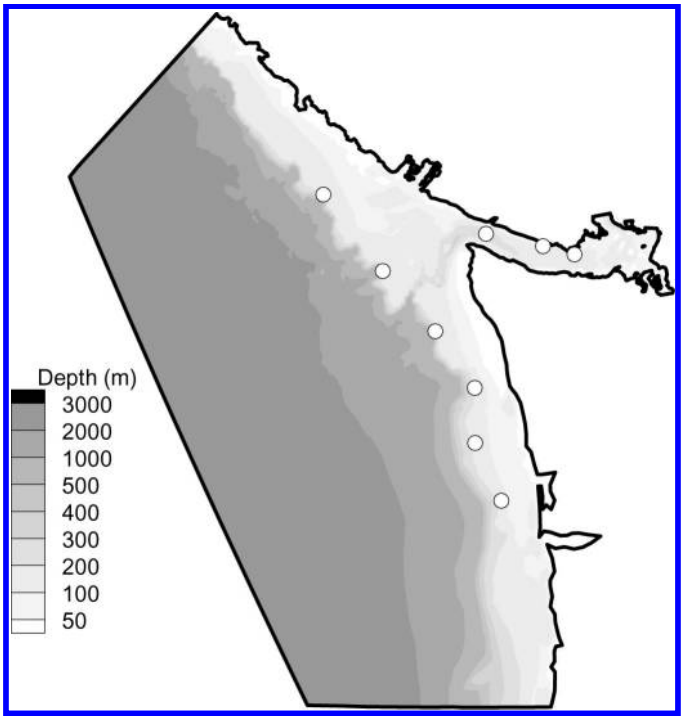
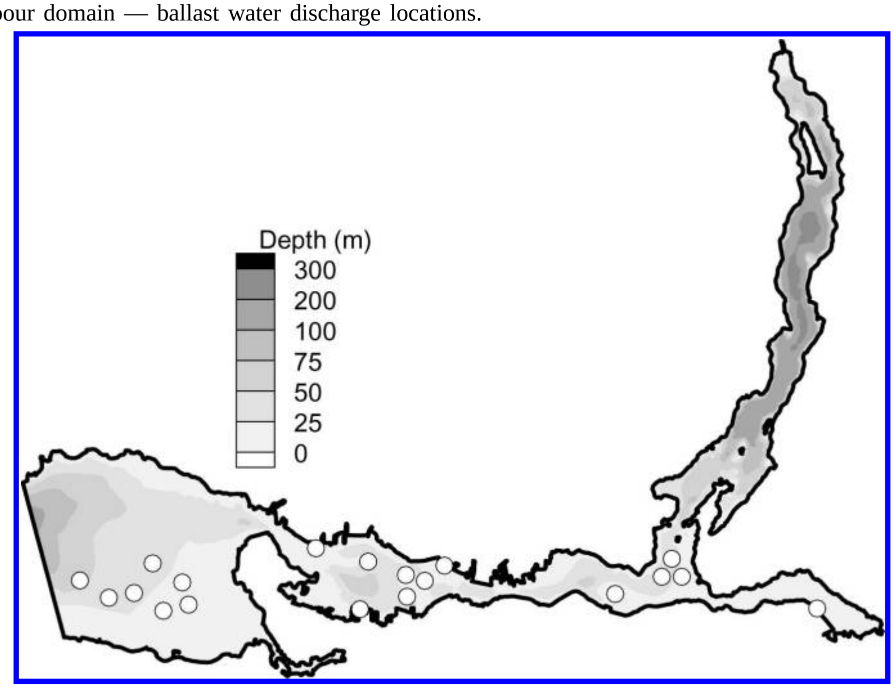


Fig. 3. Vancouver Harbour domain — ballast water discharge locations.



maximum potential time that nonindigenous organisms from mid-ocean or foreign coastal waters would require to survive and colonize B.C. marine inshore habitats. Three weeks is a liberal estimate of survival time for mid-ocean organisms based on the only known report on this topic. Wonham et al. (2001) reported that mid-Atlantic ballast water organisms survived in Baltimore Harbour for only 24 h. The experiments with Baltimore Harbour were conducted using a range of salinities of 5 to 10 psu (practical salinity units) (compare with freshwater at 0 psu and normal seawater at 35 psu). The organisms were zooplankton and no sediments were involved in the experiments. They were conducted in shallow dishes so low dissolved oxygen (DO) was not a factor. Even if some parts of Baltimore Harbour do have low DO, it is unlikely that DO would be a factor for zooplankton that live primarily in surface waters that are typically high in DO. The test emphasized salinity, since they were conducted with organisms from the eastern subtropical Atlantic Ocean which is characterized by high salinity. The

Table 1. Summary of test parameters.

Parameter	Range
Ballast water discharge	
Location	19 Vancouver Harbour and 9 JdF sites
Organism type	Passive, active
Density relative to ambient	Positive, negative
Tides	
Constituents	M_2, N_2, K_1, S_2, K_2, Q_1, P_1, and O_1
Type*	Spring, neap
Stage*	Flood, ebb
Residual buoyancy flow	Typical summer, typical winter
Wind conditions	Typical summer, typical winter

*Based on predicted tide heights at Victoria.

situation is comparable to Vancouver Harbour which is also a stratified estuary at certain times of the year; the assumption being that organisms taken aboard during MOE in mid-Pacific (characterized by high salinity) will not survive in the harbour. Trajectories were terminated if the tracer encountered the shoreline (in reality, the organism may continue to move alongshore but the hydraulics in the immediate vicinity of the shoreline are not accurately modelled) or crossed an open model boundary. In the Vancouver Harbour domain, the only model boundary is the western edge separating the harbour from the Strait of Georgia; the Juan de Fuca domain has an eastern boundary separating the Juan de Fuca Strait from the Strait of Georgia and a western boundary with the North Pacific.

Ballast water discharge locations

Ballast water may be discharged while a vessel is at rest (at berth) or underway. Vessels that have not completed MOE and are required to make use of the backup discharge sites are almost certainly underway so that the ballast water discharge locations are actually ballast water discharge regions. For the purposes of this study, discharge was assumed to occur instantaneously at the locations specified. Consistent with this assumption, the convection and dispersion associated with the moving vessel has been neglected. These effects are secondary to the much stronger forcing by ocean currents. The white circles shown on Figs. 2 and 3 indicate the ballast water discharge locations used in the Juan de Fuca and Vancouver Harbour simulations, respectively. In Vancouver Harbour, some locations were at offshore anchorages and others were at shore berths. A detailed table of discharge location coordinates is included in the appendix (Table A1).

Nineteen potential ballast water discharge locations within Vancouver Harbour were identified from CHS charts 3481, 3493, 3494, and 3495 (CHS 1996, 1997) (updated versions of these charts are available). Deballasting sites within Juan de Fuca Strait and off the Washington coast were chosen in accordance with recommended back up ballast water exchange sites from various authorities. Sites considered include: JdF1, "in the outgoing current of the north side of the Strait of Juan de Fuca, west of Race Rocks" (VPA 2002); JdF2, "off Sheringham Point, in a water depth of at least 100 m, north of the Traffic Lane and west of the military ordinance location"[2] JdF-3, "in the central portion of Juan de Fuca Strait, just north of the separation line (*between US and Canada*), not too close to the entrance" (R.E. Thomson suggestion in Gramling 2000); WC1 to WC6, "for ships off Washington and Oregon, no closer (*to the shore*) than in or along the California Current, and west of the Current where it passes close to shore" (Beeton et al. 1998). Because the western boundary of the California Current (Fig. 1) extends far beyond the limits of the JdF (Juan de Fuca Strait) model domain, an inshore variation of this (approximately 200 m water depth) was selected for the present study.

Some additional testing was done to examine other discharge locations and depths to gain some understanding of the sensitivity of the results to subtle changes in discharge conditions.

Ballast water properties

Table A2 provides an indication of the density of ballast water relative to ambient based on field measurement. Ballast water with salinity greater than 34 psu almost certainly resulted from taking in oceanic water during MOE. Water with lower salinity levels could have resulted from inefficient MOE or instances where MOE was not performed, as these data were obtained before the VPA (1998) standing orders were issued. The table contains a summary of recent ballast water density data (Piercey et al. 2000) from ships in Vancouver Harbour with historical (non-simultaneous) measurements of ambient harbour water density (Davidson 1973). Water density was computed from available temperature and salinity data.

Note that approximately 90% of the cases resulted in ballast water that is negatively buoyant relative to ambient. Ambient water density in Juan de Fuca Strait is often higher than Vancouver Harbour so a somewhat lower percentage of negatively buoyant ballast water is expected in that location.

Organism behaviour

Two types of microorganism were considered: neutrally-buoyant passive non-swimming (e.g., mollusc larvae) organisms and active (swimming) organisms (e.g., copepods or crab larvae) undergoing diel vertical migration (DVM). Diel vertical migration is a characteristic behavioural pattern for many marine organisms including species from all major zooplankton groups, dinoflagellates, diatoms, and many nektonic species (e.g., Longhurst 1976; Lalli and Parsons 1995; Villarinio et al. 1995). In general, there are three predictable patterns exhibited by marine zooplankton: (*i*) nocturnal migration, during which organisms ascend towards the surface around sunset and descend to deeper waters near sunrise, (*ii*) twilight migration, where zooplankton make two ascents, one at dusk and one at dawn, and two descents, one around midnight and one during

[2]Vancouver Port Authority. 1999. Personal communication.

the day, and (*iii*) reverse migration, where the organisms rise to the surface during the day and descend to deeper water during the night (Smith et al. 2001). Of these, nocturnal migration is the most commonly observed pattern and was chosen as the basis for this study.

The details of the assumed nocturnal DVM are schematized in Fig. 4 for a water column depth of 180 m in which organisms are assumed to migrate vertically at a speed of 0.05 m/s, which is typical of copepods and euphausiids (see Smith et al. 2001). During daylight hours, organisms remain at a depth of 180 m to avoid predation and begin ascent from depth at dusk arriving at the surface by sundown, remain on the surface until near dawn, then begin descent to arrive at depth by dawn. Organisms were assumed to be completely passive in the nonmigratory phases of their behaviour.

The two classes of organism described above were assumed to be entrained in both positively and negatively buoyant ballast water. Those passive organisms (organisms without self-propulsion) entrained in positively buoyant ballast water were assumed to be released from the hull of the ship just below the surface. Organisms entrained in negatively buoyant ballast water were assumed to descend instantaneously from the hull of the ship until initial mixing with ambient waters had effectively taken place; no further mixing was assumed to take place after release. Although mixing plays a role in dilution and transport, it has been omitted from our simulations because it is a second order effect with respect to the transport arising from tidal, wind- and buoyancy-driven currents.

Calculations based on typical ballast and ambient water properties and analogy with submerged buoyant jets indicate that a hundredfold dilution of ballast water due to initial mixing would occur at a depth of about 50 m; this was the value used in the study. In an extreme case, in which all of a ship's ballast water was exchanged at a back up location, this could result in a ballast water mass of several hundred cubic metres at depth. Given that maximum densities of cyclopoid copepods in non-exchanged ballast water were observed to be 28 000 organisms per cubic metre (Piercey et al. 2000), this corresponds to a concentration of about 300 organisms per cubic metre after dilution, which is considered to be sufficiently high to pose a potential threat.

Tides

Modelled tidal conditions are based on the computed tidal heights and currents for eight tidal constituents (M_2, N_2, K_1, S_2, K_2, Q_1, P_1, and O_1). The precise definition of these constituents may be found in standard references such as Godin (1972) or Forrester (1983), but essentially they are associated with specific components in the mathematical expansion of tide generating forces. (M_2, for example, represents the twice daily influence of the moon.) Each constituent is parameterized by an amplitude, phase, and frequency which, when taken together, can be used to generate a tidal signal. The eight constituents chosen here account for approximately 85% of the tidal height range in the Strait of Georgia (Point Atkinson). Ballast water discharge was assumed to occur at either peak ebb or peak flood tide based on predicted water levels at Victoria. Discharge during spring and neap tide conditions were also considered based on the same reference. This assumption was made to reduce the continuous variable time (along with the choice of summer/winter and spring/neap tide) to a manageable number of discrete runs with an easily described basis. Some additional runs were completed to test the sensitivity of results to time of release and the differences were found to be noticeable but to exhibit the same general trends.

Seasonal and wind driven currents

Water levels and currents generated by the effects of surface wind-stress and seasonal differences in water density were also included in the simulations. We refer to these as residual flows and elevations. In both model domains, climatological summer (July to September) and winter (January to March) buoyancy currents were calculated from historical temperature and salinity observations in a manner similar to that described in Foreman et al. (2000). Those for the Juan de Fuca region captured the same major features described in Foreman et al. (2000), namely an estuarine flow in Juan de Fuca Strait, a Vancouver Island Coastal Current, a Shelf Break Current, and a California Undercurrent. In fact, within the overlapping portions of the two model domains, our summer and winter buoyancy flows were very similar to those shown in Figs. 8 and 10 of Foreman et al. (2000). The buoyancy flows in Vancouver Harbour showed a weak estuarine flow (i.e., westward at the surface and eastward at depth) for most of the year (for example, Fig. 11, Gramling (2000)). Note that interannual variability of ocean currents (e.g., El Niño versus La Niña effects) are implicitly excluded from this analysis.

Representative wind conditions were developed following a detailed analysis of wind data from La Pérouse Bank, Race Rocks, Halibut Bank, and Point Atkinson. Statistical and hour-by-hour comparisons of these data sets were used to develop a conceptual model of the typical spatial variation of wind speed and direction in southern B.C. waters during summer and winter conditions. Figure 5 shows an example of the type of wind analysis undertaken for this study to draw general conclusions about prevailing wind conditions during summer. For example, it was determined that low wind speeds (10 kn) in eastern Juan de Fuca Strait coexist with similar wind speeds off the coast, but as wind intensity in the Strait increases, wind speeds offshore increase to a lesser extent. West winds prevail in eastern Juan de Fuca during summer and are usually paired with northwest winds offshore. Conclusions such as these were used to prescribe a series of spatially-varying, time-constant model wind fields that represent commonly occurring conditions in the study area.

To limit the number of simulations, typical summer and winter wind conditions were paired with typical associated seasonal currents for the majority of the cases examined. A limited number of additional runs were completed with varying wind speeds

Fig. 4. Assumed diel vertical migration (DVM) pattern.

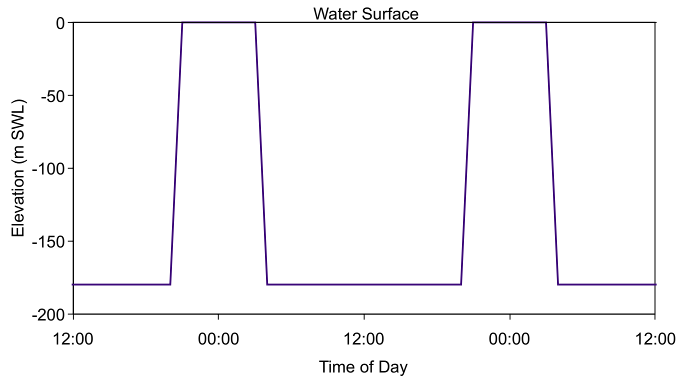
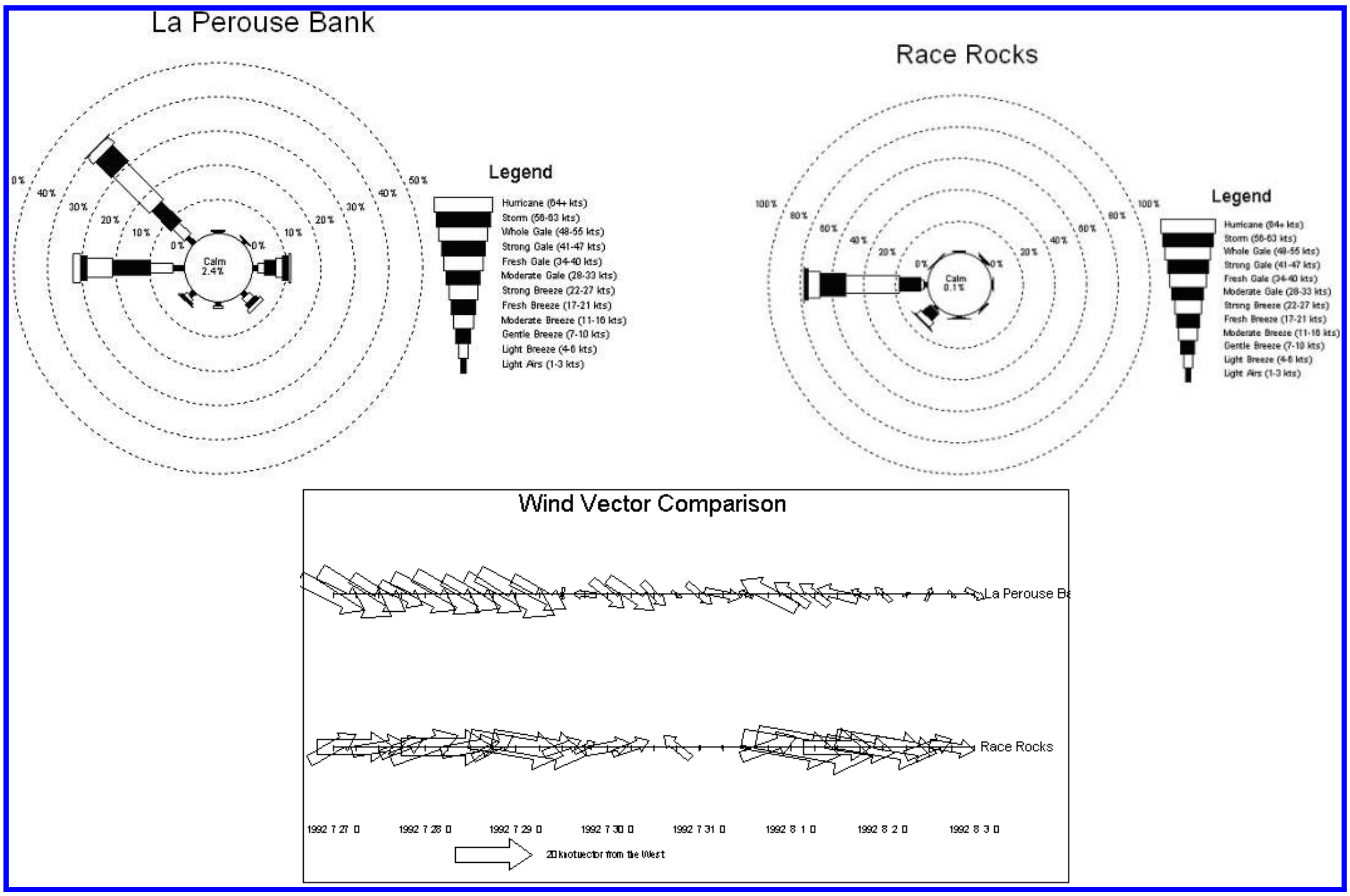


Fig. 5. Comparison of La Pérouse Bank and Race Rocks winds — summer conditions.



and directions to better understand the influence of wind on the results.

Results

Over 200 model simulations were undertaken for this study; they were designed to cover a significant sample of the large potential test matrix described by Table 1. Plots of the ballast water organism trajectories were drawn for each model run and reviewed for their implication on ballast water discharge procedures. As it is impossible to present these results here in their entirety, the results have been posted to f t p.triton.ca\BallastWater 2003.pdf. The following sections highlight the most significant of these simulations.

Juan de Fuca region

Figure 6 shows the behaviour of ballast water containing active organisms (self-propelled (swimming) organisms) discharged into the Juan de Fuca domain at peak ebb during sum-

Fig. 6. Juan de Fuca Strait — surface release of active organisms at peak-ebb summer spring tide.

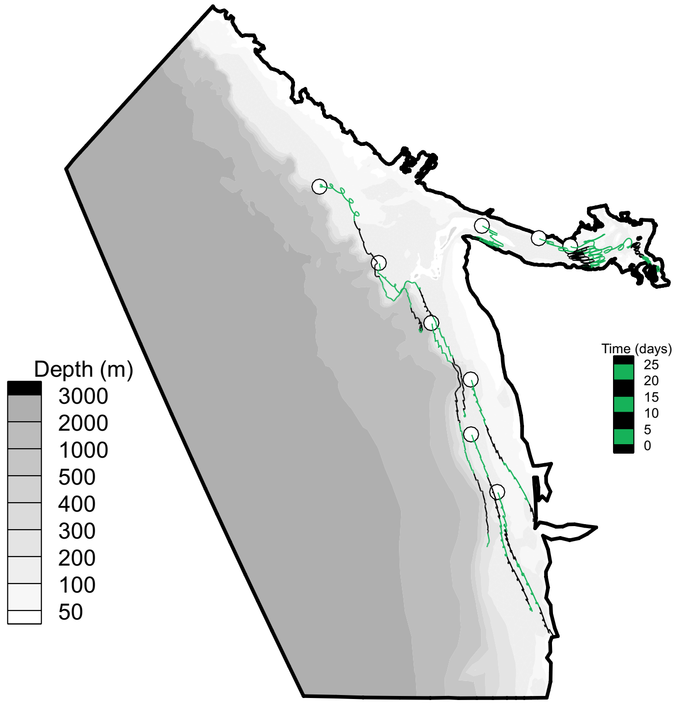
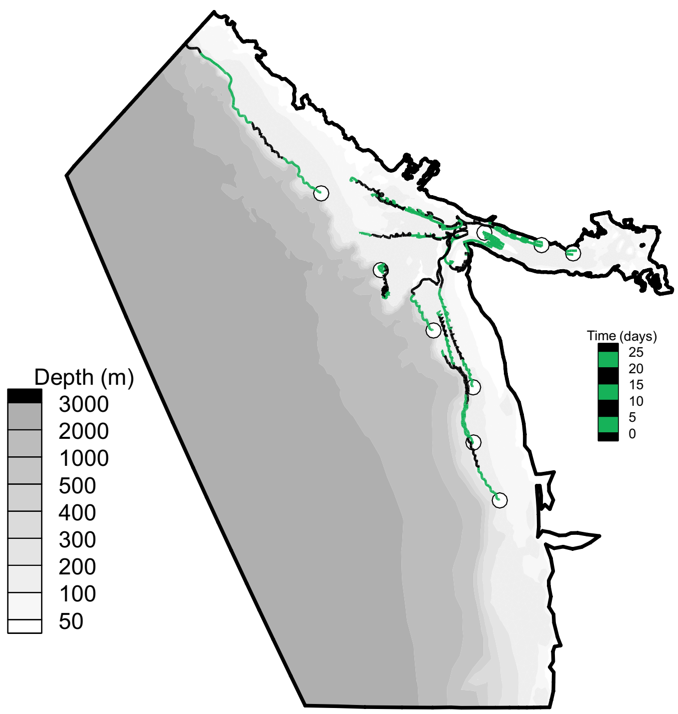


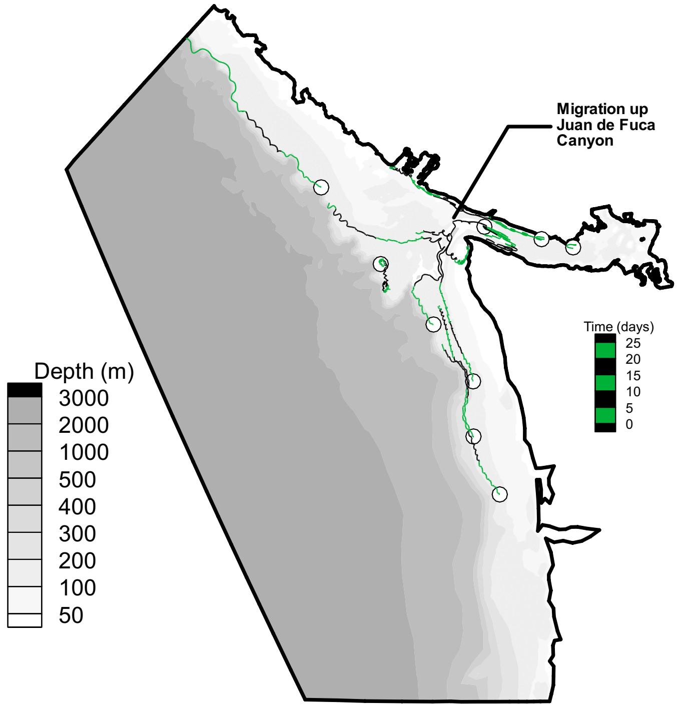
Fig. 7. Juan de Fuca Strait — at-depth release of passive organisms at peak-flood winter neap tide.



mer spring tides. Note that organisms within Juan de Fuca Strait can be transported into the Strait of Georgia, which implies a risk of colonization of inshore waters by non-indigenous species in ballast water. Organisms discharged off the coast of Washington tend to be transported to the south towards the Oregon coast.

Figure 7 shows the behaviour of ballast water containing active organisms discharged into the Juan de Fuca domain at peak flood during winter neap tides. Organisms discharged at the surface into Juan de Fuca Strait can be transported to the east; under these same conditions, organisms discharged offshore move towards the northwest and tend to remain offshore. However, if the discharged organisms sink initially to a greater depth (50 m in this example), the organisms follow a differ-

Fig. 8. Juan de Fuca Strait — at-depth release of active organisms at peak-ebb winter neap tide.



ent path (see Fig. 8). Note the trajectory of one offshore tracer migrates to the northwest and then is drawn up by the bottom estuarine flow in Juan de Fuca Canyon into Juan de Fuca Strait. The following points summarize the results as they apply to ballast water discharge in the Juan de Fuca domain:

- Organism trajectory is extremely sensitive to the depth of initial mixing with significant differences between the path of organisms discharged at the bottom, at 50 m depth, and at the surface.
- Wind plays a relatively minor role compared to discharge depth; wind conditions (within their usual range of variation) tend to slow or accelerate organism movement depending on direction and speed but rarely reverse the general migration trend of the organism due to tidal and buoyancy currents. Since winds only penetrate to the Ekman depth (which is generally 30–50 m depending the vertical viscosity), organisms below that depth tend to be unaffected.
- In Juan de Fuca Strait, summer surface and 50 m depth releases of passive particles generally resulted in westward transport while the bottom releases either moved eastward or remained more or less stationary.
- In Juan de Fuca Strait, release of active particles generally resulted in transport that remained within the Strait. Limited sensitivity testing of ballast water released further to the south (on the U.S. side of the Canada–U.S. border) also resulted in organism retention.
- Off the Washington coast, surface and 50 m depth organisms generally moved southward in the summer and northward in the winter.
- There seems to be a greater degree of retention of organisms in Juan de Fuca Strait during the winter than during summer.
- Stronger westerly winds in Juan de Fuca increase retention of surface organisms.

Vancouver Harbour region

Figure 9 shows the behaviour of ballast water containing (in this example) passive organisms discharged into the Vancouver Harbour domain at peak flood during summer spring tides. Most of the tracers tend to move onshore or out of the western boundary of the model within a few days. Those organisms discharged in English Bay and the entrance to the harbour proper (First Narrows) tend to be swept out into the Strait of Georgia within one or two days. Figure 10 shows the behaviour of ballast water containing passive organisms discharged at depth in Vancouver Harbour at peak flood during winter neap tides. In this case, the results are similar to those shown in Fig. 9 except that a longer period of time is required for the organisms to exit the study area.

The following points summarize the results as they apply to ballast water discharged in the Vancouver Harbour domain:

- In the absence of wind, only those organisms released into the western portions of English Bay are expected to be transported into the Strait of Georgia prior to the end of their viable lifespan (three weeks).
- In the presence of inflow wind conditions (i.e., winds from the west over most of English Bay/Vancouver Harbour and from the south in Indian Arm), there is an increase in organism

Fig. 9. Vancouver Harbour — surface release of passive organisms at peak-flood summer spring tide.

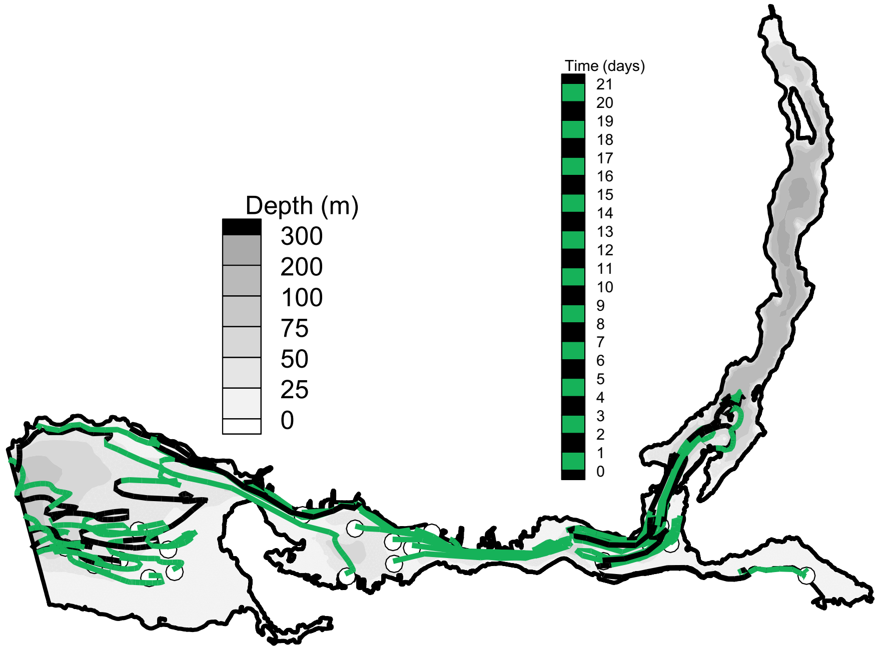
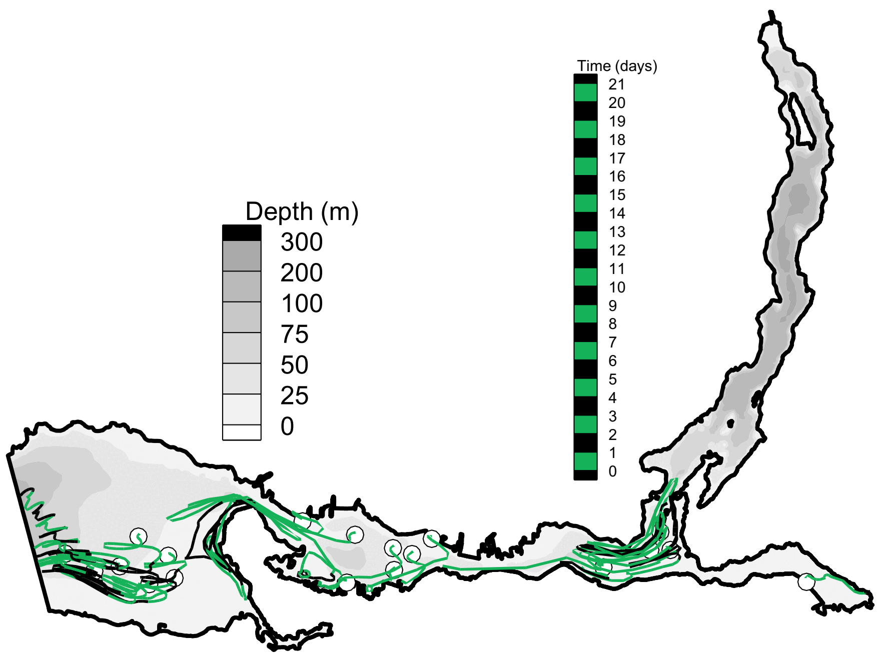


Fig. 10. Vancouver Harbour — surface release of passive organisms at peak-ebb winter spring tide.



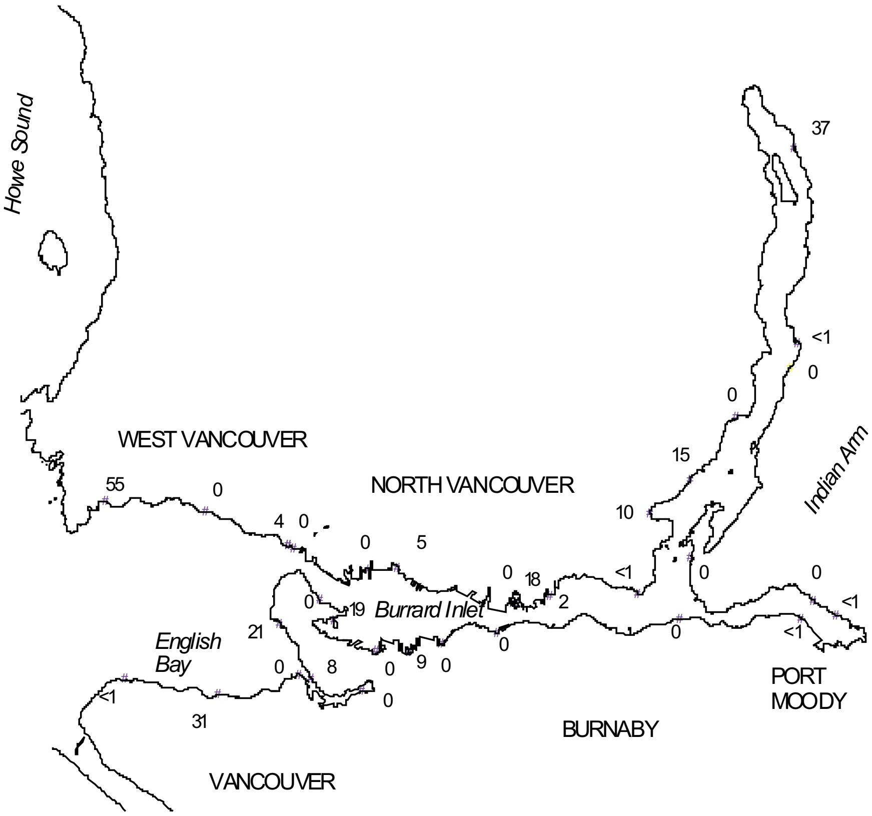
concentration within the harbour and hence a higher risk of NIS colonization within the harbour and a lower probability of escape into the Strait of Georgia.

- In the presence of outflow wind conditions (i.e., winds from the east over most of English Bay/Vancouver Harbour and from the north in Indian Arm), there is a high probability of viable organisms escaping from the English Bay anchorages and from anchorages near the harbour entrance. There is a low probability of escape from those anchorages in the more tranquil portions of the harbour and those further to the east; these escape probabilities increase with increasing wind speed.
- The trajectories of organisms discharged at a depth are similar to those discharged at the surface, except that the tidal fluctuating component of their excursions is less.

Discussion and conclusions

Given the large number of parameters influencing the dispersion of ballast water, it is impossible to examine every possi-

Fig. 11. Distribution of the varnish clam (*Nuttallia obscurata*) in Vancouver Harbour based on surveys conducted in June and October 2001. Data shown are mean numbers of varnish clams in qualitative samples obtaining by digging on beaches at low tide.



ble combination of discharge and environmental condition. The present approach has been one in which commonly occurring environmental conditions have been modelled in conjunction with a wide range of ballast water disposal times, locations, depths, and organism properties. Several consistent trends seem to emerge, leading to the following conclusions with respect to future ballast water disposal options.

- None of the existing anchorages within Vancouver Harbour can be considered to be low risk locations for ballast water discharge in all conditions. Ballast water organisms that are introduced at those anchorages located outside the harbour proper (within English Bay) and near the harbour entrance are most likely to be transported to favourable reproductive habitats in the Strait of Georgia. Moreover, even those ballast water organisms that do not escape Vancouver Harbour can reproduce significantly as demonstrated by the mapped distribution of the varnish clam. This species is now present almost everywhere in the harbour (Fig. 11).
- Though the three presently recommended sites in Juan de Fuca Strait were chosen so that discharged organisms would be transported westward in the surface estuarine flow, strong prolonged westerly winds have been observed to reverse the estuarine flow (Thomson 1981). Our simulations confirm that west winds can transport passive surface organisms (and active particles while they are at the surface) to the east. Furthermore, even under normal conditions vertically migrating organisms were seen to move eastward due to the portion of their daily cycle spent in the generally eastward-directed bottom estuarine flow.
- Based on our simulations, the safest deballasting sites are, as recommended by Beeton et al. (1998), west of the California Current indicated in Fig. 1. However, there may be practical limitations for these sites because they are relatively far offshore. The present evaluation of an inshore version (about 200 m depth) of these sites indicated that, under normal conditions, organisms moved southward (summer) or northward (winter) in the Shelf Break Current and only under strong eastward or northward winds were they transported to the Washington or Vancouver Island shorelines. Recently Barth et al. (2003) suggested that any ballast water discharged outside of the 1000 m isobath has a relatively low probability of reaching the shoreline. Further simulations at varying distances offshore from this isobath could be conducted with our model to refine this prediction.

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Appendix A:

Table A.1. Ballast water discharge locations.

Location	Easting (m)	Northing (m)	Latitude (N)	Longitude (W)
Anchorage 1	486840.859	5459769.659	49°17.439′	123°10.780′
Anchorage 2	486612.539	5460578.054	49°17.875′	123°10.970′
Anchorage 4	485926.461	5459547.712	49°17.318′	123°11.534′
Anchorage 6	485537.055	5461270.028	49°18.247′	123°11.859′
Anchorage 8	484860.429	5460193.471	49°17.665′	123°12.415′
Anchorage 10	483946.166	5460021.880	49°17.571′	123°13.169′
Anchorage 12	482894.941	5460649.450	49°17.908′	123°14.038′
Vancouver wharves	491463.899	5461818.960	49°18.543′	123°07.046′
Centerm berth	493065.112	5459606.251	49°17.350′	123°05.722′
Neptune berth	496130.087	5461189.279	49°18.206′	123°03.194′
Pacific Coast terminals	509664.204	5459632.607	49°17.362′	122°52.026′
Anchorage A	493360.497	5461334.598	49°18.283′	123°05.480′
Anchorage C	494729.129	5460851.372	49°18.023′	123°04.350′
Anchorage E	494770.788	5460062.018	49°17.597′	123°04.315′
Anchorage Y	495415.982	5460637.678	49°17.908′	123°03.783′
Anchorage N	502331.592	5460160.078	49°17.651′	122°58.076′
Anchorage K	504022.873	5460785.467	49°17.988′	122°56.680′
Anchorage L	504749.900	5460784.194	49°17.987′	122°56.080′
Anchorage M	504385.866	5461436.096	49°18.339′	122°56.380′
JdF1			48°17.262′	123°34.800′
JdF2			48°21.372′	123°54.840′
JdF3			48°27.582′	124°31.440′
WC1			48°45.948′	126°16.560′
WC2			48°12.660′	125°38.760′
WC3			47°46.248′	125°05.820′
WC4			47°21.378′	124°41.700′
WC5			46°57.696′	124°42.480′
WC6			46°32.466′	124°27.180′

Table A.2. Ballast water buoyancy data.

No.	Date	Ballast water[a] density (kg/m^3)	VH Surface water[b] density (kg/m^3)	Penetration[c] elevation in VH (m MSL)	JdF Strait Surface water[d] density (kg/m^3)	Penetration[c] elevation in JdF Strait (m MSL)
1A	29 Dec. 1995	1028.6	1020.3	−30	1023.7	−120
1B	30 Dec. 1995	1028.6	1020.3	−30	1023.7	−120
2A	19 Jan. 1996	1020.3	1020.3	0	1023.7	0
4	23 Jan. 1996	1028.9	1020.3	−30	1023.7	−120
5	25 Jan. 1996	1028.4	1020.3	−30	1023.7	−120
6	27 Jan. 1996	1027.2	1020.3	−30	1023.7	−120
7	27 Jan. 1996	1027.8	1020.3	−30	1023.7	−120
8	5 Feb. 1996	1027.4	1020.3	−30	1023.7	−120
9	21 Feb. 1996	1026.5	1020.3	−30	1023.7	−97
10	6 Mar. 1996	1028.8	1020.3	−30	1023.7	−120
11	7 Mar. 1996	1027.1	1020.3	−30	1023.7	−120
12	7 Mar. 1996	1026.7	1020.3	−30	1023.7	−116
13A	29 Feb. 1996	1027.3	1020.3	−30	1023.7	−120
13B	29 Feb. 1996	1018.0	1020.3	0	1023.7	0
13C	20 Feb. 1996	1026.5	1020.3	−30	1023.7	−97
14	13 Mar. 1996	1026.7	1020.3	−30	1023.7	−116
15	14 Mar. 1996	1027.8	1020.3	−30	1023.7	−120

Table A.2. (*Concluded.*)

No.	Date	Ballast water[a] density (kg/m^3)	VH Surface water[b] density (kg/m^3)	Penetration[c] elevation in VH (m MSL)	JdF Strait Surface water[d] density (kg/m^3)	Penetration[c] elevation in JdF Strait (m MSL)
16	21 Mar. 1996	1026.2	1020.3	−30	1023.7	−78
17	27 Mar. 1996	1026.4	1020.3	−30	1023.7	−90
18	28 Mar. 1996	1028.2	1020.3	−30	1023.7	−120
19	15 Mar. 1996	1027.0	1020.3	−30	1023.7	−120
21	13 Mar. 1996	1026.7	1020.3	−30	1023.7	−116
24	5 May 1996	1027.0	1013.3	−30	1023.6	−120
25	8 May 1996	1027.7	1013.3	−30	1023.6	−120
26	23 May 1996	1027.6	1013.3	−30	1023.6	−120
27	24 May 1996	1011.8	1013.3	0	1023.6	0
28	12 June 1996	1027.3	1013.3	−30	1023.6	−120
29	13 June 1996	1025.6	1013.3	−30	1023.6	−65
30	19 June 1996	1026.5	1013.3	−30	1023.6	−120
31	26 June 1996	1023.7	1013.3	−30	1023.6	−2
32	15 July 1996	1026.3	1013.3	−30	1023.6	−102
33	16 July 1996	1025.0	1013.3	−30	1023.6	−42
34	16 July 1996	1022.4	1013.3	−30	1023.6	0
35	29 July 1996	1022.3	1013.3	−30	1023.6	0
36	9 July 1996	1027.1	1013.3	−30	1023.6	−120
37	12 Aug. 1996	1024.4	1013.3	−30	1023.6	−21
38	13 Aug. 1996	1024.6	1013.3	−30	1023.6	−27
39	13 Aug. 1996	1000.1	1013.3	0	1023.6	0
40	22 Aug. 1996	998.9	1013.3	0	1023.6	0
41	27 Aug. 1996	1026.1	1013.3	−30	1023.6	−88
42	28 Aug. 1996	1022.4	1013.3	−30	1023.6	0
43	28 Aug. 1996	1000.8	1013.3	0	1023.6	0
44	6 Sept. 1996	1024.6	1013.3	−30	1023.6	−27
45	9 Sept. 1996	1025.0	1013.3	−30	1023.6	−42
46	10 Sept. 1996	1025.5	1013.3	−30	1023.6	−61
47	10 Sept. 1996	1025.3	1013.3	−30	1023.6	−53
48	11 Sept. 1996	1024.5	1013.3	−30	1023.6	−24
49	11 Sept. 1996	1025.5	1013.3	−30	1023.6	−61
50	12 Sept. 1996	1024.5	1013.3	−30	1023.6	−24
51	13 Sept. 1996	1000.8	1013.3	0	1023.6	0
52	18 Sept. 1996	1022.9	1013.3	−30	1023.6	0
53	26 Sept. 1996	1025.0	1013.3	−30	1023.6	−42
54	1 Oct. 1996	1024.2	1020.3	−30	1023.7	−11
55	21 Oct. 1996	1025.6	1020.3	−30	1023.7	−53
56	13 Nov. 1996	1027.1	1020.3	−30	1023.7	−120
57	14 Nov. 1996	1027.1	1020.3	−30	1023.7	−120
58	20 Nov. 1996	1022.2	1020.3	−10	1023.7	0
59	20 Nov. 1996	1026.8	1020.3	−30	1023.7	−120
60	21 Nov. 1996	1027.6	1020.3	−30	1023.7	−120
61	30 Nov. 1996	1027.9	1020.3	−30	1023.7	−120
62	7 Jan. 1997	1027.6	1020.3	−30	1023.7	−120
63	8 Jan. 1997	1027.4	1020.3	−30	1023.7	−120
	Number of positively buoyant samples			7		12
	Number of negatively buoyant samples			55		50
	Total samples			62		62

[a] Inferred from Piercey et al. (2000) measurements of ballast water properties.

[b] Average summer or winter surface water density in Vancouver Harbour (Anchorage 6).

[c] Ignoring mixing and based on mean summer or winter profiles at Vancouver Harbour (Anchorage 6) or Juan de Fuca Strait (JdF2).

[d] Average summer or winter surface water density in Juan de Fuca Strait (JdF2).

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