APPENDIX 8B

EFFLUENT DISPERSION MODELLING

APPENDIX 8B-1

BALLAST WATER DISCHARGE AT STEENSBY INLET

Ballast water discharge in Steensby Inlet – Summer and Winter Scenarios

Report Submitted

to

North/South Consultants Inc.
Winnipeg, Manitoba

by

Coastal and Ocean Resources Inc.
Victoria, British Columbia

October 20, 2010

1. Introduction

This report considers the fate of ballast water discharged over a period of 20 hours in winter and 7 hours in summer from a 50 m wide vessel with a draft of 18 to 20 m docked in Steensby Inlet. We assume simultaneous point-source discharge from the port and starboard sides of the vessel near the waterline in water depths of 25 to 30 m. The Labrador Sea ballast water is assumed to have an *in situ* density (sigma-*t*) of 27.17 in winter and 26.763 in summer, where sigma-*t* = (density-1000) and density is measured in units of kilograms per cubic meter (kgm^{-3}). The density of the ballast water is significantly greater than that of the receiving water in summer but comparable to that of the receiving water in winter (Table 1).

Table 1. Observed temperature, salinity, and density at near-surface and 30 m depth in Steensby Inlet. Density values are used for estimating the fate of ballast water discharged during winter and summer months. Ballast water desnity is assumed to be 27.17 in winter and 26.763 in summer.

	Temperature (°C)		Salinity (psu)		*Density (sigma-t)*	
	Surface	30 m	surface	30 m	surface	*30 m*
Winter	-0.9	-1.7	32.96	34.04	26.40	*27.61*
Summer	*3.1*	*1.2*	*25.50*	*26.60*	*20.38*	*20.71*

The following parameters have been used in the analysis (see Table 2 for summary):

Winter ballast water volume discharge, Q_{winter}

Volume discharge is 2.0×10^5 m^3 (2.0×10^8 kg = 2.0×10^5 tonnes) over a 20-hour period, whereby Q = 2.78 m^{3}s^{-1}.

Summer ballast water volume discharge, Q_{summer}

Volume discharge is 0.7×10^5 m^3 (0.7×10^8 kg = 0.7×10^5 tonnes) over a 7-hour period, whereby Q = 2.78 m^{3}s^{-1} (a smaller volume of ballast water is taken aboard in summer).

Winter ballast water density (sigma-*t*)

Density values listed below are based on a year-round salinity of ~34.0 psu and five specified water temperatures (which take into account possible heating of the ballast water).

T	$\rho_{ballast}$	sigma-t
2 °C	1027.17 kgm^{-3}	27.17
4 °C	1026.99 kgm^{-3}	26.99
6 °C	1026.76 kgm^{-3}	26.76
8 °C	1026.49 kgm^{-3}	26.49
10 °C	1026.17 kgm^{-3}	26.17

Summer ballast water density (sigma-*t*)

This has a value of 26.763 ($\rho_{ballast}$ = 1026.763 kg m^{-3}) based on a year-round salinity of ~34.0 psu and summer water temperature of around 6 °C. Additional estimates have been provided for temperatures of 8 °C and 10 °C, which account for possible heating of the ballast water.

Winter receiving water density (sigma-*t*)

This ranges from 26.40 near the surface to 27.61 at 30 m depth ($\rho_{Steensby}$ = 1026.40 to 1027.61) (see Table 1).

Summer receiving water density (sigma-*t*)

This ranges from 20.38 near the surface to 20.71 at 30 m depth ($\rho_{Steensby}$ = 1020.38 to 1020.71) (see Table 1).

Discharge is assumed to occur just above the water surface (~ 0 m elevation) in depths of 25 to 30 m. If there is an alongshore tidal and/or wind-driven current at the time of discharge, the discharge will behave slightly more like a line-source than a point-source.

Bottom slopes: for the first ~200 m seaward from the ship at the dock, bottom slopes are variable but generally range from about 9-11° and span water depths of between 30 and 50 m. For distances of roughly 200 m to 400 m offshore from the ship, bottom slopes decrease to ~ 3° (water depths of 50 and 60 m) while for distances of 400 to 600 m offshore, slopes are ~ 1.75° (water depths between 60 and 75 m). Beyond this, bottom slopes are locally variable but generally less about 1.0 to 1.25° at water depths greater than 75 m.

Tidal currents: principally semidiurnal with a maximum alongshore speed of 0.25 ms^{-1}.

Table 2. Summary of winter and summer ballast water volume discharges, ballast water densities (taking into account possible ballast water heating of up to 10 °C) and receiving water densities for the port site in Steensby Inlet. Steensby water densities are presented for near-surface depths and near-bottom (30 m) depths at the port site.

	Ballast discharge rate Q (m^3s^{-1})	Ballast water density $\rho_{ballast}$ (kgm^{-3})	*Steensby water density* $\rho_{Steensby}$ *(kgm^{-3})*	
			surface	*30 m*
Winter	2.78 m^3s^{-1}	1026.17 - 1027.17	1026.40	*1027.61*
Summer	*2.78 m^3s^{-1}*	*1026.17 – 1026.76*	*1020.38*	*1020.71*

2. Downslope gravity current

The above parameters have been used to provide an empirical estimate of the fate of the seafloor gravity (density) current generated during ballast water discharge from the sides of the vessel. The advance of the gravity current traveling down a slope of angle θ measured relative to the horizontal has been investigated in laboratory experiments (Britter and Linden, 1980). According to this study, the head of the gravity current advances at a speed U_f which satisfies the relationship

$$\frac{U_f}{(g'Q/W)^{1/3}} = 1.5 \pm 0.2 \qquad (1)$$

for slope angles 5° ≤ θ ≤ 90°. In this equation, we initially set

$$Q = ½ \times 2.78\ \mathrm{m^3s^{-1}} \sim 1.39\ \mathrm{m^3s^{-1}} \qquad (2)$$

as the ballast volume discharge for both the port and starboard sides of the ship, W is the width of the discharge flow parallel to the alongshore direction at the point of entry into the inlet, and

$$g' = g\,\frac{\Delta\rho}{\rho_{Steensby}} \qquad (3)$$

is the "reduced gravity" based on a water density, $\rho_{Steensby}$, in Steensby Inlet. Here, g = 9.81 ms^{-2} is the usual acceleration of gravity, and

$$\Delta\rho = \rho_{ballast} - \rho_{Steensby} \qquad (4)$$

is the difference in density between the ballast water and the ambient receiving water in Steensby Inlet at the point of discharge.

2.1 Winter downslope gravity current

The water density in the upper 30 m of Steensby Inlet in winter is assumed to have a density $\rho_{steensby}$ = 1026.40 kgm^{-3} (sigma-t = 26.40) while the Labrador Sea ballast water has a density $\rho_{ballast}$ = 1027.17 kgm^{-3} (27.17; Tables 1, 2). Using the above density values, we obtain

$$\Delta\rho = \rho_{ballast} - \rho_{Steensby} = 0.77 \text{ kgm}^{-3} \quad (5)$$

so that the reduced gravity in equation (3) has the value

$$g' = g\frac{0.77}{1026.40} = 0.0074 \text{ ms}^{-2}. \quad (6)$$

Using this set of parameters and equation (1), we estimate that one-meter wide (W = 1 m) discharge ports on the starboard and port sides of the vessel will give rise to downslope gravity currents with speeds of advance

$$U_f = 1.5\,(g'Q/W)^{1/3} \approx 0.41 \text{ ms}^{-1}. \quad (7)$$

According to this result, it will take the gravity current in winter only about 2 minutes to progress downslope from one side of the 50 m wide ship to the other.

We also examined the above results for possible scenarios whereby the ballast water temperature is increased to 4, 6,…, or 10 °C. As shown in Table 3, U_f = 0.32 ms^{-1} for 6 °C and U_f = 0.20 ms^{-1} for 8 °C. If the water were heated to 10 °C, the gravity current would not go downslope because the density of the ballast water would then be smaller than the density of the receiving water. Thus, in this case, the ballast water would spread laterally near the surface.

Table 3. Winter downslope velocity, U_f, of the head of a gravity current for a ballast volume discharge $Q = 2.78$ m^{3}s^{-1} if the winter ballast water were heated to temperatures in the range 2 to 10 °C. Here, $\rho_{ballast}$ denotes the density of the ballast water.

Heated ballast water temperature (°C)	Ballast water density $\rho_{ballast}$ (kgm^{-3})	Reduced gravity g' (ms^{-2})	*Downslope gravity current* U_f *(ms^{-1})*
2	1027.17	0.0074	*0.41*
4	1026.99	0.0056	*0.37*
6	1026.76	0.0034	*0.32*
8	1026.49	0.0009	*0.20*
10	*1026.17*	*-0.0022*	-

Because the gravity current formed on the upslope side of the ship will rapidly merge with the gravity current formed on the downslope side of the ship, we can treat the total discharge as one value

$$Q = 2.78 \text{ m}^3\text{s}^{-1} \quad (8)$$

(see Table 2) as if the discharge for the port and starboard sides of the vessel in winter contribute simultaneously to the generation of a single gravity current on the downslope side of the vessel. Table 4 provides a set of estimates of the gravity current speed for the winter ballast water density and two values of the Steensby water density (water density at the surface and at 30 m depth) for a range of ballast discharge widths, *W*. It should be noted that the ballast water discharged in winter has larger density ($\rho_{ballast}$ = 1027.17 kg/m^3) than the receiving water at the surface (ρ_{surface} = 1026.40 kg/m^3) but smaller density than the water at 30 m depth (ρ_{bottom} = 1027.61 kg/m^3). This means that the ballast water discharged in winter will not be able to reach 30 m but will accumulate just under the pycnocline.

Table 4. Winter downslope velocity, U_f, of the head of a gravity current for a ballast volume discharge Q = 2.78 m^3s^{-1} for the winter ballast water density ($\rho_{ballast}$), receiving water densities ($\rho_{steensby}$), and alongshore discharge width, W. Here, ρ_{surface} denotes a range of *maximum* velocity estimates obtained by setting $\rho_{steensby}$ equal to the water density at the surface (the *minimum* possible upper layer density). Similarly, ρ_{bottom} denotes a range of *minimum* velocity estimates obtained by setting $\rho_{steensby}$ equal to the winter density at 30 m depth (the *maximum* upper water density) (see Table 2).

	$\rho_{ballast}$ (kg/m^3)	$\rho_{steensby}$ (kg/m^3)	W (m)	U_f (m/s)
ρ_{surface}	1027.17	1026.40	1	0.41
	1027.17	1026.40	2	0.33
	1027.17	1026.40	5	0.24
	1027.17	1026.40	10	0.19
ρ_{bottom}	1027.17	1027.61	1	-
	1027.17	1027.61	2	-
	1027.17	1027.61	5	-
	1027.17	1027.61	10	-

2.2 Summer downslope gravity current

We repeat the analysis of Section 2.1 but using the summer ballast water and Steensby Inlet water densities. In this case, the water density in the upper 30 m in summer can be assumed to have a density $\rho_{steensby}$ = 1020.38 kgm^{-3} (sigma-t = 20.38) while the Labrador Sea ballast water has a density $\rho_{ballast}$ = 1026.763 kgm^{-3} (26.763; Table 2). Using the above density values, we obtain

$$\Delta\rho = \rho_{ballast} - \rho_{Steensby} = 6.383 \text{ kgm}^{-3} \qquad (9)$$

so that the reduced gravity in equation (3) for summer months has a value

$$g' = g\frac{6.383}{1020.38} = 0.0614 \text{ ms}^{-2}. \qquad (10)$$

Using this set of parameters and equation (1), we estimate that one-meter wide (W = 1 m) discharge ports on the starboard and port sides of the vessel will give rise to downslope gravity currents with speeds of advance

$$U_f = 1.5\ (g'Q/W)^{1/3} \approx 0.83\ \text{ms}^{-1}. \qquad (11)$$

Based on this estimate, it will take the gravity current only about 1 minute to progress downslope from one side of the 50 m wide ship to the other. As in winter, the gravity current formed on the upslope side of the ship will rapidly merge with the gravity current formed on the downslope side of the ship, so that we can again treat the total discharge as one value and set

$$Q\ =\ 2.78\ \text{m}^3\text{s}^{-1}. \qquad (12)$$

Once again, we estimated the effect of heating the ballast water up to 8-10 °C. Results presented in Table 5 show that, because the ballast water has much larger density than the receiving water in summer, the effect of heating is negligible. Estimates of the gravity current velocity in summer are presented for a range of Steensby water densities for a ballast discharge width, W.

Table 5. Downslope velocity, U_f, of the head of a gravity current for summer for a ballast volume discharge Q = 2.78 m^3s^{-1} for ballast water heated to temperature 6-10 °C. Here $\rho_{ballast}$ denotes the density of the ballast water.

Heated ballast water temperature (°C)	Ballast water density $\rho_{ballast}$ (kgm^{-3})	Reduced gravity g' (ms^{-2})	*Downslope gravity current* U_f *(ms^{-1})*
6	1026.76	0.0614	*0.83*
8	1026.49	0.0587	*0.82*
10	*1026.17*	*0.0557*	*0.81*

Table 6. Downslope velocity, U_f, of the head of a gravity current in summer for a ballast volume discharge $Q = 2.78$ m^{3}s^{-1} for summer ballast water density ($\rho_{ballast}$), receiving water densities ($\rho_{steensby}$), and alongshore discharge width, W. Here, ρ_{surface} denotes a range of *maximum* velocity estimates obtained by setting $\rho_{steensby}$ equal to the water density at the surface (the *minimum* possible upper layer density); ρ_{bottom} denotes a range of *minimum* velocity estimates obtained by setting $\rho_{steensby}$ equal to the summer density at 30 m depth (the *maximum* upper water density) (see Table 2).

	$\rho_{ballast}$ (kg/m^3)	$\rho_{steensby}$ (kg/m^3)	W (m)	U_f (m/s)
ρ_{surface}	1026.763	1020.38	1	0.83
	1026.763	1020.38	2	0.66
	1026.763	1020.38	5	0.49
	1026.763	1020.38	10	0.39
ρ_{bottom}	1026.763	1020.71	1	0.82
	1026.763	1020.71	2	0.65
	1026.763	1020.71	5	0.48
	1026.763	1020.71	10	0.38

Results indicate that downslope density current speeds in summer are roughly twice those in winter.

3. Seaward extent of the ballast water gravity current

The empirical calculations in the previous sections reveal that for a discharge "footprint" of 1 to 10 m and water densities in the upper 30 m of Steensby Inlet close to those observed near the inlet surface, the head of the gravity current will advance down the sloping bottom of the inlet at velocities of U_f ~ 0.40 to 0.80 ms^{-1} in summer and U_f ~ 0.10 to 0.40 ms^{-1} in winter. Although a much smaller volume of water is discharged in summer than in winter, the much greater density difference between the ballast water density and receiving water density in summer will cause the summer discharge to move offshore at roughly twice the speed as in winter. Results for this model are valid until the gravity current reaches an offshore distance of roughly 600 m whereupon the current will begin to slow considerably due to frictional effects as the bottom slope diminishes to near zero in the offshore direction. With maximum downslope speeds in excess of 0.10 ms^{-1}, it will typically take winter ballast water less than about an hour to advance 600 m offshore to the flatter regions of the bottom where average slopes diminish to less than 2°. In summer, the time to advance 600 m offshore is less than 25 minutes. On the basis of these results, we expect the relative warm, salty ballast water to begin to "pool" over the slope while advancing much more slowly to deeper water beyond 600 m.

While it is flowing downslope, the ballast water will also be advected in the alongshore direction by the reversing semidiurnal tidal currents. For semidiurnal tidal currents with maximum ebb and flood velocities $U_o \sim 0.25$ ms^{-1} in the alongshore direction, turbulently mixing gravity currents will be advected a distance, *d*, relative to the ship with alongshore displacements

$$d = \frac{U_o T}{2\pi}\int_0^{\pi} \sin\theta \, d\theta = \frac{U_o T}{\pi} \approx 3.6\,\text{km} \qquad (13)$$

for both the flood and ebb portions of a T = 12.42-hour semidiurnal tidal period. The vertical and lateral shear within the tidal currents will augment the normal turbulence within the flow causing the ballast water to more rapidly diffuse in the alongshore and offshore directions as it mixes with the ambient bottom waters in the inlet. Depending on the degree of tidal current shear and turbulence in the gravity current, we expect mixing ratios of 100:1 to 1000:1 between the ambient and ballast water at the outer boundaries of the gravity flow.

4. Offshore confinement of the ballast water by rotational forces

In addition to the downslope loss of speed associated with the diminishing slopes and increasing depth, the offshore extent of the gravity current will also be affected by Coriolis (rotational) effects as it moves downslope. Due to earth's rotational effects, the time averaged downslope flow will assume a radius of curvature, *r*, given by

$$r = \frac{U}{f} \quad (14)$$

where U is the downslope speed and f is the Coriolis parameter

$$f = 2\Omega \sin(\varphi) \quad (15)$$

where φ is the geographical latitude and Ω =0.72921×10^{-4} s^{-1} is the Earth's rate of rotation. For the proposed dock site in Steensby Inlet (latitude = 70.33° N) we obtain f = 1.3733×10^{-4} s^{-1}. Using $U \approx$ 0.1–0.4 ms^{-1} for winter and $U \approx$ 0.4–0.8 ms^{-1} for summer, we obtain

$r \approx$ 0.7 - 2.9 km (winter)

$r \approx$ 5.8 km (summer)

These distances – which mainly exceed the maximum offshore extent $r \approx 1$ km of the gravity current based on the diminishing bottom slope – provide a very rough estimate of the maximum offshore extents possible for the gravity current irrespective of the bottom slope. Both the 7-hour discharge period in summer and the 20-hour discharge period in winter are comparable to the time $T_f = 2\pi / f \approx 12.7$ hrs of the inertial period associated with Coriolis effects to become fully established. This, in turn, suggests that within the time that the ballast water discharge is taking place, an alongshore geostrophic bottom current can be set up which adds a weak to moderate advective flow to the north. As a consequence, the bottom currents near the vessel in summer and in winter (assuming that the vessel rides in broken ice) will consist of a slow northward drift superimposed on relatively strong back-and-forth semidiurnal motions. This northward geostrophic current will help to advect the high salinity, high temperature ballast water along the slope as it diffuses and mixes over time.

We further speculate that the patch of ballast water discharged during each visit to the Steensby Inlet dock site will deform into a relatively warm, high salinity clockwise-rotating "ballast-water eddy" over the sloping bottom seaward of the vessel. Although this speculation needs to be verified by numerical modeling and/or observation, we suggest that each eddy will self-advect to the north along the slope while slowly moving into deeper water. Assuming that diffusion and viscosity effects cause the thickness, *h*, of bottom-hugging ballast water eddies to increase with time and the relative vorticity, ζ (shear in the current velocity field) of each eddy to decrease with time, the "conservation of vorticity" requirement (Gill, 1982) for an eddy

$$\frac{f+\zeta}{h} = \text{constant}\,. \qquad (16)$$

indicates that each ballast-water eddy will move to higher latitudes (increasing Coriolis parameter, *f*) with time. If this analysis is correct, ballast-water eddies will maintain their integrity for considerable time (days to weeks) while slowly moving northward along the outer slope centered at a distance greater than approximately 500 m seaward of the vessel. This will be especially true for the larger eddies in winter. Such translation speeds for topographically trapped eddies is typically of the order of a few centimeters per second.

5. Summary

The empirical results presented in this report indicate that ballast water discharged from the port and starboard sides of vessels docked in Steensby Inlet will merge within minutes into a single gravity current which will flow downslope at speeds of 0.10 to 0.80 ms^{-1} (~0.2 to 1.6 knots) depending on season. Downslope speeds are greater in summer than in winter. The offshore extent of the ballast water gravity current is determined primarily by the reduction in bottom slope, which for the vicinity of the docked vessel, changes from roughly 10° near the vessel to less than 2° beginning around 400 to 600 m seaward of the vessel. Water depths over this distance increase from roughly 30 m under the ship to 75 m at 600 m offshore. It will take the head of the gravity current less than an hour to travel the 600 m to the base of the slope. As a consequence, even during times of maximum (~0.25 ms^{-1}) tidal flow, tidal currents will have little time to deflect gravity currents from their downslope course. In all instances, offshore pooling of the ballast water is therefore likely to occur directly offshore, less than one kilometer from the vessel.

Over the summer and winter discharge periods, the gravity currents will diffuse laterally and vertically due to the effects of background turbulence and shear associated with tidal and wind-driven currents in the region. Based on maximum alongshore semidiurnal tidal currents of 0.25 ms^{-1}, the ballast water will experience four ebb-flood directional changes and reach alongshore excursions of around 4 km to the north and south of the discharge location. We speculate that pooling of the ballast water will occur at distances greater than about 400 m offshore where the bottom diminishes to less than 2° and that this pooling effect will lead to the formation of a near-bottom, clockwise rotating "ballast-water eddy". Because the clockwise rotational effects will tend to retard the lateral spreading of the ballast water into the surrounding ambient waters of the inlet, eddies will retain a degree of spatial integrity as they are being advected backwards and forwards along-slope by the semidiurnal tidal currents. This leads to the conclusion that the relatively warm and salty Labrador Sea water that make up the eddies will slowly self-advect to the north near the base of the slope centered at water depths of around 75 m. Confirmation of these empirical results and speculation for the formation of a ballast-water eddy requires further analysis based on three-dimensional numerical simulations that permit both tidal and wind-generated currents along with a time-varying input of dense Labrador Sea water at the surface of the inlet near the discharge location.

References

Britter, R.E. and P.F. Linden. 1980. The motion of a front of a gravity current travelling down an incline. *J. Fluid Mechanics*, 99, 531-543.

Gill, A.E. 1982. *Atmosphere-Ocean Dynamics*. Academic Press, 662 p.