Local environmental conditions determine the footprint of municipal effluent in coastal waters: A case study in the Strait of Georgia, British Columbia

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HIGHLIGHTS

• Municipal wastewater fluxes are compared to regional geochemical budgets.
• Wastewater contributes ≤1.5% of organic C, N, and oxygen demand in the Strait.
• Wastewater contributes ≤10% of metals and PCBs captured in the sediment.
• Wastewater contributes about 60% of PBDEs captured in the sediment.
• Effects on benthos are limited to 1–10 km and result from organic carbon flux.

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ABSTRACT

To predict the likely effects of management action on any point source discharge into the coastal ocean, it is essential to understand both the composition of the effluent and the environmental conditions in the receiving waters. We illustrate a broadly-applicable approach to evaluating the comprehensive environmental footprint of a discharge, using regional geochemical budgets and near-field monitoring. We take as a case study municipal effluent discharged into the Strait of Georgia (west coast of Canada), where there has been public controversy over the discharge of screened or primary-treated effluent directly into the ocean. Wastewater contributes ≤1% of the nitrogen, organic carbon and oxygen demand in the Strait and is unlikely to cause eutrophication, harmful algal blooms or hypoxia in this region. Metals (Hg, Pb, Cd) are controlled by natural cycles augmented by past mining and urbanization, with 0.3–5% of the flux contributed by wastewater. Wastewater contributes ~5% of PCBs but ≤60% of PBDEs and is likely also important for pharmaceuticals and personal care products. Effects of high organic flux on benthos are measurable in the immediate receiving environment. The availability of particle-active contaminants to enter the food chain depends on how long those contaminants remain in the sediment surface mixed layer before burial. Secondary treatment, slated for completion in Vancouver in 2030, will reduce fluxes of some contaminants, but will have negligible effect on regional budgets for organic carbon, nitrogen, oxygen, metals and PCBs. Removal of PBDEs from wastewater will affect regional budgets, depending on how the sludge is sequestered.

1. Introduction

The coastal ocean links land with the open sea. Geochemical cycles driven by global-scale circulation are augmented in coastal waters by discharges from human activities on land that can have profound effects on local ecosystems. With limited resources managers have to decide how to prioritize possible actions to limit the effects of those activities. Municipal wastewater is one highly visible discharge that carries a complex mixture of contaminants. In some parts of the world wastewater discharge has led to eutrophication, harmful algal blooms, hypoxia, extinctions of bottom fauna and fish mortality (Islam and Tanaka, 2004). However, the effects of wastewater discharge are not the same everywhere. For example, phosphates in household wastewater can have dramatic effects on lakes, causing eutrophication and harmful algal blooms, while anthropogenic phosphate has little effect on marine

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ecosystems, where productivity is more often limited by nitrate (Correll, 1998). Similarly, wastewater can affect one coastal sea differently from another, depending on processes occurring in the receiving environment. Consequently, management actions that are developed for one area, such as introducing a particular level of wastewater treatment, might not have the anticipated effect when applied to another.

The purpose of this paper is to present a blueprint for a comprehensive and specific analysis of the effects of a point-source discharge that can be applied to any coastal setting, taking into account both the potentially harmful characteristics of the effluent and the local characteristics of the receiving environment that may amplify or reduce harm. We use regional geochemical mass balance budgets, together with a local monitoring programme, to determine the total effect on the environment, or environmental footprint, of municipal wastewater in a particular coastal sea, with the ultimate aim of informing local management action. We illustrate this type of analysis, taking as a case study the discharge of municipal wastewater into the Strait of Georgia, a semi-enclosed sea on the west coast of Canada bordered by two metropolitan areas.

Metro Vancouver (population 2.3 million; 2011 census) and Victoria’s Capital Regional District (population 0.36 million) together treat and discharge approximately $5 \times 10^{11}$ L of municipal wastewater each year into the Strait of Georgia, through 5 treatment plant outfalls near Vancouver and 3 outfalls near Victoria (Fig. 1). Wastewater is also discharged into the Strait from the smaller cities of Nanaimo, Comox and Campbell River, as well as from the Gulf Islands. The wastewater contains nutrients (N, P), organic carbon, persistent organic pollutants, metals, pharmaceuticals and pathogens. Because the effluent at some sites is treated only to primary level (including a settling step), and at two sites is only screened (Table 1), local environmental organizations have raised concerns about the potential for municipal wastewater to pollute and cause eutrophication in the Strait of Georgia.

As a relatively deep coastal sea (max depth 420 m) with restricted circulation, the Strait of Georgia might seem particularly vulnerable to contamination and to the development of hypoxia or even anoxia in the deep basins, driven by the discharge of nutrients, organic carbon and other contaminants near the surface. However, the effects of municipal wastewater are modified by local circulation, sedimentation and biogeochemical cycles. In addition, wastewater discharge is only one of many pathways of material to the Strait of Georgia: others are rivers, atmospheric deposition, exchange with the Pacific Ocean, and other anthropogenic discharges (pulp mills, aquaculture, ocean dumping).

We use geochemical mass balance budgets for components of municipal wastewater to assess the regional contribution of the discharge, comparing components that have large, natural cycles with those that
do not. We also evaluate the spatial extent of measurable biological effects (population and diversity of benthic organisms) in the proximal sea bed. We discuss the effects of chemical properties, circulation, sedimentation in the receiving environment, and climate variability. Finally, we comment on the likely effects of upgrading the screened and primary effluents to secondary treatment, and show how the approach outlined here might be applied in other coastal seas.

2. Approach

Contaminants in wastewater fall into two categories: those which have natural background cycles in coastal seas (organic carbon, dissolved inorganic nitrogen, oxygen demand and metals: Cu, Pb, Hg, Cd), and those contaminants which are wholly products of human activities (PCBs, PBDEs, detergents and pharmaceuticals). To estimate footprints for the former category, we have begun by describing the physical processes and natural cycles, which have been augmented by local human activities including wastewater disposal. Whether effects might reasonably be expected in the environment depends on the magnitude of the wastewater loading compared to the natural cycles and their variability.

For nitrogen, carbon and oxygen we draw on budgets, cycles and residence time estimates already published for the Strait of Georgia, based on sediment cores, sediment traps, water column and river measurements and emission data from municipalities and pulp mills (Johannessen et al., 2003, 2008b, 2014; Pawlowicz et al., 2007; Sutton et al., 2013).

For metals we interpret published (Macdonald et al., 2008) and new effluent discharge data to determine the importance of metal loading from outfalls. We collected sediment box cores at seven sites in the Strait of Georgia (Fig. 1) in 2003 and 2004. Subsections of the cores were analysed for a suite of metals by inductively coupled plasma-optical emission spectroscopy, as described by Macdonald et al. (2008), with a standard deviation of 1.4–11%. Mercury was analysed in the sediment by atomic fluorescence detection, as described by Johannessen et al. (2005), with a coefficient of variation of 5.35%.

We have applied an exploratory principal components analysis (Meglen, 1992) to the 139 sediment samples from the cores, including key metals as variables (Cd, Zn, Ag, Cu, Hg, Pb).

The Strait of Georgia is an open system, exchanging with the greater Pacific Ocean and the atmosphere, and we do not have confident assessments of the exchange fluxes for metals, PCBs and PBDEs. In these cases we can still assess the scale of the municipal contribution for contaminants that associate with particles, because we have robust estimates of the total sink via sediment burial within the Strait of Georgia from published and new sediment core profiles (Johannessen et al., 2003, 2005, 2008a; Macdonald et al., 2008), and we have direct measurements of the composition of municipal effluent.

In addition to the contribution of wastewater components to regional budgets, we also illustrate the effects of the nearby receiving environment on the fate of contaminants discharged with wastewater, based on detailed studies at two of the outfall sites (Iona Island (Vancouver) and Macaulay Point (Victoria)). To calculate annual fluxes (kg yr⁻¹) of various components in wastewater, we rely on annual reports and data collected by each municipality (Capital Regional District, 2013; Metro Vancouver, 2013; Regional District of Nanaimo, 2013a,b,c,d; City of Campbell River, 2012; Greater Vancouver Regional District, 2005). Not all components are measured at some of the smaller outfalls. Consequently, we have tabulated the contributions from the top five outfalls by volume (Table 1), which together account for ~90% of the volume discharged, and factored these up to 100% for the components that were not measured at the smaller sites. All concentrations and loads are reported on a dry weight basis.

3. Results: wastewater components in the context of regional cycles and the spatial extent of the footprint

3.1. Nitrogen/nutrients/eutrophication

Nitrogen enters the coastal ocean in dissolved and particulate, organic and inorganic forms. The dissolved inorganic fraction causes the greatest concern, because it provides a ready source of nutrients for phytoplankton and might lead to eutrophication, harmful algal blooms and hypoxia. The dissolved inorganic nitrogen (DIN) cycle of the Strait of Georgia is dominated by exchange through Juan de Fuca Strait (~380 × 10⁶ kg yr⁻¹, Sutton et al., 2013)(Fig. 2). This nitrogen supports the high rate of primary production in the Strait (~320 × 10⁶ kg yr⁻¹ N, Sutton et al., 2013). The nitrogen discharged through all the municipal wastewater outfalls combined (8.7 × 10⁶ kg yr⁻¹; Table 1) represents only ~1% of the total influx. In addition, for most of the year in most of the Strait, phytoplankton are limited by light, not by nutrients (Li et al., 2013).

<table>
<thead>
<tr>
<th>Outfall</th>
<th>Treatment level</th>
<th>Discharge (10¹¹ L yr⁻¹)</th>
<th>TSS (10⁶ kg yr⁻¹)</th>
<th>DIN (10⁶ kg yr⁻¹)</th>
<th>POC (10⁶ kg yr⁻¹)</th>
<th>BOD (10⁶ kg yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iona Is.</td>
<td>Primary</td>
<td>2.06</td>
<td>10.9</td>
<td>2.69</td>
<td>3.82</td>
<td>15.1</td>
</tr>
<tr>
<td>Annacis Is.</td>
<td>Secondary</td>
<td>1.80</td>
<td>1.87</td>
<td>3.78</td>
<td>0.26</td>
<td>1.15</td>
</tr>
<tr>
<td>Macaulay Pt.</td>
<td>Screened</td>
<td>0.16</td>
<td>3.64</td>
<td>0.43</td>
<td>0.38</td>
<td>3.43</td>
</tr>
<tr>
<td>Clover Pt.</td>
<td>Screened</td>
<td>0.18</td>
<td>3.16</td>
<td>0.44</td>
<td>0.32</td>
<td>3.51</td>
</tr>
<tr>
<td>Lions Gate</td>
<td>Primary</td>
<td>0.32</td>
<td>1.73</td>
<td>0.46</td>
<td>0.77</td>
<td>2.82</td>
</tr>
<tr>
<td>Sum of 5 outfalls</td>
<td></td>
<td>4.54</td>
<td>21.3</td>
<td>7.80</td>
<td>5.55</td>
<td>26.0</td>
</tr>
<tr>
<td>Total from wastewater</td>
<td></td>
<td>4.99</td>
<td>23.4</td>
<td>8.58</td>
<td>6.10</td>
<td>28.6</td>
</tr>
<tr>
<td>% from wastewater</td>
<td></td>
<td>0.1%</td>
<td>1.2%</td>
<td>0.2%</td>
<td>3.3%</td>
<td>1.5%</td>
</tr>
</tbody>
</table>

*Screened = effluent passes through a 6 mm mesh; Primary = effluent passes through settling tanks; Secondary = effluent passes through settling tanks and a microbial decomposition chamber.*

Table 1: Volume discharge of effluent and fluxes of selected components (dry weight) from the top 5 outfalls and contribution of wastewater to regional budgets. These 5 outfalls account for 90% of the municipal wastewater discharged to the Georgia Basin. To calculate the total flux of each component from municipal wastewater we factored up to 100%. TSS = total suspended sediment; BOD = biochemical oxygen demand; POC = particulate organic carbon; DIN = dissolved inorganic nitrogen.
unlikely to cause eutrophication or harmful algal blooms in the Strait of Georgia or Juan de Fuca Strait.

3.2. Organic carbon

Like N, organic C enters the Strait of Georgia in dissolved and particulate, organic and inorganic forms. However, it is the particulate organic carbon (POC) discharged with wastewater that causes concern. POC can sink into the deep water, where its decomposition and metabolism consume oxygen, possibly leading to hypoxia. In contrast to the balance of DIN, most of the POC in the Strait of Georgia is produced inside the Strait by phytoplankton (2170 × 10⁶ kg yr⁻¹) (Fig. 3). The next largest sources are rivers (220 × 10⁶ kg yr⁻¹, Johannessen et al., 2003, 2008a), especially the Fraser River, and the inflow through Juan de Fuca Strait (which is effectively balanced by outflow). The concentration of organic carbon is higher in wastewater than in river water or in the ambient seawater, but the total discharge of organic carbon is three orders of magnitude lower than the flux from primary production. The 6.2 × 10⁶ kg yr⁻¹ discharged through the municipal outfalls represents approximately 0.2% of the total of the sources. This is negligible in the

![Diagram showing dissolved inorganic nitrogen budget](image1)

![Diagram showing particulate organic carbon budget](image2)
context of the whole Strait. However, the influx of organic carbon through outfalls does have local effects in the area immediately surrounding each outfall, as described in the “Spatial extent of chemical and biological footprint of the Iona Island outfall” section below.

3.3. Biochemical oxygen demand

Subsurface oxygen is declining in coastal waters around the world (Gilbert et al., 2010). In some places biochemical oxygen demand associated with wastewater has caused local waters to become hypoxic or even to develop dead zones (Diaz and Rosenberg, 2008; Hofmann et al., 2011). The dynamics of oxygen in the deep water of the Strait of Georgia are controlled by consumption, due to remineralization of organic matter, and resupply during deep-water renewal in late spring and late summer (Fig. 4). The annual biochemical oxygen demand of municipal wastewater is $2.9 \times 10^7$ kg yr$^{-1}$ (Table 1), which represents ~1% of the annual drawdown for the whole Strait (Johannessen et al., 2008b; Pawlowicz et al., 2007). Given the vertical decomposition rate of organic matter in the Strait, it is unlikely that more than ~4% of the particulate organic matter discharged with wastewater (or any of the dissolved organic matter) reaches the deep water, which seasonally approaches hypoxia. On a basin scale, therefore, municipal wastewater does not add significantly to the pressure on oxygen in the Strait. In the sediment near the outfall, however, the biochemical oxygen demand of the effluent has measurable chemical and biological effects, as described in Section 3.7 below.

3.4. Metals

For the seven sediment box cores discussed here, we have measured the metals Pb, Cd, Cr, Zn, Cu, Hg, Ni, and Ag. Like nitrogen, carbon and oxygen, all metals have natural cycles onto which human activities are imposed. Metals can exist in seawater in dissolved or particulate phases. The major sink for metals in the ocean is burial as sediments, with little metal contamination. These samples come from cores far from point sources, or from sediments deep within sediment cores. The other samples show distributions that are significantly splayed out toward the various metals. In particular, the distribution for Core 2, collected just outside Vancouver Harbour and Howe Sound, implies a strong influence by Cu, Hg and Pb. In contrast, the core collected nearest to the Iona Island outfall (Core 3) implies an influence by Cd with some pull toward Ag.

Although there is some metal contamination in Strait of Georgia sediment, most of this relates to past mining activity or to the various sources of Hg mentioned above. The distribution of metals in surface sediment (Fig. 6 upper panels) supports this interpretation. There is little indication of contamination by Pb, Zn or Cu from the Iona Island outfall, and indeed most of the effluent measurements for Pb and Zn were below detection limits (Metro Vancouver, 2013). However, the story is different for cadmium.

3.4.1. Cadmium

For British Columbia, Cd has posed a particular problem to the shellfish industry where Cd concentrations high enough to prohibit export were identified over a decade ago (Kruzyński et al., 2002), although no specific local sources of contaminant Cd were identified. Rather, it seems far more likely that high Cd concentrations in shellfish of the

![Fig. 4. Schematic of the oxygen cycle in the Strait of Georgia (Johannessen et al., 2014).](image-url)
NE Pacific Ocean derive from natural Cd enrichments that occur within ocean waters as they transport around the globe, with the oldest, and most Cd-rich, water being found in the North Pacific (Bruland and Franks, 1983).

However, sediment core profiles show Cd enrichment toward the surface only in the core collected closest to the Iona Island outfall (Core 3), indicating a role for municipal effluent (Fig. 7; compare Core 3 with Core 1). The amount of Cd supplied by municipal outfalls, 288 kg yr\(^{-1}\) (Table 2), is small compared to the estimated flux to Strait of Georgia sediments (6346 kg yr\(^{-1}\)), suggesting that other sources dominate this system. (In particular, the Fraser River is a large source, estimated at 3900 kg yr\(^{-1}\).) The surface enrichment at the outfall site likely results from the elevated organic carbon flux at this site. As explained in detail by Macdonald et al. (2008), dissolved Cd in bottom water or pore water is strongly sequestered by sulphide. This process can lead to very large Cd enrichments in sediments (e.g. Pedersen et al., 1989). High organic carbon flux leads to sulphate reduction, which has likely enhanced the rate of sequestration of Cd within the Iona footprint.

3.4.2. Other metals (Zn, Ni, Cr)

Although substantial amounts of Cu, Zn, Ni and Cr are passing through municipal outfalls (Table 2), these are in all cases dwarfed by other sources, especially the Fraser River, and have little opportunity to contribute detectable signals to the sediments. The wastewater source of Cu (20,000 kg yr\(^{-1}\)), for example, is only about 2% of the total sediment sink, which is mostly supplied by the Fraser River and mining activities.

3.5. Persistent organic pollutants: PCBs and PBDEs

Polychlorinated biphenyls (PCBs) and polybrominated diphenyl ethers (PBDEs) represent particle-active, persistent organic pollutants with different discharge histories. The footprint of municipal wastewater is different in the two cases (Johannessen et al., 2008a). Wastewater is a small conduit of PCBs into the environment (\(\leq 10\%\)); however, it is one of the main routes of entry for PBDEs (\(\leq 60\%\)). PCBs are not in current use in Canada. Their import, manufacture and sale were banned in 1977; their continued presence in our local environment is due mainly to their persistence, as well as to some ongoing use in other countries (Ross et al., 2009). The annual load of wastewater PCBs, which is \(-4\ kg\ yr^{-1}\) of the total \(40\ kg\ yr^{-1}\ buried\ in\ sediment\ (Table\ 2)\), likely derives largely from rainfall and surface soil particles collected by
storm drains and funnelled through outfalls. We do not have a complete budget for PCBs or PBDEs, so the % contribution from the outfalls is based on a comparison with the sediment burial rate. The contributions of these compounds to the whole regional budget are likely lower than these estimates, since the burial sink does not capture the portion that is metabolized or exported from the Strait. The percent contribution is larger for PCBs than for C or N, because there is no natural source of PCBs: all of the PCBs come from human activities. A sediment core collected near the Iona outfall indicates that the beginning of wastewater discharge at the current outfall site in 1988 diluted the flux of PCBs, actually reducing the concentration in local sediments (Fig. 8). The distribution of PCBs in Strait of Georgia sediments is now mainly controlled by sedimentation and mixing rates. Natural sedimentation is gradually burying PCBs, especially near Vancouver where there is a high flux of relatively clean sediment from the Fraser River.

The situation is different for PBDEs. The import and production of PBDEs have recently been banned in Canada, but there remains a huge reservoir on land in households and businesses, where PBDEs have been used as flame retardants in furniture, fabrics, clothing, toys and electronics. PBDEs have only been in use since ~1978 near the Strait of Georgia, and they have not yet reached a steady state with the environment. They are still mainly concentrated in sediments near their main points of entry: the urban harbours of Vancouver and Victoria and their wastewater outfalls.

3.6. Other components not measured

Other classes of contaminants that enter the Strait of Georgia in association with wastewater are pesticides and other POPs, pharmaceuticals and personal care products (surfactants, artificial fragrances, dyes), pathogens, and newly-developed household chemicals. Although the cycling of these contaminants has not been examined in detail locally, we can propose likely fates for them based on the patterns in components that have been measured (see Discussion section).

3.7. Spatial extent of chemical and biological footprint of the Iona Island outfall

The spatial footprint of an outfall depends largely on local sedimentation and water circulation, as well as on the properties and fluxes of contaminants. The discharge region for the Iona outfall has high sediment biomass and production relative to the rest of the Strait, due to the considerable particulate discharge from the Fraser River (Burd et al., 2013; Burd, 2014). The abundance of large, burrowing echinoderms in this region promotes considerable sediment bioturbation and aeration. High natural sedimentation has resulted in sufficient

<table>
<thead>
<tr>
<th></th>
<th>Pb (kg yr$^{-1}$)</th>
<th>Zn (10$^3$ kg yr$^{-1}$)</th>
<th>Cu (10$^3$ kg yr$^{-1}$)</th>
<th>Hg (kg yr$^{-1}$)</th>
<th>Ag (kg yr$^{-1}$)</th>
<th>Cd (kg yr$^{-1}$)</th>
<th>TotPCB (kg yr$^{-1}$)</th>
<th>TotPBDE (kg yr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iona Is.</td>
<td>400</td>
<td>11.0</td>
<td>8.90</td>
<td>&lt;10</td>
<td>&lt;200</td>
<td>&lt;230</td>
<td>2.66</td>
<td>29.6</td>
</tr>
<tr>
<td>Annacis Is.</td>
<td>&lt;200</td>
<td>7.00</td>
<td>4.60</td>
<td>&lt;9</td>
<td>&lt;90</td>
<td>&lt;30</td>
<td>0.34</td>
<td>5.7</td>
</tr>
<tr>
<td>Lions Gate</td>
<td>80</td>
<td>2.30</td>
<td>1.90</td>
<td>&lt;2</td>
<td>&lt;20</td>
<td>&lt;7</td>
<td>0.27</td>
<td>4.98</td>
</tr>
<tr>
<td>Clover Point</td>
<td>157</td>
<td>1.64</td>
<td>2.51</td>
<td>2</td>
<td>24</td>
<td>6</td>
<td>0.19</td>
<td>3.19</td>
</tr>
<tr>
<td>Macaulay Point</td>
<td>100</td>
<td>1.50</td>
<td>1.80</td>
<td>1</td>
<td>17</td>
<td>9</td>
<td>0.15</td>
<td>5.11</td>
</tr>
<tr>
<td>Sum of 5 outfalls</td>
<td>936</td>
<td>23.4</td>
<td>19.7</td>
<td>24</td>
<td>351</td>
<td>281</td>
<td>3.6</td>
<td>48.6</td>
</tr>
<tr>
<td>Total wastewater</td>
<td>1030</td>
<td>25.8</td>
<td>21.7</td>
<td>26</td>
<td>386</td>
<td>309</td>
<td>4.0</td>
<td>53.4</td>
</tr>
<tr>
<td>Total sediment sink</td>
<td>3.63 x 10$^5$</td>
<td>3180</td>
<td>866</td>
<td>2100</td>
<td>8.79 x 10$^3$</td>
<td>6.23 x 10$^3$</td>
<td>4.0</td>
<td>90</td>
</tr>
<tr>
<td>% of sink from wastewater</td>
<td>0.3%</td>
<td>0.8%</td>
<td>2.5%</td>
<td>1.2%</td>
<td>4.4%</td>
<td>5.0%</td>
<td>10%</td>
<td>60%</td>
</tr>
</tbody>
</table>

Fig. 8. (a) Total PCB and (b) Total PBDE sediment profiles in Core 3, collected just north of the Iona Island outfall.

Table 2
Discharge of metals, PCBs and PBDEs from the top 5 wastewater outfalls and maximum bound of contribution of wastewater to regional budgets. Lacking complete regional budgets for these substances, we compared the flux from wastewater to the rate of burial in local sediment, based on 7 sediment cores from the Strait of Georgia. Values marked "<" indicate that the component was sometimes undetectable in the effluent. In these cases the limit of detection was substituted for the value.
flushing and burial of the Iona outfall particulates to produce a measureable but temporally stable footprint and moderate biotic effects (Burd et al., 2012).

Coprostanol, a biomarker for animal and human waste, is a useful current tracer of municipal effluent, because it is integral to sewage and associates strongly with particles. This allows it to outline the spatial extent of the footprint in local sediment. Based on annual surveys, the influence of the Iona Island outfall, for example, is apparent in elevated coprostanol concentrations for 1 km south and 6 km north of the outfall along the 80 m depth contour (Fig. 9). The width of this zone is less well defined, but appears to be <1 km (McPherson et al., 2008). The asymmetrical distribution of the area of elevated concentration of coprostanol reflects the stronger currents associated with flood tides than with ebb tides, which causes generally northward migration of sediment in this area (McLaren and Ren, 1995).

Other tracers indicate a similar extent of outfall influence. PBDEs largely enter the Strait in association with municipal wastewater (Johannessen et al., 2008a), and the distribution of PBDEs in sediment surrounding the Iona Island outfall reflects that association.

Oxygen stress is evident in the surface sediment in the immediate vicinity of the outfalls. The extra consumption of oxygen in bottom water and sediment due to remineralization of the organic carbon has resulted in elevated acid-volatile sulphide within 5 km of the outfall, as well as clear patterns in iron oxide staining of the shells of the bivalve Axinopsida serricata (Burd et al., 2008b) and in profiles of redox-sensitive metals such as Cd.

The biological effects in this area are consistent with oxygen stress and/or sulphide toxicity (Burd et al., 2008a). Both species richness and the number of organisms are low in the maximum deposition zone (1 km S to 3 km N of the outfall; Fig. 9f–g), and the benthos include considerable abundances (>1000 animals m$^{-2}$) of opportunistic species that take advantage of organic enrichment (Capitella capitata complex — Tsutsumi et al., 1990a,b), and of the low oxygen head-down redox boundary feeder, Heteromastus filobranchus (Holte and Guliksen, 1998; Pearson and Rosenberg, 1978; Witt et al., 2004). In addition, low oxygen, high sulphide sensitive taxa (echinoderms and infaunal crustaceans) are notably absent in this zone (Burd et al., 2012).

Regionally, the deposition of organic particulates from the Iona outfall off Vancouver produces a nearfield footprint of oxygen stress (Burd et al., 2012), and a biota which has a low standing stock biomass and high biomass turnover (2.5 times yr$^{-1}$) relative to the surrounding region (1.27 times yr$^{-1}$; Burd et al., 2013, 2014). This is due to loss of larger fauna, proliferation of smaller opportunists and high bacterial production near the outfall (Burd et al., 2013). Conversely, at the Macaulay outfall near Victoria, organic deposition results in a high sediment concentration of organic carbon and greatly elevated sulphides, but no evident oxygen stress within sediments (due to high bottom currents and sandy substrates). Organic biomass appears to be normal relative to background in sediment around the Macaulay outfall (based on annual monitoring data for CRD), although biomass turnover (currently unmeasured) is expected to be high due to the predominance of small, opportunistic polychaetes, infaunal nematodes and high bacterial production.

It is not presently possible to associate the elevated concentrations of PBDEs and other contaminants with specific biological effects on the benthos. Certainly PBDEs are preferentially consumed by benthic infauna near the Iona and Macaulay outfalls as part of a diet particularly rich in outfall particulates (Burd et al., 2014), whereas PCBs tend to be taken up by infauna from sediments more quickly near the outfalls because of the high biomass turnover. In spite of this, tissue contaminant levels of both groups of compounds are not high compared with higher trophic level organisms (Burd et al., 2014), and are not likely to have acute toxic effects on benthos. Elevated organic carbon flux alone can explain the observed biotic effects near outfalls.

### 4. Discussion

The footprint of an outfall depends on what and how much is discharged but also on the properties of the receiving environment. For particle-active contaminants, local sedimentation rates and the tidal and current energy near the outfall strongly affect the surface sediment concentration of each contaminant and its potential for entry into the benthic and pelagic food chains. Where the sedimentation rate is high relative to the rate and depth of sediment mixing by the benthos, particle-active contaminants tend to be largely buried (Fig. 10).

Sediments within the Strait of Georgia have a surface mixed layer (SML), which is produced by benthic animals foraging at the surface and within the sediments. While a contaminant is in the SML, it is subject to degradation by bacteria or other metabolism by benthic animals and re-entry into the food web. It is not sequestered out of reach of the pelagic food web until it has passed below the SML.

The depth of the SML divided by the sedimentation velocity ($t^* = h / v$) provides an estimate of the average time, $t^*$, a substance spends in the SML before being buried in deeper, unmixed sediment (Fig. 10). Near the Iona Island (Vancouver) outfall, for example, the benthos mix the sediments to a depth of about 7 cm, and the sedimentation rate is 1.3 cm yr$^{-1}$. This means that contaminants deposited onto the

![Fig. 9. Transects of (a–e) chemical tracers and (f–g) biological effects along the 80 m depth contour from 10 km south to 8 km north of the Iona Island outfall. The station dots and solid line indicate the three-year average (2011–2013) value for each parameter, while the dotted line represents 2011 to illustrate the degree of variability observed. The outfall location is indicated by the dashed vertical line, while the south arm of the Fraser River discharges ~2–4 km south of the outfall, contributing to the variability in acid-volatile sulphide and biological abundance at that distance.](image-url)
were captured within its sediments (Johannessen et al., 2003). Particles indicated that virtually all of the particles that entered the Strait probably remain within the Strait of Georgia. A regional budget for persistent organic pollutants (POPs) indicated that about 90% of the PBDEs are distributed more widely than the immediate vicinity determined by direct diffusion or by biological uptake (Johannessen et al., 2012b). Even in the case of Iona, however, where there is a high outfall, where bottom currents are faster, stay near that outfall (Dinn et al., 2012a). However, despite relatively high surface concentrations of contaminants near the Macaulay outfall, the benthic animals living in its immediate receiving environment are less contaminated with PBDEs than those near Iona, apparently because of the high concentration of organic carbon in the untreated Macaulay Point effluent (Dinn et al., 2012b). The high energy and low sedimentation rate near Macaulay disperse even the particle-active contaminants more quickly than does Iona’s receiving environment, and the elevated concentrations of contaminants in sediment and biota at this site are confined to within 1 km of the outfall pipe (Dinn et al., 2012a).

Although we have not carried out a detailed assessment of the fate of contaminants discharged with wastewater into Burrard Inlet through the Lions Gate outfall, the high energy and low sedimentation rate at that site make it likely to receive contaminants in a manner that lies between the receiving environments at Macaulay and Iona.

A final consideration applicable to the submarine Fraser delta is the potential for sediments to undergo episodic massive slumping, which then remobilizes the sediment surface and transports down the foreslope via turbidity currents (Hill et al., 2008). This process interrupts burial, removing contaminated sediments from the source region, and initiates a new burial process in deeper water, which therefore lengthens the actual burial time (Burd et al., 2000). Although the process has the potential to occur, we have not detected contaminants transported in this manner in our sediment cores.

The chemical characteristics of each contaminant also help to determine how it will interact with the local environment. A contaminant’s solubility or particle affinity determines which pathway (dissolved or particulate) it will predominantly follow. Its persistence and volatility determine how long it will last in the environment relative to the time scales of burial or export. In addition, the significance of an outfall to the total budget depends in part on the magnitude of other sources of that same contaminant. For example, carbon and nitrogen from the outfalls are swamped by natural sources to the Strait of Georgia, while, with no natural sources for PBDEs, outfalls play a more dominant role for those contaminants.

Fig. 10. A schematic diagram comparing the importance of sediment burial and degradation for removing contaminants from the Strait of Georgia. The shaded zone shows the range of burial half-lives of contaminants in the sediment surface mixed layer. For contaminants with degradation half-lives less than the burial half-life (e.g., labile organic carbon; many pharmaceuticals), degradation is the most important removal process in the SML. Where degradation and burial rates are similar, both processes play a role in the removal. Where degradation is slow or absent, burial becomes the only process of removal. Most of the classical contaminants (pesticides, PCBs, PBDEs, PAHs, metals) fall into the latter category. Estimates of degradation ranges were taken from various literature sources (Doick et al., 2005; Hu et al., 2012; Mrozik and Stefanska, 2014; Nyholm et al., 2010; Paasivirta and Sinkkonen, 2009; Robinson and Hellou, 2009; Shang et al., 1999; Sinkkonen and Paasivirta, 2000; Tokarz et al., 2008; Zhang et al., 2013).
Dissolved contaminants, similarly to dissolved N and C, will travel with local water masses until they are broken down or consumed. Since the water at Iona’s discharge depth has a residence time of 1–2 weeks (Pawlowicz et al., 2007), dissolved components that break down in less than a week will likely be consumed within the water column of the Strait of Georgia, while those that persist for longer than two weeks will likely be exported from the Strait. Many pharmaceuticals and other substances that may be consumed (e.g., caffeine) are soluble, and they or their metabolic products will end up in municipal effluent via human waste (e.g., see Khetan and Collins, 2007). Some pathogens (viruses and bacteria) would likely have a similar fate, circulating through the Strait suspended within a water mass, with a residence time determined partly by the rate of water exchange and partly by their lifespan in salt water. Faecal coliform, for example, becomes non-viable within a few hours to a few days of exposure to salt water (Neger, 2002), while enteroviruses can persist for 2–130 days (Melnick et al., 1980). Some pathogens will be associated with particulates and will, therefore, end up in sediments or in foodwebs initiated by particle feeders.

The footprint of a wastewater outfall changes with time. This can be due to variations in the discharge itself—the total discharge of wastewater, the load of a particular contaminant, the level of treatment or the method of discharge. Even with a constant flux from the outfall, however, the size of the sediment footprint can change with time, particularly for persistent, particle-active contaminants. Other particle-active contaminants will follow the patterns for PCBs or PBDEs: if they have been in the environment for decades and their discharge has stopped or declined significantly, they, like PCBs, will probably be distributed throughout the sediments of the Strait, with surface sediment concentrations determined largely by local rates of sedimentation and mixing. More recently introduced particle-active contaminants are likely still concentrated near their points of entry, as observed for PBDEs. Some artificial fragrances fall into this category, as they are persistent and adhere to particles in sewage (Guo et al., 2010).

The receiving environment in the Strait of Georgia is far from static (Johannessen and Macdonald, 2009; Riche et al., 2014). Short-term variability due to storms, blooms, and seasonal processes, together with long-term trends due to climate change, including sea-level rise, increasing temperature, ocean acidification, changing hydrology, and declining subsurface oxygen, alter the manner in which the receiving environment interacts with the effluent, and the vulnerability of biota within the environment to the effects of added stressors (Couillard et al., 2008). For example, a constant biochemical oxygen demand from an outfall superimposed on subsurface water exhibiting seasonally variable dissolved oxygen concentration, which is also undergoing a long-term decline (Johannessen et al., 2014) could cause waters near an outfall to cross the threshold into hypoxia before any such conditions were observed farther afield. This might more likely apply to the low energy receiving environment of the Iona outfall, since the greatest biochemical oxygen demand is associated with the dissolved phase of the effluent, which is not mixed away so rapidly near Iona as it is near Victoria’s Macaulay outfall. Sessile benthic organisms, which often live in surface sediments under conditions of oxygen stress, are particularly vulnerable to further oxygen declines due to regional trends in bottom water. Consequently, animals whose distribution around outfalls is controlled by oxygen stress from the added organic loadings likely provide frontal indicators of regional oxygen declines, manifested as an expansion of the affected zone around the outfall. Present trends in bottom water dissolved oxygen, if continued, imply that the area of such zones might increase at some sites.

Monitoring focused on the near-field receiving environment of wastewater outfalls (with background reference stations) can help to assess whether the spatial footprint of an outfall is worsening or expanding spatially. It is useful to accompany nearfield monitoring with an ambient monitoring programme that puts fluxes, effects and variability into a regional context. Data from ambient monitoring permit the construction of geochemical budgets, which can be used to show the contributions of individual stressors and the magnitude of integrated stressors: the contribution of an outfall to a regional budget may be small or large, depending on what else is discharged into that environment. Such budgets can help to determine whether the contribution of the outfall is part of a small or a large overall stress. Budgets can also inform the result that we may expect from treatment. Without budgets a decision made in isolation to treat one stressor out of many might not have the desired effect.

Treatment of municipal wastewater is most powerful where 1) the process substantially breaks down the targeted component into innocuous by-products, and 2) the component released by wastewater is a major contributor to the regional budget. For example, although we could remove organic carbon and nutrient nitrogen from effluent by secondary or higher-level treatment, converting it to CO₂ and N₂, such action would have a relatively small effect on the receiving environment, which is already well-supplied with nutrient. In contrast, the removal of PBDEs, which are far harder to break down into non-toxic components, would reduce loadings of these compounds directly to the Strait of Georgia significantly. Budgets provide a powerful basis to quantify the likely benefit consequent to removal.

Increasing the level of treatment of the primary and screened effluents to secondary, as currently planned, will likely reduce effluent concentrations of all the components considered here. During primary treatment, BOD is reduced by about 30% and TSS by 60%. Secondary treatment should increase both of those reductions to 90% (calculated from Metro Vancouver, 2013). Such an upgrade will, however, have a negligible effect on budgets for the whole Strait for N, organic C, and PCBs, although it will likely decrease the oxygen stress somewhat in the bottom waters and sediment immediately around the outfall. Secondary treatment will decrease the direct input of PBDEs considerably, but it is not designed to break down persistent organic pollutants. Consequently, the effect of increasing the level of treatment will largely be to move PBDEs from marine effluent into sludge that will have to be further managed to prevent its potential re-entry into the aquatic environment. The effect of secondary treatment on pharmaceuticals and personal care products will be mixed. Some of these are easily broken down in treatment, while the more persistent ones, such as some artificial fragrances, will likely move into the sludge along with the PBDEs and other persistent organic pollutants. Source control, such as the manufacturing bans on PCBs and PBDEs, can be more effective than treatment at removing persistent contaminants from the environment.

A comprehensive and specific analysis of the effects of any point-source discharge can be made for any coastal setting following the format presented in this paper. The advantage of this format is that it takes into account both the potentially harmful characteristics of the effluent and the local characteristics of the receiving environment that may amplify or reduce harm. The first step is to construct a regional budget for each component of concern in the discharge. This budget, which demands a quantitative understanding of processes in the coastal system, can then be used to provide an estimate of the maximum benefit that could be realized regionally by reducing or eliminating the source. Furthermore, a budget provides the basis for determining whether or not impacts associated with the effluent discharge could be detected regionally. The second step is to conduct monitoring in the area local to the point source to provide a quantitative estimate of the footprint of detectable biological effects. The third step is to collect regional time series of water and sediment properties to determine whether large-scale trends imposed by natural processes or other anthropogenic pressures are altering the functioning of the coastal system in a way that will alter the risks from the point source and thereby alter the area or severity of its impact. Given this information, management can make an informed decision of whether or not to institute controls, and set the likely benefit of such controls against their costs or against the cost–benefits of other actions.


