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NOTE

When the Tides Don't Turn: Floodgates and Hypoxic Zones in the Lower Fraser River, British Columbia, Canada

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Abstract Floodgates are common flood control structures in coastal river systems, which allow tributary drainage into river main stems and decrease flooding risk of land upstream of diking systems. Floodgates have been shown to impact upstream aquatic habitats and alter organismal community structures in some systems by impounding water and acting as a physical barrier to migratory species; their impacts on water quality have been less well described. This study investigated water quality in tidal creeks with and without floodgates on the lower Fraser River, British Columbia, Canada. There are an estimated 500 floodgates in this region. Water quality measurements were taken upstream and downstream at three floodgate sites and three reference sites across a 10-day period in July/August. The average dissolved oxygen (DO) concentration upstream of floodgates was 2.47 mg/L and fell as low as 0.08 mg/L, which was significantly lower than the comparable region of reference sites (8.41 mg/L) during this sampling period. In contrast, the average DO concentration downstream of floodgates was 7.38 mg/L and in reference sites 8.35 mg/L. All DO concentration measurements upstream of floodgates in July and August fell below the 6-mg/L minimum set by the Canadian Council of Ministers of the Environment. These hypoxic zones extended at least 100 m upstream of floodgates. Thus, floodgates may be facilitating the occurrence of local hypoxic zones in summer months in these locations. Floodgate-induced hypoxia may not only cause local exclusion of sensitive native fishes but may also act as a chemical barrier that decreases connectivity among aquatic systems. Understanding these environmental impacts associated with floodgates can inform floodgate design and post-installation management, which is an increasingly important issue as coastal municipalities across the world deal with aging floodgate infrastructure and sea level rise.

Keywords Agriculture · Coastal · Estuary · Fish · Impoundment · Sea level rise · Water quality

Introduction

Coastal river deltas and their intricate marshes and tidal channels connect freshwater to marine ecosystems and are often extremely productive and biologically diverse (Peterson and Ross 1991). For example, these habitats often serve as critical nursery habitats for commercially and ecologically important fish species (Beck et al. 2001; Kroon and Ansell 2006). However, coastal river deltas are also often heavily altered by urban or agricultural developments (Vitousek et al. 1997; Gedan et al. 2009). For instance, diking systems are installed to provide protection for developed low-lying coastal areas against tidal action and flood events. However, these structures can act as barriers that sever connectivity between habitats (Pollard and Hannan 1994; Raposa and Roman 2003). As a result of this and other alterations, the water quality and native biodiversity of many coastal aquatic ecosystems have been degraded (Lotze et al. 2006).

Floodgates are one ubiquitous anthropogenic alteration of coastal river deltas with potentially large impacts on water quality and biodiversity. Floodgates, or tide gates, are installed in dikes to allow drainage of tributaries into river main stems while preventing water from back-flowing during seasonal and tidal flooding events (Giannico and Souder 2005). The

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floodgates consist of culverts with self-closing flap gates that close when the river main stem water levels are higher than the land protected by the dike. During seasonal flooding events, such as the spring freshet, extended closures of the flap gates often cause the upstream tributary waters to become impounded (Pollard and Hannan 1994). At some floodgates, pump stations are installed to further control upstream water levels by pumping water over the floodgate without risking back-flow from the main stem.

Previous research, primarily from Australia and New Zealand, has found that floodgates can alter upstream habitats, water quality, and biological communities compared to tidal creeks without barriers (e.g., Pressey and Middleton 1982). Habitats upstream of floodgates had reduced fringing vegetation and altered fish community structure (Pressey and Middleton 1982; Pollard and Hannan 1994; Johnston et al. 2005). Fish were observed to pass through floodgates half as frequently as through unblocked streams (Doehring et al. 2011). Accordingly, fish abundance, biomass, and diversity were reduced in streams with floodgates (Kroon and Ansell 2006). Most North American research on floodgate impacts have focused on changes in upstream temperature and salinity in tributaries primarily influenced by tidal action and situated at the mouth of estuaries, close to the ocean (Roman and Burdick 2012). Typically, systems upstream of floodgates at these locations have higher temperatures, lower pH, lower salinity levels (Roman and Burdick 2012; Giannico and Souder 2005), and reduced nekton density and diversity (Raposa and Roman 2003), likely due to reduced connections with the saltier estuarine waters. While low levels of dissolved oxygen (DO) can degrade water quality for oxygen-sensitive fish species (Doudoroff and Shumway 1970; Beitinger 1990), and might be expected to arise from floodgate impoundment of potentially nutrient-rich agricultural runoff (Schindler 1974; Daniel et al. 1998), understanding of the potential impacts of floodgates on DO is relatively limited. Johnston et al. (2005) found that periodic opening of floodgates was associated with increased DO in eastern Australian swamps. Although floodgates could lead to hypoxia that renders water quality unsuitable for oxygen-sensitive fishes or further reduces movements of fishes, there remains little understanding of DO dynamics in tidal creeks with floodgates.

This study examined patterns of water quality in relation to floodgates in tidal creeks. Specifically, we compared the water quality in tributaries with floodgates to reference tributaries that did not have floodgates in the Lower Fraser River in Southwestern British Columbia, Canada. The Fraser River is one of the most productive salmon rivers in the world (*Oncorhynchus* spp) that supports recreational, First Nation, and commercial fisheries. Previous research has observed the use of lower Fraser River tidal creeks as nursery habitats by out-migrating juvenile Chinook salmon (*Oncorhynchus tshawytscha*), chum salmon (*Oncorhynchus keta*), and pink salmon (*Oncorhynchus gorbuscha*) (Levy and Northcote 1982). However, specific information on how these habitats are being altered by the presence of floodgates is lacking. We hypothesized that oxygen levels upstream of floodgates would be lower than oxygen levels downstream and throughout reference sites due to impoundment of nutrient-rich water, potentially reaching hypoxic levels with implications for habitat suitability for fishes.

Methods

Study System

This study focused on tidal creeks in the lower Fraser River watershed (Fig. 1a). At 1325 km in length and carrying over 7000 m^3/s in flow during peak spring melt, the Fraser River is the largest river in British Columbia, and its drainage basin is home to over 2.73 million people (The Fraser Basin Council 2010a). Three reference and three floodgate sites were studied throughout Metro Vancouver in the South Coast Region of the British Columbia, Canada (Fig. 1b). Fenton Slough (49.286308 N, 122.667871 W), Cranberry Slough (49.261282 N, 122.663375 W), and Yorkson Creek (49.1909 N, 122.65542 W) intersect with larger rivers in the Fraser River watershed and contain flood mitigation structures that were installed to prevent flooding events associated with tidal and river fluctuations. The Cranberry Slough pump station was installed in the 1980s and is located 65 m from the confluence with the Alouette River. It was discovered that there are no floodgates installed in the pump station after the sampling was complete; for this site, water cannot move upstream but is transported downstream by the pump station. However, all sites containing flood mitigation structures will be referred to as floodgate sites for simplification.

All floodgate sites appeared to remain closed for the duration of the summer (D. Scott, personal observation), driven by the Fraser River freshet. Accordingly, there was approximately an equal amount of blockage between tributaries and main stems for all floodgate sites. Fenton Slough has a floodgate with top-mounted flap gates and a pump station located 100 m from the confluence with the Pitt River. The floodgate in Yorkson Creek has a “fish-friendly” Archimedes screw pump station and was installed 700 m from the confluence with the Fraser River in 1994. The zero points in reference sites were paired with floodgates installed equidistant from the confluence with a main stem. The reference sites West Creek (49.161898 N, 122.530649 W), McKenny Creek (49.239961 N, 122.6333 W), and Nathan Creek (49.15969 N, 122.48848 W) are located within the same watershed as the floodgate sites. Sites were located approximately 40 km upstream of the mouth of the estuary, about 20 km upstream of

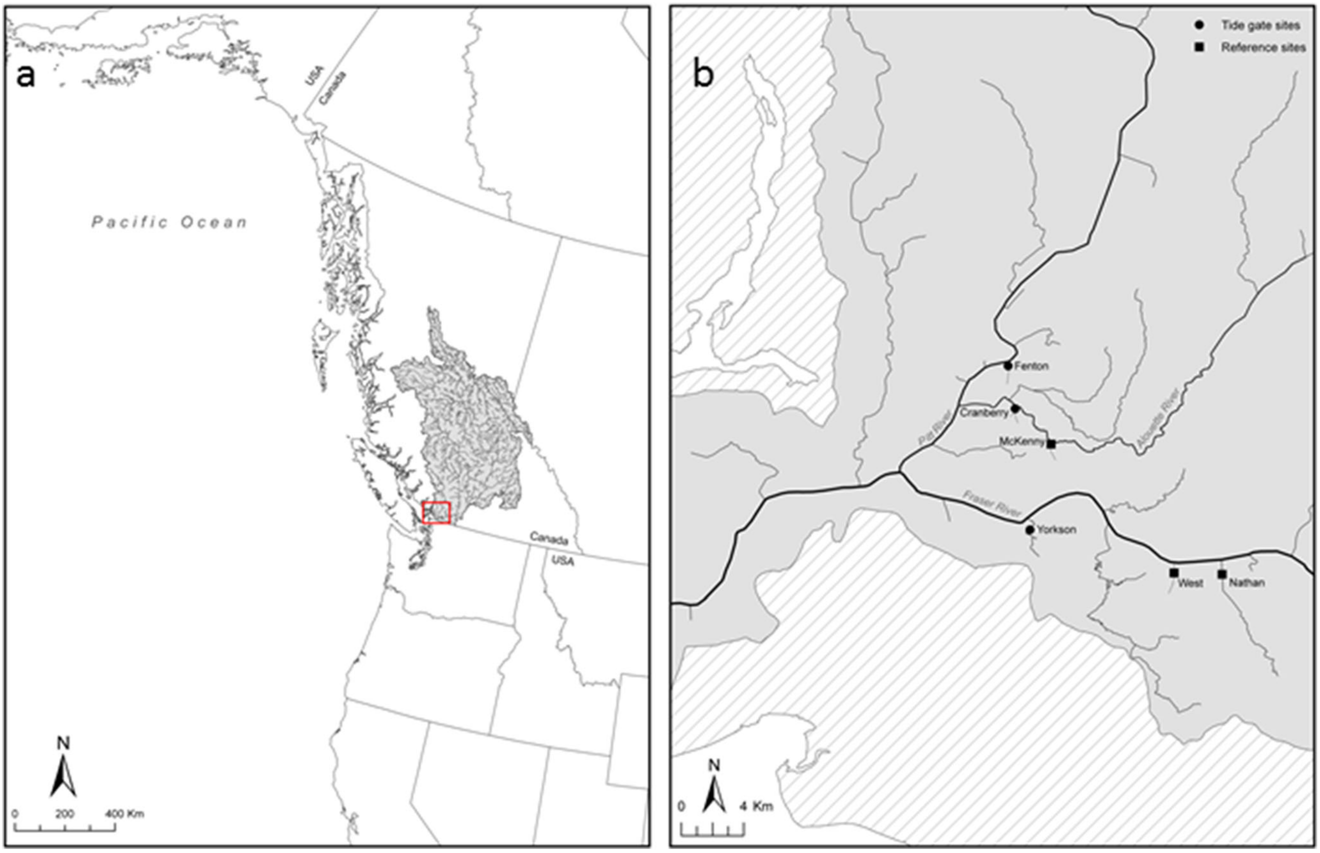

Fig. 1 Location and extent of the entire Fraser River watershed within western North America (**a**) and the location of floodgate and reference sites at tributaries within the lower Fraser River watershed (**b**). Filled circles indicate floodgate sites and filled squares indicate reference sites

the extent of the salt wedge (Ward 1976). The tidally influenced component of the Fraser River extends 30 km upstream of the sites. Sites were selected according to accessibility and similarity in surrounding land use and area subset of a larger collection of sites involved in ongoing studies of floodgate impacts on lower Fraser River aquatic ecosystems.

Sampling Design

Reference and floodgate sites were sampled between July 31 and August 10, 2013. Because oxygen levels may decrease at night, measurements were taken at dusk and dawn at 5-, 10-, 25-, 50-, and 100-m intervals upstream and downstream from the floodgate or reference point. Dissolved oxygen (percent and mg/L), temperature (°C), conductivity (mS/ccm), salinity (parts per thousand), and pH were measured using YSI model 556 MPS (YSI Inc, Yellow Springs). Measurements were taken at 25-cm-depth intervals at each distance from the floodgate or reference point. Additionally, single-point measurements were taken from April to August upstream of the floodgates and at reference sites.

Hourly weather and precipitation data were collected for each site during the sampling period from weather stations closest to the sites. Average air temperature ranged between 21.0 and 22.4 °C during the day and 16.8 and 22.4 °C during the night, and there was no precipitation.

Land Use

We used geographic information systems to analyze the total area and land uses for the watersheds of our study sites. Specifically, we created polygons of our watersheds using a digital elevation model with 25-m resolution, a layer with stream and river locations in British Columbia and the watersheds tools in ArcGIS. We used site knowledge and Google Earth to error-check these watershed designations and modified watershed boundaries as needed. To determine land usage, we obtained a land use dataset created by MetroVancouver in 2006 with 25-m resolution at a 1:20,000 scale which indicates the dominant land use for each parcel. We then grouped watershed usage into the following categories: (1) agriculture, (2) urban which includes residential, commercial, and institutional land use, (3) other human uses which represented industrial, transportation, recreation, and parks, and (4) undeveloped and protected areas. Proportions of land use were then calculated using the spatial statistics tools in ArcGIS. Part of one watershed extended beyond the coverage of the land use layer, and we used the % land use information for this site for which we had data. Visual inspection of Google Earth images revealed similar patterns of land use in the covered and uncovered portions of the watershed, suggesting that this assumption did not introduce major errors. All analyses were conducted using ArcGIS version 10.2.

Statistics

We used a linear mixed effects model approach to examine the relationship between DO and site type (reference or floodgate) for data collected during the 10-day sampling period in July and August. Of the collected co-variables, conductivity (mS/°C/cm), salinity (ppt), pH, and air temperature (°C) were related to water temperature, and thus only water temperature was included in model testing. For this analysis, site type, depth (cm), time of sampling (dawn/dusk), water temperature (°C), and either distance from floodgate or reference point (m), or location of sample (upstream/downstream) were included as fixed effects in the full model, and creek was included as a random effect. We also included an interaction term between site type, and either distance from floodgate or reference point (m), or location of sample (upstream/downstream). A significant distance by site type (reference or floodgate) interaction would support our hypothesis that floodgates negatively impact upstream oxygen levels. We ran all combinations of variables and compared AIC corrected for small sample sizes (AICc) to determine the most parsimonious model (Burnham and Anderson 2002). Strength of effect was determined using frequentist methods to determine which variables accounted for the most residual variation. Tukey's planned contrasts were used to examine interaction effect. Statistical analyses were done using R 2.15.306 (R Development Core Team 2011) with 'nlme' (Pinheiro et al. 2013), 'AICcmodavg' (Mazerolle 2012), and 'multcomp' (Hothorn et al. 2008) packages.

Results

Average DO concentrations were lower in reaches upstream of floodgate sites than in downstream reaches and reference sites (Fig. 2). Upstream floodgate reaches had an average DO concentration of 2.39±0.50 mg/L (95 % CI), extending

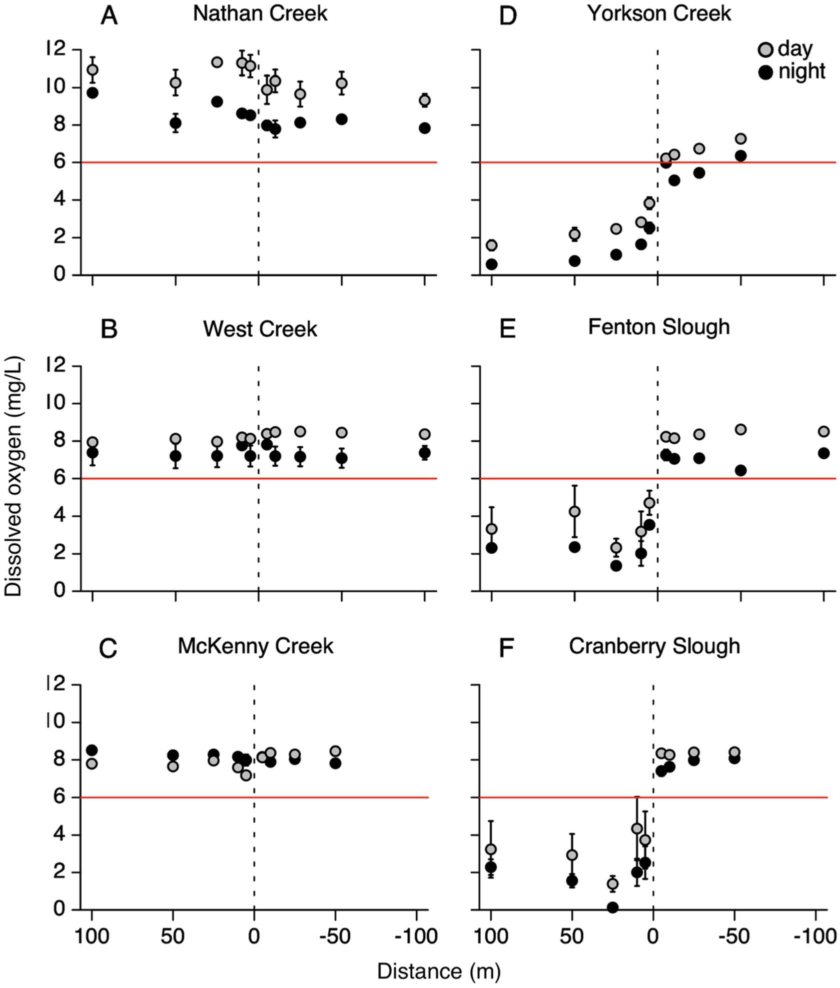

Fig. 2 Mean dissolved oxygen concentrations (± SE) at reference sites (**a**–**c**) and floodgate sites (**d**–**f**). Positive distances are upstream of floodgate or reference position equidistant from confluence. *Horizontal red line* at 6 mg/L indicates minimum recommended criterion for protection of aquatic life (CCME 1999)

throughout the entire 100-m range sampled. Concentrations upstream of some floodgates were as low as 0.08 mg/L. All measurements upstream of floodgates in this study fell well below the Canadian Council of Ministers of the Environment (CCME) minimum criteria of 6 mg/L and the local British Columbia Provincial Criteria for the Protection of Aquatic Life of 5 mg/L. In contrast, in reference systems without floodgates, oxygen levels were consistently higher, 8.37± 0.15 mg/L (95 % CI), around saturation levels 8.55–9.13 mg/L (Truesdale and Gameson 1957). Downstream of flood gates, DO concentrations were slightly lower than DO concentrations in reference sites, but higher than upstream of floodgates. DO concentrations were generally higher at dusk than at dawn for all sites; however, time of day (dusk/dawn) was not included in the top model. Generally, DO concentration decreased with depth in both reference and floodgate sites.

These results were supported by findings from the mixed-effects modeling. Of all candidate models, the best model predicting DO included water temperature, depth, and an interaction between stream type and distance from floodgate (ΔAIC=1). All variables were highly significant, demonstrating that water temperature ($p<0.0001$), depth of sample ($p<0.0001$), type of site ($p<0.0001$), distance from floodgate ($p<0.0001$), and the interaction between type of site and distance from floodgate ($p<0.0001$) strongly influenced DO. Planned comparisons of reference and floodgate sites at each distance from floodgate or reference point showed that DO levels were significantly lower in floodgate sites compared to reference sites at all locations ($p<0.001$), except for 100 m downstream of the floodgate ($p=0.262$). This effect was much stronger upstream of the floodgate compared to downstream of the floodgate.

Land use patterns among sites were broadly similar, being almost exclusively agriculture and other human land usage (Table 1). Specifically, undeveloped and protected land usage was low for both reference sites (range: 0.35 % to 8.04 %) as well as floodgate sites (range: 0 % to 6.65 %). The majority of land usage was agriculture for two out of three sites for both reference locations (range: 24.89 % to 89.59 %) and floodgate sites (range: 24.34 % to 90.84 %), and urban land usage was the most prevalent land use category for one reference and one floodgate site.

Single point measurements showed that DO concentrations changed over the course of the summer. DO concentrations were lowest at upstream floodgate sites as the summer progressed (Fig. 3). Measurements ranged from 0.5-17.5 mg/L in floodgate sites and from 5.6-12.05 mg/L in reference sites.

Trends of other water quality measurements were less pronounced (Table 2). Salinity and conductivity levels were lower in reference sites than in upstream floodgate sites, and were 39 % higher on average in upstream reaches compared to downstream reaches of floodgate sites. In reference sites, pH levels ranged from 6.97 to 7.98 compared to 6.80 to 7.63 in floodgate sites. Water temperature ranged between 19.7 °C and 21.8 °C during the day and 18.3 °C and 20.3 °C during the night. No obvious trend in water temperature was observed between upstream and downstream reaches or between reference and floodgate sites.

Discussion

We discovered striking evidence of hypoxic zones in tidal creeks with floodgates and no evidence of hypoxia in reference creeks without floodgates. Upstream of floodgates, oxygen levels dropped well below the Canadian national water quality criteria minima of 6 mg/L (CCME 1999). These habitats would thus represent "dead zones" to native fish that require higher oxygen concentrations (Eby et al. 2005; Mandic et al. 2009). Statistical models, and the lack of differences in land use across sites, indicate that floodgates are significantly associated with hypoxic zones.

Two interacting processes are likely contributing to the patterns of dissolved oxygen levels found at floodgate sites. First, impoundment of water by the floodgates is likely decreasing water circulation and preventing mixing and periodic renewal of oxygen. The upstream impact of these impoundments is evident from the pronounced upstream-downstream pattern of hypoxia. Second, nutrient-rich water from surrounding agricultural lands are likely enabling this

Table 1 Land use information for the watersheds of our study sites (calculated using MetroVancouver land use dataset created in 2006; watershed area determination and land use analysis completed using ArcGIS)

	Reference sites			Floodgate sites		
	Nathan	West	McKenny	Yorkson	Fenton	Cranberry
Agriculture (%)	89.59	77.84	24.89	34.34	86.8	90.84
Urban (%)	0.21	0.79	51.71	46.34	8.36	0
Other human use (%)	6.87	13.33	23.06	12.68	4.84	9.1
Undeveloped/protected (%)	3.34	8.04	0.35	6.65	0	0.06
Total area (km^2)	10.54	15.29	5.42	17.12	3.33	5.27

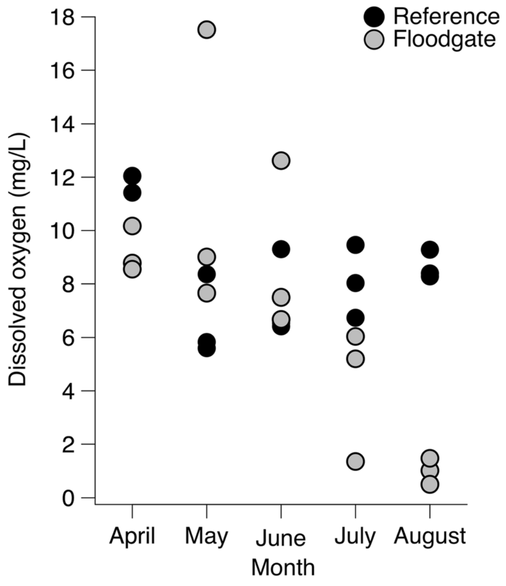

Fig. 3 Monthly single-point dissolved oxygen concentrations at floodgate and reference sites from April to August 2013

eutrophication. Phosphorous is typically the limiting factor for algal productivity in freshwater ecosystems, and is a common ingredient in industrial fertilizers (Schindler 1974; Daniel et al. 1998). The leaching of this phosphorous into tributaries promotes algal growth that can block sunlight and prevent production of oxygen deeper in the water column. Throughout the season, the death of algae creates hypoxic conditions as aerobic bacteria decompose the organic material. Given that both reference and floodgate creeks drain agricultural and other human-modified watersheds (Table 1), our study provides evidence that floodgates are the proximate driver of hypoxia.

The hypoxic water quality we observed likely has consequences for fish communities (Killgore and Hoover 2001). Tolerance of dissolved oxygen concentrations varies among fishes (Davison et al. 1959; Davis 1975), and hypoxic conditions have been shown to impact fish communities by limiting habitat availability, changing prey composition, and creating a "chemical barrier" for migratory fish species (Alabaster 1988; Portnoy 1991; Eby et al. 2005; Pollock et al. 2007). Differences in dissolved oxygen tolerances between species may drive shifts in fish communities and their prey (Dauer 1993; Burleson 2001; Blevins et al. 2013), and the presence of these hypoxic zones upstream of floodgates may create non-physical barriers which filter communities for species traits (Noatch and Suski 2012). In particular, many non-native species have a higher tolerance of hypoxic conditions than native species (Davis 1975). This type of community shift towards non-natives has already been observed in New Zealand lowland fish communities in areas with low dissolved oxygen (Franklin and Hodges 2012). In the lower Fraser River ecosystem, there is relatively high freshwater fish biodiversity, but also emerging populations of non-native species (Nowosad and Taylor 2012). The hypoxic habitats associated with floodgates may not only filter out native fish but also provide habitats that allow populations of non-native species to flourish.

Our study represents a step towards quantifying the impacts of floodgates on hypoxia. We only examined three (out of hundreds) of tidal creeks with floodgates. Given this limited sample size, caution is needed in extrapolating our results to other floodgates; variation in floodgate management may alter water quality. Furthermore, this study sampled intensively day/night for one specific period during the summer. Longer term and less intensive oxygen sampling suggested that this anoxia is focused on the warmest summer period (Fig. 3). In addition, this study found that hypoxic zones extended at least 100 m upstream of the floodgates, but the complete spatial extent of this hypoxia is unknown. Ongoing research is investigating water quality and fish diversity in more sites over longer time periods.

Management Implications

This study shows that small-scale floodgates facilitate hypoxic "dead zones" that extend upstream of these barriers. In developed river deltas such as the Fraser River, which contains an estimated 500 floodgates (The Fraser Basin Council 2010b), these small-scale barriers and their impacts on water quality may cumulatively lead to large-scale losses of native fish habitat and decreased function as nursery habitat for species such as Chinook salmon. Aging infrastructure and sea level rise means many of the current flood infrastructure programs will

Table 2 Mean values of additional water quality measurements. Salinity, conductivity, and pH are averaged values for day and night measurements

	Upstream		Downstream	
	Floodgate	Reference	Floodgate	Reference
Water temperature (°C)				
Day	21.8	19.8	21.4	19.7
Night	−20.3	−18.4	−19.3	−18.3
Salinity (permille)	0.16	0.074	0.041	0.071
Conductivity (mS/°C/cm)	0.334	0.154	0.093	0.147
pH	7.22	7.5	6.967	7.417

require upgrades to maintain the functionality of flood mitigation structures (Walsh and Miskewitz 2013). The occurrence, extent, and duration of coastal hypoxic sites has been increasing steadily over the past few decades and are expected to increase as human populations in coastal ecosystems increase and climate continues to warm (Vaquer-Sunyer and Duarte 2008). While there is increasing scientific and public appreciation of large-scale hypoxic zones, such as those in the Gulf of Mexico, Kittegat Sea, Baltic Sea, Black Sea, and northern Adriatic Seas (Diaz 2001; Dybas 2005; Diaz and Rosenberg 2008), there is limited understanding of the potential cumulative effects of smaller-scale hypoxic zones such as those that we document here and how they alter the function of tidal streams and estuaries as nursery habitat. Increasing understanding of the cumulative effects of flood protection structures on coastal habitat may be increasingly important given the threat of rising sea levels and plans for development of new flood mitigation structures across the globe.

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