Floodgate Operations and Implications for Tidal Creek Fish Communities

by

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Ethics Statement

Abstract

Tidal creeks represent important fish habitats that are often highly modified by human activities. Floodgates can protect developed areas but also restrict connectivity of tidal creek habitats; however, floodgate operations and their effects are not well quantified. I used time-lapse cameras to quantify the timing of gate openings for 22 tributaries of the Lower Fraser River in British Columbia, Canada, and related these operational data to differences in fish communities above and below floodgates. I found that floodgate operations varied substantially, with some floodgates opening daily while others opened less than 20% of the day. Where floodgates opened infrequently, I found lower upstream dissolved oxygen concentrations, greater differences in fish communities, and lower native species richness relative to sites where floodgates opened more. Thus, improvements in floodgate operation will likely benefit fish communities. These data can inform management activities to balance fish and flood protection in the region.

Keywords: Flood mitigation; fish communities; tide gates; aquatic barriers; habitat connectivity; Fraser River

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1 Introduction

Coastal floodplains and estuaries are among the most diverse and productive ecosystems on the planet, but have also served as key locations of human settlement for millennia (Tockner and Stanford 2002). Over 500 million people live in coastal floodplains around the world, though coastal deltas cover only 5% of the global land area (Kuenzer and Renaud 2012). They also provide human communities with fertile soil, fresh water, and access to marine resources and transportation routes. These coastal floodplains also provide important rearing habitat for numerous juvenile fishes in tidal creeks and wetlands (Beck et al. 2001), many of which are commercially important. However, recent rapid population growth and associated human activities have resulted in widespread habitat degradation and severe biodiversity losses in estuaries around the world (Lotze et al. 2006).

One of the key challenges of floodplain management is providing flood protection while maintaining ecosystem connectivity. Cities located in coastal deltas are prone to floods on two fronts: from the ocean and from upriver. This flood risk has led to extensive development of flood control infrastructure to protect property and people from flood damages. Flood control structures typically consist of dikes or levees along river mainstems, with floodgates and pumping stations installed at tributaries to allow drainage out to sea while preventing the river or tides from backing up water levels behind the dikes. Floodgates, also known as tide gates or flood boxes, are culverts with a flap gate on the downstream end that closes when water levels in the river mainstem rise above water levels in the tributary. In the majority of cases, floodgates will open only when there is a sufficient head differential across the gates, with enough water accumulated above the gates to overcome the weight of the gate, the friction in the hinges, and the pressure exerted on the flap gates by downstream water levels (Giannico and Souder 2005, Thomson 2005). Thus, floodgates generally close with the rising tide and open with the falling tide, though they can remain closed for weeks at a time in river systems during seasonal flood events (Thomson 2005). Closed floodgates are associated with reduced fish passage and altered habitats around the world (Giannico and Souder 2004, Kroon and Ansell 2006, Scott et al., In Press), and therefore highlight the challenges of balancing flood protection and floodplain connectivity.

Floodgates can sever connectivity within tidal floodplains, with negative consequences for water quality and biodiversity (Giannico and Souder 2005). These flood control structures may impact fishes in two ways: altering water quality and restricting fish passage (Kroon and Ansell 2006). First, floodgates can alter water quality by restricting tidal exchange (Raposa and Roman 2003, Ritter et al. 2008). Floodgates are associated with hypoxic dead zones due to eutrophication in the stagnant upstream habitats (Portnoy 1991, Gordon et al. 2015). Impounded water in tidal creeks also tends to have higher concentrations of nutrients, fecal coliforms, and heavy metals, as well as high turbidity and siltation rates (Giannico and Souder 2004, Portnoy and Allen 2006). Second, when closed, floodgates physically restrict fish passage, impeding migratory fishes from entering or leaving tidal creeks (Bass 2010, Doehring et al. 2011, Wright et al. 2014). These impacts may together contribute to the observed alterations to fish communities associated with floodgates around the world (Pollard and Hannan 1994, Halls et al. 1998, Scott et al., In Press). In Australia's lower Clarence River, for example, gated creeks had lower richness and abundance of commercially important fish and crustacean species than un-gated tidal creeks (Pollard and Hannan 1994, Kroon and Ansell 2006). Furthermore, non-native fishes, many of which may be more tolerant of poor water quality, have been found in greater numbers above floodgates in New Zealand and on the west coast of North America (Franklin and Hodges 2012, Scott et al., In press).

Modifying floodgate operations to allow for greater connectivity could reduce negative impacts on fish and fish habitats while maintaining flood protection capacity. Fish and crustacean communities may respond to improvements in tidal exchange following removals of dikes and culverts by becoming more similar to communities found in fully connected creeks (Raposa and Roman 2003, Boys and Williams 2012). Increasing tidal exchange across floodgates may reduce negative impacts by improving water quality and allowing estuary-dependent fish to recolonize tidal creeks (Boys et al. 2012). Numerous design and management options have been proposed to alleviate the impacts of floodgates (Charland 1998). These options include removing barriers, replacing them with alternative designs, and altering management routines to allow floodgates to open for longer periods of time (Pollard and Hannan 1994, Giannico and Souder 2004). For example, self-regulating tide gates use floats to remain open for a longer portion of the tidal cycle (Giannico and Souder 2005). Alternatively, manually leaving some floodgates open except during periods of high flood risk could improve flushing and fish passage (Franklin and Hodges 2015). A study in Washington demonstrated a correlation between the density of Chinook salmon and other estuary-dependent species and the ‘connectedness’ across tide gates (an index based on the tide gate’s opening size and duration) (Greene et al. 2012). Furthermore, Wright et al. (2014) found that opening floodgates for longer periods of time may reduce delays in sea trout passage in the United Kingdom’s River Meon. Therefore, modifying floodgate operations may be a promising option for mitigating their negative impacts on fish.

Despite recent interest in alternative flood infrastructure and management options, there are limited data available on floodgate operations. Many studies on floodgate impacts have compared biotic and abiotic characteristics of gated and reference creeks, without quantifying differences in connectivity across the floodgates (Pollard and Hannan 1994, Kroon and Ansell 2006, Scott et al., In Press). Thomson (2005) quantified gate opening for a few floodgates in the Lower Mainland of British Columbia (BC), Canada, and observed that side-mounted gates appeared to open more often than top-mounted gates. A handful of studies from other systems have quantified floodgate operations for a limited number of sites or over short time periods (e.g. (Bass 2010, Greene et al. 2012)). However, sampling at greater spatial and temporal scales is needed to understand how much variation exists in floodgate operations and how this relates to potential differences in fish communities.

The lower Fraser River in southern British Columbia exemplifies the challenges of balancing flood protection and fish habitat in coastal floodplains. The Fraser River is the longest river in BC, draining more than a quarter of the province, and has historically supported some of the world’s largest runs of Pacific salmon (Northcote and Larkin 1989). Furthermore, the Fraser watershed is home to over 2.7 million people, representing more than half the population of BC (The Fraser Basin Council 2010b).

Most of this population resides in the Lower Fraser region, which has over 400 floodgates and 600 kilometers of dikes to protect urban and rural areas from flooding (The Fraser Basin Council 2010a). The development of flood control infrastructure has, however, resulted in reductions in the quantity and quality of fish habitats. Since diking began in the late 1800's, an estimated 70-80% of wetland habitats have been partially or fully isolated from the Lower Fraser River (Birtwell et al. 1988). Tidal creeks and wetlands represent important rearing habitats for juvenile coho and Chinook salmon (*Oncorhynchus kisutch, O. tshawytscha*) (Levy and Northcote 1982, Craig et al. 2014); however, floodgates can diminish water quality and restrict access to these habitats. In a recent study of gated and un-gated Fraser River tributaries, every creek with floodgates had dissolved oxygen concentrations below minimum provincial standards for aquatic life (Gordon et al. 2015). Furthermore, gated creeks can have altered fish communities, with greater abundances of non-native fishes and reduced abundances of native fishes, including two salmon species (Scott et al., In press). These impacts may vary depending on differences in floodgate operations that affect the frequency and duration of gate openings. Although we know that many flood gates may remain closed for weeks to months during seasonal high flows (i.e., the freshet) (Thomson 2005), there are limited data on floodgate operations for the rest of the year. Furthermore, there is limited understanding of how different designs and management strategies may influence native fishes and their habitats. With the imminent challenges of sea level rise and aging infrastructure, most of the region's flood infrastructure will require replacement or upgrades in the near future (Delcan 2012). Thus, improving understanding of floodgate operations and their impacts on fishes could inform infrastructure upgrades or mitigation efforts.

I compared the floodgate operations and fish communities of tidal creeks in the Lower Fraser region to answer two questions: (1) How do floodgates differ in their operation (i.e. the amount of time gates are open)? (2) How do floodgate operations influence fish communities in gated tributaries? To assess floodgate operation, I used time-lapse photography from July 2014 to July 2015 to quantify when gates were open or closed. I also sampled fish communities above and below the floodgates to determine how the relative differences in upstream fish communities varied with gate operations. Upstream fish communities were compared to those found in sections of the tributary situated downstream of the floodgates, where habitats are connected to the river mainstem. Given that there are a variety of floodgate designs and management regimes, I hypothesized that floodgate openness would vary widely, with some gates remaining closed most of the time and other gates opening daily with the changing tides. I also hypothesized that where gates are open for longer periods of time on average, fish communities found upstream of the floodgates would be more similar to those found downstream of the floodgates. Collectively, these data can be used to identify opportunities to move towards fish-friendly flood protection.

2 Methods

2.1 Site Selection

For this study, I sampled 22 tributaries in the Lower Fraser region, including tributaries that flow directly into the Fraser River as well as those that flow into the Pitt, Coquitlam, and Harrison Rivers. Of these, 18 sites had floodgates of various designs and configurations and four had no floodgates (Figure 1, Table 1). These non-floodgate sites were chosen to represent fully connected habitats. Candidate sites were selected after reviewing the Lower Fraser Strategic Streams Review (DFO 1999) and Lower Fraser River floodplain maps (BC MFLNRO 2011). Site selection criteria included accessibility for sampling, availability of pre-existing data on floodgate opening or a suitable place to secure a time-lapse camera, and a sufficient channel width and length to conduct two seine hauls in the tributary on either side of the floodgates.

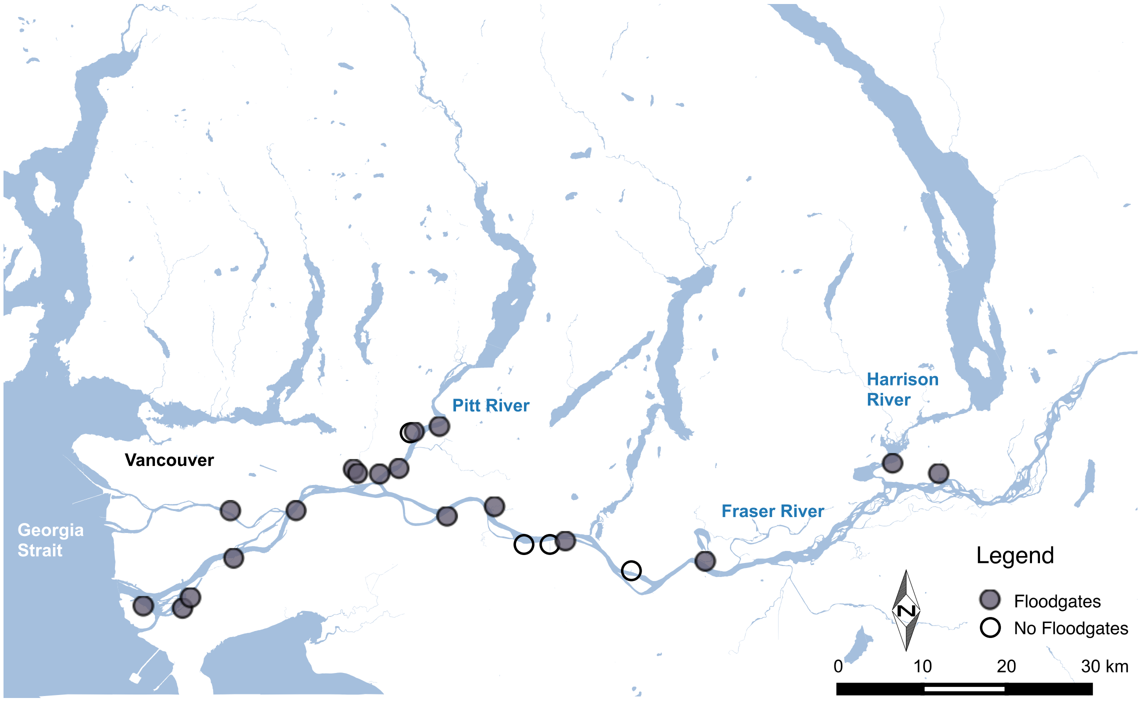

Figure 1 **Map of sampling sites**
This map shows the locations of sampling sites within the Lower Fraser region of British Columbia, Canada. Filled circles indicate sites with floodgates and open circles sites without floodgates.

2.2 Quantifying Floodgate Operations

There is a limited amount of data on floodgate operations in the Lower Fraser, with most published data limited to a few sites and short time frames (Thomson 2005). Here I addressed this data gap on floodgate opening and closing by compiling existing data from municipalities and by using time-lapse photography to capture floodgate position at one-hour intervals. Only two sites had available pre-existing data – Spencer Creek and Mountain Slough. At Spencer Creek, a computer controls the floodgate and sends data on the gate position and water levels to the Engineering Department of Maple Ridge. At Mountain Slough, the District of Kent manually closes floodgates when the downstream water level rises above 11 meters. As such, staff at the District provided the dates of opening and closing during the study period.

Time-lapse cameras were used to quantify operations at the remaining 16 floodgate sites. I installed Brinno TLC200 time-lapse cameras to photograph the floodgates every daylight hour from July 2014 to January 2015, and then again from April – July 2015. Cameras were removed from January to April 2015 to avoid losing cameras due to vandalism and water damage during particularly high tides or winter storms, when large volumes of water are pumped over the dikes. Once every 4-6 weeks, I visited the sites to check the cameras, change batteries, and download the photos. Images were then reviewed to determine whether gates were open or closed every daylight hour at each site. Cameras were mounted inside of a PVC pipe housing and locked to railings, grates, or fences around the floodgates (Appendix Figures A1-A3). Despite attempts to protect cameras within this housing, some data are missing for some sites and time periods due to theft, water damage, and the camera shifting positions.

The collected time-lapse videos were reviewed frame-by-frame to assess gate openness. The gates were described as open or closed based on a minimum threshold of openness set when water was able to visibly flow between the edge of the gate and any adjacent structures such as walls or other gates (typically a ~5-10 degree opening angle). In Oregon, juvenile coho salmon have been observed passing through a top-hinged floodgate while it was open to angles of 7-16 degrees (Bass 2010). Although larger fish may be unable to move through floodgates that are only open 5-10 degrees, the majority of fish captured in this study were under 40 mm fork length, and a wider minimum opening may exclude times when these fish can pass through the floodgates.

Many flood boxes have multiple gates (Table 1), but due to flood box configurations and limited camera mounting positions, I was not able to photograph all gates at all sites. Where possible, I photographed all of the floodgates at a site and classified the flood box as open when at least one floodgate opened. If it was not possible to fit all of the floodgates in the frame, I randomly selected one or one pair of floodgates and mounted the camera to photograph the representative gate or pair of gates (Table 1). High tides or river levels frequently submerge floodgates completely, obscuring them from the view of the cameras. When floodgates were completely submerged, I assumed the pressure from the high water level downstream of the gates was keeping the gates closed. In order to open, floodgates must have sufficient head differential (i.e., pressure due to differences in water level), with enough water accumulated above the gates to overcome friction in the hinges and the pressure of water downstream of the floodgates holding them closed (Giannico and Souder 2005, Thomson 2005). In the time-lapse footage, floodgates typically closed before the water fully submerged them and were also closed when the tide receded several hours later (personal observation). Furthermore, most floodgates are accompanied by pumping stations that remove excess water from upstream when the downstream water level is high (Thomson 2005), thereby reducing the hydraulic head and the likelihood that floodgates would open when underwater. Accordingly, I am confident that this approach provides reliable information on patterns of floodgate operation.

To quantify floodgate operations, I calculated the proportion of the recording time (i.e., daytime hours) that the floodgates opened for each date and site, and then took the mean value across the entire video recording period (July 2014 – July 2015). I calculated the proportion of the day that gates were open instead of counting the number of hours. This was to account for the cameras' inability to record images at night and the rapidly changing day lengths in the autumn months at this temperate latitude. I also calculated the 'mean proportion of the day gates opened' over subset time periods and based on a stricter gate openness threshold (~30 degrees opening angle), but found that all openness metrics were highly correlated ($r^2>0.85$), and did not include these other metrics in further analyses.

2.3 Fish Sampling

I sampled fish at all sites to understand how floodgate operations influenced fish communities. Each site was sampled once between July 30th and August 29th of 2014. Previous studies in the area have identified late summer as a period when the impacts of flood boxes on fish and water quality are most severe (Gordon et al. 2015, Scott et al., In Press).

At each site, I sampled fish communities with four seine hauls using a 15.24 m by 2.44 m net with a 3.175 mm mesh size. At sites with floodgates, I performed two seine hauls on each side of the floodgates (upstream and downstream). To conduct these seine hauls, one crew member held one end of the net on the bank near the water's edge while another member waded with the other end toward the center of the channel and then back to shore, where crewmembers quickly pulled up the excess net onto the bank while forming a purse to hold the captured fish. Some sites were too deep to safely wade with the seine net. At these locations, I rowed an inflatable raft to pull one edge of the seine net while the other end was held at the waters' edge. Captured fish were given a unique fish ID number, identified to species, measured to fork length, and weighed before being released back to the location of capture.

Exact locations of seine hauls were chosen based on practical and biological reasons. At the four sites without floodgates, seines were conducted approximately 30-50 m apart and on either side of a place that might have had a floodgate. For example, dikes can often occur under railroads or roads, but at the sites without floodgates, bridges were installed over an interruption in the dike rather than floodgates. Exact seine locations were selected based on the ability to pull the seine net up on the bank (influenced by slope of bank), safe access to the shoreline, and the need to be a safe distance from pump intakes and outfalls. As much as possible, I selected seine locations to represent one or two habitat types and attempted to find similar habitats upstream and downstream where they existed. At some sites, seine locations were limited by short channel length, woody debris snagging the net, and water depth.

In addition to fish data, I recorded water quality data, channel width and depth, and weather conditions at each site. Using a YSI device (Model 556 MPS, YSI Incorporated 2009), I measured dissolved oxygen, salinity, conductivity, and temperature at a distance of 15 m from the flood box on its upstream and downstream sides. The YSI probe was placed near the middle of the channel at a depth of approximately 0.5 m. Channel wetted and bankful widths were recorded at each seine haul location. Depth was measured in the center of the channel near the seine haul location. These dimensional measurements were taken just after sampling fish, as water levels can quickly change in these tidal creeks.

2.4 Geographic Site Information: Watershed Area, Distance Upriver & Land Use

This analysis included three geographic variables that may affect fish abundance and diversity: distance up the Fraser river from the ocean to the floodgate, watershed area upstream of the floodgates, and land use within each site’s watershed. Distance upriver was estimated using the Path and Measurement tools within Google Earth to draw and measure a path along the river to the mouth of the river (version 7.1.5.1557, Google, Inc., 2015). Because the Fraser River splits into north, middle, and south arms in the delta, I took the measurement via the arm that produced the shortest path from the ocean to the floodgates. Watershed areas were estimated in ArcGIS version 10.2 (ESRI, 2014) after drawing watershed polygons with the Hydrology tools. In several cases the watershed’s topography was too flat for the Hydrology tools to correctly draw the watershed boundaries. In these cases, I drew watershed boundaries manually while referencing aerial photos from Google Earth. I summed the land use areas within each watershed into four categories: Agricultural, Urban, Undeveloped, and Other Human Uses (e.g. industrial, transportation, resource extraction, and utilities). The developed percentage of the watershed was obtained by summing the percent areas of all agricultural, urban, and other human land uses (Table 1). Metro Vancouver, the District of Kent, the Fraser Valley Regional District, and the District of Mission provided land use data for watersheds within their respective jurisdictions.

Table 1 **Information about study sites, including land uses in the watershed.**

Site Name	Municipal-ity	Coordinates	Floodgate Description	Camera Set-Up	Dist. from the Ocean (km)	Water-shed Area (km²)	Land Use (% of Watershed Area)			
							Agr. & Rural	Urban	Undevel. Areas, Parks & Protected Areas	Other Human Use (e.g. Roads, Industry)
De Boville Slough	Coquitlam/ Port Coquitlam	49° 16.850'N 122° 42.938'W	N/A	N/A	43.6	8.64	16.69%	20.01%	49.35%	13.95%
Nathan Creek	Langley/ Abbotsford	49° 9.726'N 122° 29.310'W	N/A	N/A	59.1	35.19	94.46%**	0.23%	2.56%	2.66%
Silverdale Creek	Mission	49° 8.044'N 122° 21.370'W	N/A	N/A	69.8	21.87	26.02%	26.35%	43.07%	4.56%
West Creek	Langley	49° 9.724'N 122° 31.837'W	N/A	N/A	56.2	15.32	70.65%	0.15%	9.73%	19.48%
80th Avenue Slough	Delta	49° 8.788'N 123° 0.116'W	4 Side-mounted gates	Camera focused on 1 pair of gates	16.6	5.17*	21.15%	0.00%	0.00%	27.53%
Chillukthan Slough	Delta	49° 5.570'N 123° 5.106'W	6 side-mounted gates	Camera focused on 5 of 6 gates	8.4	13.66*	70.94%	15.83%	3.45%	9.79%
Crescent Slough	Delta	49° 6.268'N 123° 4.330'W	4 side-mounted gates	Camera focused on 1 pair of gates	11.7	18.94*	41.05%	7.58%	28.55%	22.83%

Site Name	Municipality	Coordinates	Floodgate Description	Camera Set-Up	Dist. from the Ocean (km)	Watershed Area (km^2)	Land Use (% of Watershed Area)			
							Agr. & Rural	Urban	Undevel. Areas, Parks & Protected Areas	Other Human Use (e.g. Roads, Industry)
Duncan-Bateson	District of Kent	49° 14.838'N 121° 55.898'W	1 side-mounted gate	Camera focused on 1 gate	111.6	5.73	29.31%	17.97%	0.71%	52.01%
Fenton Slough	Pitt Meadows	49° 17.197'N 122° 40.073'W	1 side-mounted gate	Camera focused on 1 gate	46.2	3.34	90.78%	0.00%	1.01%	8.21%
Harbour Creek	Port Coquitlam	49° 14.153'N 122° 45.883'W	2 side-mounted gates	Camera focused on both gates	36.6	3.98	0.00%	27.47%	10.07%	62.47%
Hatzic Slough	Mission	49° 8.577'N 122° 14.152'W	4 top-mounted gates	Camera focused on all gates	79.8	83.83	83.80%	3.48%	8.37%	4.35%
Katzie Slough	Pitt Meadows	49° 14.500'N 122° 44.001'W	2 side-mounted gates	Camera focused on 1 gate	38.8	34.93*	54.65%	13.96%	13.18%	18,21%
Manson Canal	Surrey	49° 11.828'N 122° 54.039'W	2 side-mounted gates	Camera focused on both gates	26.3	8.46	0.00%	38.77%	16.99%	44.25%
McLean Creek	Coquitlam	49° 16.848'N 122° 42.502'W	4 top-mounted gates	Camera focused on 3 gates	43.8	4.05	55.26%	0.00%	43.09%	1.65%
Mountain Slough	District of Kent	49° 14.193'N 121° 51.402'W	3 manual sluice gates	N/A	113.4	29.07	45.29%	3.90%	0.03%	50.78%

Site Name	Municipal-ity	Coordinates	Floodgate Description	Camera Set-Up	Dist. from the Ocean (km)	Water-shed Area (km^2)	Land Use (% of Watershed Area)			
							Agr. & Rural	Urban	Undevel. Areas, Parks & Protected Areas	Other Human Use (e.g. Roads, Industry)
Mundy Creek	Coquitlam	49° 14.448'N 122° 48.446'W	1 side-mounted gate	Camera focused on 1 gate	35.4	3.84	0.00%	36.44%	49.14%	14.42%
Nathan Slough	Langley/ Abbotsford	49° 9.874'N 122° 27.786'W	2 side-mounted gates	Camera focused on both gates	61.7	15.55	94.37%**	0.10%	4.00%	1.53%
Spencer Creek	Maple Ridge	49° 12.074'N 122° 34.704'W	1 automated sluice gate	N/A	51.8	2.58	28.79%	23.22%	31.75%	17.24%
Sussex Creek	Burnaby	49° 11.819'N 123° 0.431'W	1 side-mounted gate, 2 top-mounted gates	Camera focused on all gates, but only evaluated side-mounted gate	16.2	3.21	0.00%	41.57%	29.70%	28.74%
Tamboline Slough	Delta	49° 5.731'N 123° 8.927'W	2 top-mounted flap/sluice hybrid gates	Camera focused on 1 gate	5.2	1.70*	97.34%	0.15%	0.83%	1.68%
Wilson's Farm Tide Gate	Port Coquitlam	49° 14.198'N 122° 48.040'W	2 side-mounted gates	Camera focused on the self-regulating gate	34.6	1.97	0.00%	22.99%	68.34%	8.67%

Site Name	Municipal-ity	Coordinates	Floodgate Description	Camera Set-Up	Dist. from the Ocean (km)	Water-shed Area (km^2)	Land Use (% of Watershed Area)			
							Agr. & Rural	Urban	Undevel. Areas, Parks & Protected Areas	Other Human Use (e.g. Roads, Industry)
Yorkson Creek	Langley	49° 11.464'N 122° 39.331'W	2 side-mounted gates	Camera focused on 1 gate	45.4	17.13	39.82%	26.74%	16.93%	16.51%

* These areas are very flat; consequently the ArcGIS watershed tools were unable to predict the watershed boundaries. These estimates are based on hand-drawn polygon estimating the watershed outline using comparisons between layers in ArcGIS and Google Earth.

** Nathan Slough and Nathan Creek watersheds cross the boundaries between Langley and Abbotsford and consequently have different available data. Land Uses in the Abbotsford portions of these watersheds were estimated based on lands lying within the Agricultural Land Reserve and areas covered by roads, water, and built environment land covers (Metro Van Land Cover Classification 2010). The Langley portions of the watershed were estimated based on the Metro Vancouver Land Use 2011 database, which does not cover the City of Abbotsford.

2.5 Statistical Analysis

I conducted two main analyses to a) examine patterns in gate openings and explore what site characteristics could affect gate openings and b) to understand how differences in fish communities on either side of the dikes relate to floodgate openness. These analyses also included several site characteristics as variables (Table 1).

I constructed generalized linear mixed-effects models (GLMM) to determine whether site characteristics affected the amount of time gates opened. Given that the response data were repeated observations of whether the gates were open or closed, I used the binomial family with a logit-link for this model set. Gate opening data were summarized by date, with the model input formatted as a two-column integer matrix containing the proportions of the day that floodgates were open and closed (Hastie and Pregibon 1992). Initial model comparisons based on Akaike's Information Criterion (AIC) indicated strong support for including the daily mean discharge of the Fraser River (Water Survey of Canada Station # 08MH024) as a covariate in all candidate models. Specifically, including daily mean discharge reduced the model's AIC score by 30.2 ΔAIC units. In addition, all models incorporated a random intercept by site (ΔAIC = 213.7 with a lower AIC score for the model with the random effect) and an AR1 temporal autocorrelation term (ΔAIC = 9626.6 with a lower AIC score for the model with the autocorrelation term) based on results of initial model comparisons between models with and without each of these terms. These three factors were then included in all models in a different set of candidate models, which were compared using AIC model selection to determine which fixed effects were best supported by the data. Candidate models included all subsets of the following fixed effects: distance from the ocean, watershed area, pumps (present/absent), gate type (side-hinged, top-hinged, or manual sliding gate), and the proportion of the watershed with developed land uses. The continuous variables were standardized by their sample standard deviations and centered to aid in model convergence (Schielzeth 2010). The model set also included a 'null' model with only the autocorrelation term, daily mean Fraser discharge, and the random effect. No interaction terms were considered due to poor coverage of some variables (e.g. pumps present in larger watersheds but not smaller ones) and failure of models to converge.

Models were created using the lme4 package (v. 1.1-9, Bates et al. 2015) in R (v. 3.1.2, R Core Team 2015).

To examine potential relationships among site-level variables, I conducted a Principle Components Analysis using PAST (v. 2.17, Hammer et al. 2012). These variables included floodgate type, pump presence or absence, watershed area, location on the river, and percentage of the watershed with developed land uses.

I calculated differences between the upstream and downstream fish communities using community dissimilarity metrics and log-response-ratios. First, I sought to understand how the entire fish communities differed upstream and downstream of floodgates, and to investigate how these community differences varied with floodgate operations (i.e. are communities more different where floodgates stay closed?). To do this, I constructed a community dissimilarity matrix using Bray-Curtis differences, taking each upstream/downstream section as a separate site. Given that fish samples were dominated heavily by three-spine stickleback (*Gasterosteus aculeatus*), I square-root-transformed species abundances before calculating Bray-Curtis distances, as this metric can be driven by abundances of a dominant species (Legendre and Legendre 2012). Bray-Curtis distances for the upstream and downstream portions of each site were then extracted from the community dissimilarity matrix for further analysis against floodgate operations. Bray-Curtis dissimilarities were computed using the vegan package (v. 2.3-0, Oksanen et al. 2015).

To characterize potential differences between upstream and downstream fish communities, I computed the log-response-ratios of several metrics based on fish samples. These metrics included the richness, biomass and number of fish captured upstream and downstream of floodgates. I computed these metrics for total fish captured and for sub-groups of fishes (e.g., native and non-native fishes) The log-response-ratio (lnRR) is typically used to express the effects of a treatment relative to a control or reference state (Hedges et al. 1999). Here, I treat the downstream fish community as a reference state and the upstream fish community as a treatment, to compute the log-response ratio as:

$$\mathit{ln}\mathrm{RR} = \mathit{ln}(1+ (\mathrm{upstream} - \mathrm{downstream})/\mathrm{downstream})).$$

To test whether the downstream fish communities would be suitable for use as the ‘reference state’, I plotted downstream fish captures, biomass, and richness against floodgate openness and did not find any strong relationships between openness and downstream fish variables, thus I am confident that the log-response ratio is an effective metric for this purpose.

After breaking the data out into groups of species (e.g., native or non-native fishes), several sample units had zero values and resulted in undefined or infinite estimates of the log-response-ratio. These zero-values are potentially important features of the data, so I adjusted them by adding the minimum non-zero value for that variable to every observation before calculating the log-response-ratio. This method of adjustment has been used as a conservative estimate of the log-response-ratio in data where species are not detected in some samples (Viola et al. 2010). I also computed log-response ratios for the richness, biomass, and number captured for the four most commonly sampled taxa: three-spine stickleback (*Gasterosteus aculeatus*), pumpkinseed sunfish (*Lepomis gibbosus*), prickly sculpin (*Cottus asper*), and juvenile minnows (Cyprinidae). I captured many unidentified juvenile cyprinids (most of which were under 40 mm fork length), and therefore pooled them with all minnows for calculations of fish taxonomic richness.

The computed Bray-Curtis distances and log-response-ratios were then used as response variables in a series of linear models to understand relationships between upstream-downstream community differences and floodgate openness. A separate set of candidate models was created for each of the response variables (e.g. species richness, abundance). Each of the candidate models included up to two of the following explanatory variables: mean proportion of the day gates opened, number of floodgates, watershed area, distance upriver, and the percent developed area in the watershed. Top models were selected based on small-sample-size corrected Akaike’s Information Criterion (AICc) values, and parameter estimates were obtained by averaging models within 8 ΔAICc units of the top model (Burnham and Anderson 2002). Before model averaging, I checked that the candidate models met the assumptions of linear modeling by examining residuals and normal Q-Q plots.

I also used linear modelling to explore whether floodgate operations related to water quality measurements. I constructed a series of linear models relating dissolved oxygen concentrations to floodgate operations and site characteristics. All models for dissolved oxygen measurements appeared to meet the assumptions of linear modelling, based on residuals, normal Q-Q plots, and Cook’s distances. These models were compared using AICc model comparison and parameter values and weights were estimated using model averaging. I used the direct measurements and modelled upstream and downstream dissolved oxygen separately, rather than calculating a response-ratio based on these measurements. For all analyses, model selection and averaging were performed with the AICcmodavg (v. 2.0-3, Mazerolle 2015) and MuMIn (v. 1.15.1, Bartoń 2015) packages implemented R (v. 3.1.2, R Core Team 2015).

3 Results

Time-lapse camera footage, combined with pre-existing data from two sites, revealed high levels of variability in operation of floodgates in this region. Many of the floodgates were closed almost all of the time – approximately 40% of all sites had floodgates that opened for less than 10% of the day on average (Figure 2). While most sites opened infrequently or for short periods of time, five of these 18 sites (~30%) opened for more than half of the day on average. Thus, there is a wide range of existing variation in floodgate operations in this region.

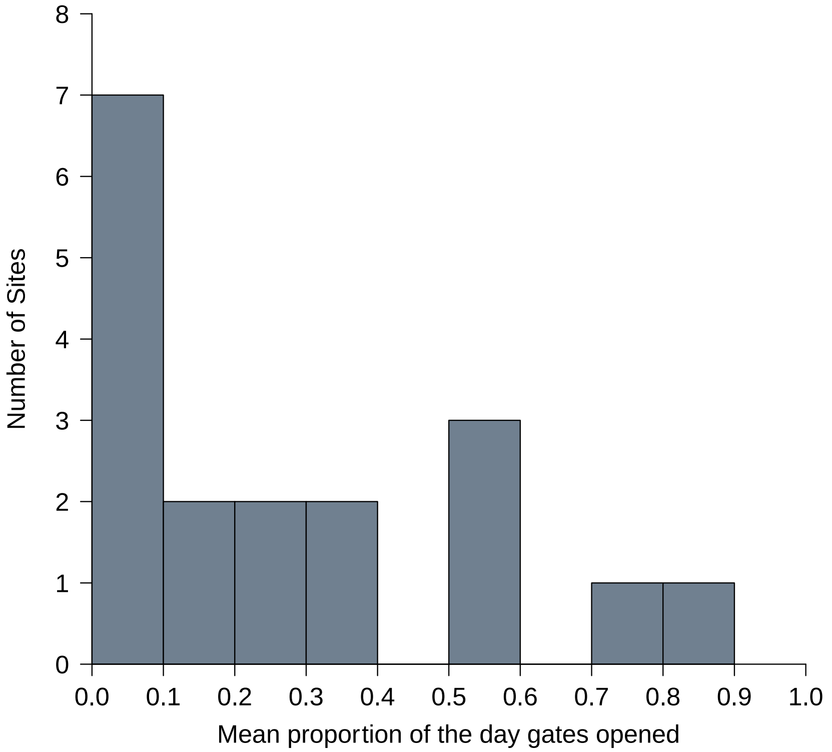

Figure 2 Variation in floodgate operations
Histogram showing the frequency of sites by the annual average proportion of daylight hours that their floodgates opened. Reference sites without floodgates were not included in this figure.

There were seasonal patterns in floodgate openings, where many floodgates remained closed for most of the Fraser River freshet in July 2014 and again from mid-May through June of 2015, but opened and closed more sporadically during the rest of the year (Figure 3, Appendix Figure A4). Floodgate opening patterns also appeared to vary regionally, with sites closer to the ocean possibly showing more of a tidal signature and those further upriver more closely following the freshet patterns (Figure 3b-f).

Fraser River discharge was the only factor that was consistently supported for explaining patterns of floodgate operations, with an inverse relationship between mean daily discharge and floodgate opening time (Table 2, Figure 3), such that gates were closed more during periods of high flow. The top model included distance upriver, Fraser River discharge, and the temporal autocorrelation parameter as fixed effects, but since all models ranked similarly (ΔAIC<8), I report the unconditional model averaged coefficients and parameter weights (Table 2). Mean discharge was the only parameter with confidence intervals not intersecting zero. Site-level factors received much less support than flow for their ability to explain gate openness patterns. Although the distance from the floodgate to the ocean may have some influence on gate openness, it received only 53% of the support based on model averaged fixed effects.

Table 2 Summary of AIC model averaging output for floodgate openness GLMM

Parameter	Parameter Estimate	95% Confidence Interval	Parameter Weight	# Models with Parameter
Intercept (manual gates, no pumps)*	-0.29	-1.02 to 0.45	NA	32
Mean Discharge (m^3/s)	-0.13	-0.17 to -0.08	1.00	32
AR1 Temporal Component	1.09	1.06 to 1.12	1.00	32
Distance Upriver (km)	0.26	-0.07 to 0.59	0.53	16
Pumps (Present)	-0.20	-1.06 to 0.67	0.30	16
Watershed Area (km^2)	0.06	-0.29 to 0.41	0.29	16
% Watershed with Developed Land Use	0.03	-0.39 to 0.45	0.28	16
Gate Type			0.23	16
• Manual sluice gate	-	-		
• Side-hinged	-0.32	-1.38 to 0.73		
• Top-hinged	-0.7397	-1.98 to 0.50		

* The base model was for a site with manual floodgates and no pumps.

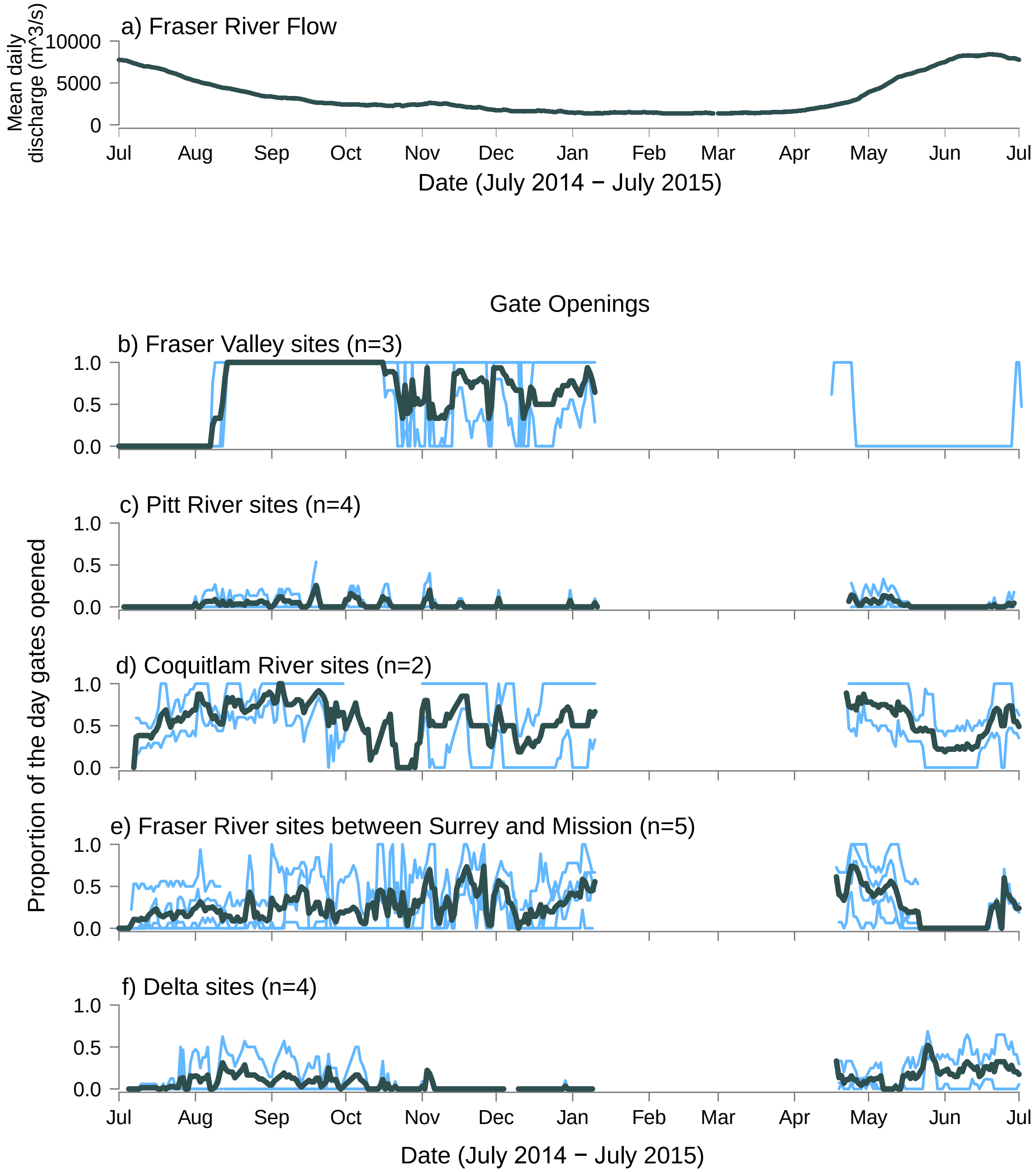

Figure 3 **Time series of Fraser River flow and floodgate operations**

Time series of a) Daily mean discharge in the Fraser River at Mission (Data courtesy of the Water Survey of Canada - Station # 08MH024); b-f) proportion of each day the floodgates opened in different sections of the Lower Fraser. Lighter lines represent individual sites' timeseries, while the dark bolded lines represent the average across sites for that subregion. Site groupings are roughly listed from sites furthest upriver (b) to sites that are closest to the ocean (f). Data were not collected during the blank period to avoid losing cameras due to vandalism and water damage during winter storms that can lead to high water levels in the tributaries.

I explored potential relationships among flood box characteristics, site location, and watershed land use with Principal Components Analysis (PCA). The PCA analyses revealed that pumps seem to be placed at floodgates situated in larger, more developed watersheds (Appendix Figure A5). Differing gate types did not appear to correlate strongly with other site level factors (Appendix Figure A6).

I captured a total of 7,531 fish across all sites between July 30th and August 27th, 2014. Most of the fish captured were likely juveniles of their species, as over 75% of all fish captured had a fork length of less than 40 mm. Over half of the fish captured were three-spine stickleback (*Gasterosteus aculeatus*, 4697 in total), and 1319 were unidentified juvenile cyprinids. Other commonly captured species (with more than 100 individuals) were pumpkinseed (*Lepomis gibbosus*), northern pikeminnow (*Ptychocheilus oregonensis*), prickly sculpin (*Cottus asper*), and peamouth chub (*Mylcheilus caurinus*). I captured few juvenile salmon - 11 chum (*Oncorhynchus keta*) and 17 coho (*O. kisutch*) - in the sampling period. Full details on the fish species counts for each site are given in Appendix Table A1.

There was a negative relationship between floodgate openness and observed fish community differences above and below floodgates, such that fish communities differed more where floodgates opened less (Figure 4). For linear models with Bray-Curtis community dissimilarities as the response variable, models with floodgate openness ranked highly in AICc model selection. Openness received the highest parameter weight (0.69) while site covariates received much less relative support (Table 3). The model averaged openness parameter estimate was the only one with confidence intervals excluding zero. Based on model-averaged results, upstream and downstream fish communities were on average 23% more similar (less dissimilar) in fully connected sites when compared to sites where floodgates never or rarely opened (Table 3).

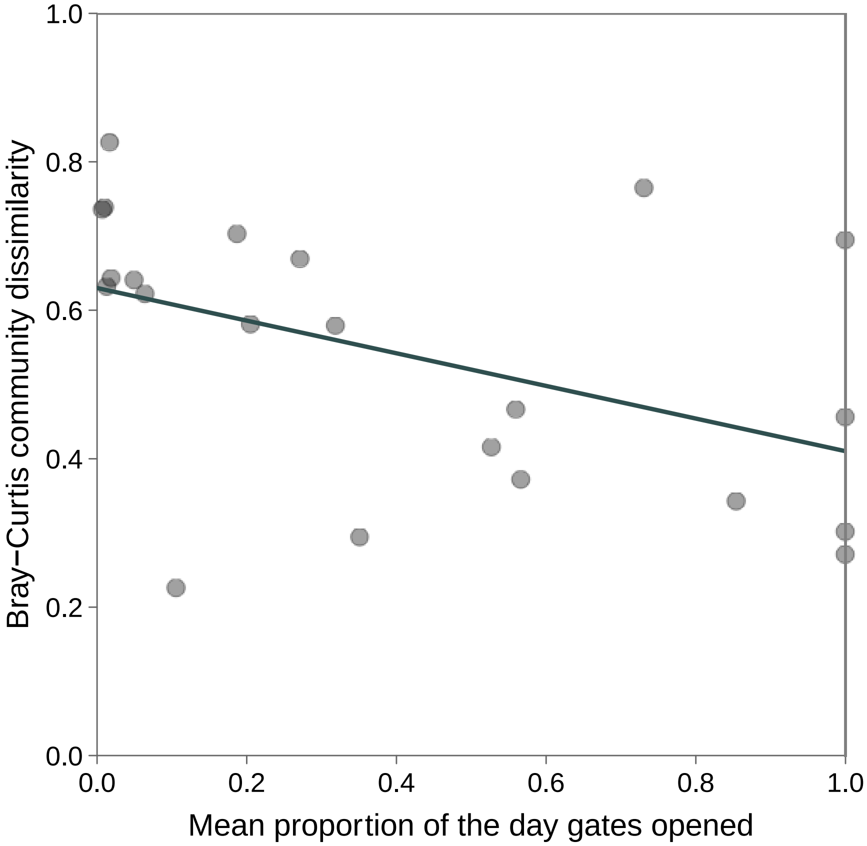

Figure 4 Fish community differences by floodgate operations
Shown is the Bray-Curtis dissimilarity of fish communities upstream vs. downstream of floodgates (or equivalent sampling locations for un-gated sites). Values closer to one indicate more different fish communities while values closer to 0 indicate more similar fish communities. Floodgate operations are represented by the mean proportion of the day gates opened at each site, such that values closer to one are, on average, open for a longer portion of the day. The line presented here represents the single-variable linear model comparing Bray-Curtis dissimilarities with floodgate operations (not the full model) and is meant for visualization purposes.

Floodgates that were more open also had higher relative native species richness (Figure 5a, Table 2). After performing AICc model selection and model averaging on response ratios for native species richness, I found that the data supported an effect of openness over other site-level covariates (Table 2). The model-averaged openness parameter estimate was the only parameter to have confidence intervals not crossing zero. This model indicated that sites with low floodgate openness tended to have fewer native species upstream of the floodgates relative to downstream. Sites where floodgates opened very rarely (intercept = 0, i.e., never) would on average have 32% fewer fish species upstream of the floodgates. On average, I found 3.5 (s.d. = 1.26) native fish species downstream of floodgates, so this would translate to approximately one fewer native species upstream if floodgates never opened. This model, however, shows a relative increase in upstream native species richness as floodgate openness increases, with little to no difference in upstream-downstream native species richness where there are no floodgates. Conversely, AICc model selection and averaging results did not show much support for an effect of floodgate operations on differences in the richness of non-native fishes (parameter weight= 0.17, Figure 5b, Table 3).

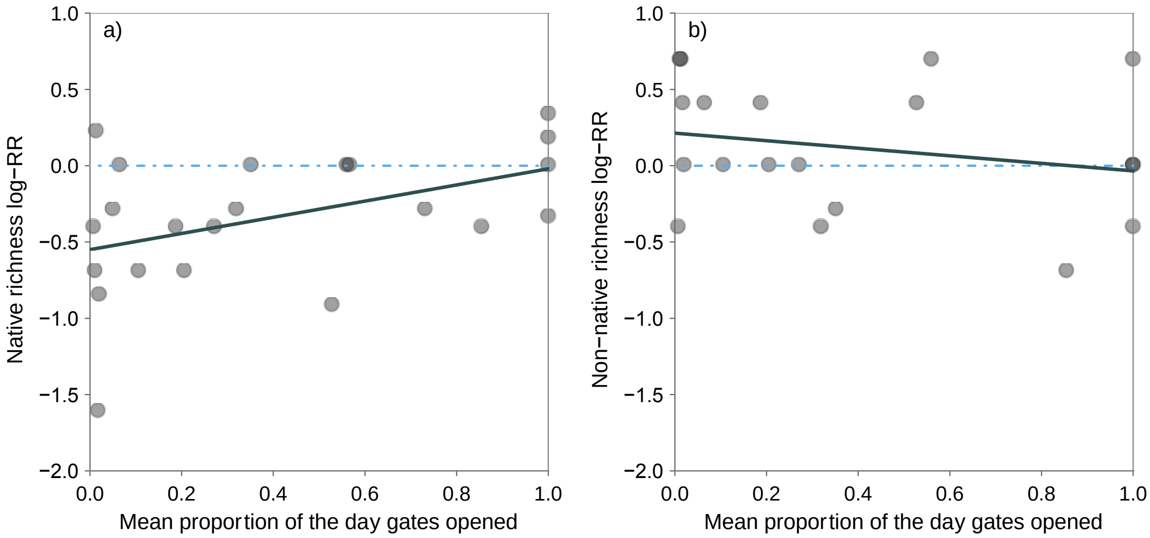

Figure 5 **Log-response-ratios of (a) native and (b) non-native richness and floodgate operations**

When the log-response-ratio is zero, there is no difference in richness above and below floodgates. Negative values of the log-response-ratio correspond with reduced native species richness upstream of the floodgates relative to that found downstream. For example, a log-RR of -0.5 means there would be 39% fewer unique taxa above the floodgates. Positive values indicate higher richness upstream of the floodgates than downstream. The linear relationships presented represents the single-variable linear model comparing (a) native richness and (b) non-native richness log-response-ratios with floodgate operations and are meant for visualization purposes.

Floodgate openness did not appear to be an important factor for explaining upstream-downstream differences of overall fish counts, biomass, or taxonomic richness. For all of these response variables, the intercept-only (null) model was the top model or ranked within two ΔAICc units of the top model, indicating that neither floodgate operations nor other site characteristics were important for explaining the differences in these variables above and below floodgates. Additionally, neither the site-level covariates nor floodgate openness appeared to have any effect on the response ratios of biomass or counts of native or non-native fish.

Table 3 Summary of AICc model averaging output for fish community models

Response Variable	Parameter	Parameter Estimate	95% Confidence Interval	Parameter Weight
Bray-Curtis Community Dissimilarities	Intercept	0.60	0.41 to 0.80	NA
	Mean Proportion Open	-0.23	-0.43 to -0.03	0.69
	Watershed Area (km^2)	0	-0.01 to 0.00	0.27
	Number of floodgates	0.02	-0.05 to 0.08	0.17
	% Watershed with Developed Land Use	0.08	-0.30 to 0.46	0.13
	Distance Upriver (km)	0.00	0.00 to 0.00	0.13
Native Species Richness log-response-ratio	Intercept	-0.39	-0.91 to 0.11	NA
	Mean Proportion Open	0.55	0.05 to 1.05	0.63
	Number of floodgates	-0.09	-0.22 to 0.04	0.27
	Watershed area (km^2)	-0.01	-0.02 to 0.00	0.27
	Distance Upriver (km)	0.00	-0.01 to 0.01	0.13
	% Watershed with Developed Land Use	-0.10	-1.01 to 0.81	0.12
Non-native Species Richness log-response-ratio	Intercept	-0.13	-0.76 to 0.56	NA
	Number of floodgates	0.11	-0.01 to 0.22	0.49
	% Watershed with Developed Land Use	0.58	-0.32 to 1.47	0.25
	Watershed area (km^2)	0.01	0.00 to 0.02	0.23
	Mean Proportion Open	-0.21	-0.83 to 0.41	0.17
	Distance Upriver (km)	0.00	-0.01 to 0.01	0.16
Prickly sculpin catch log-response-ratio	Intercept	-1.40	-3.33 to 0.54	NA
	Mean Proportion Open	1.72	0.17 to 3.27	0.53
	Distance Upriver (km)	0.02	0.00 to 0.04	0.44
	% Watershed with Developed Land Use	-1.80	-4.78 to 1.18	0.23
	Number of floodgates	-0.25	-0.66 to 0.16	0.22
	Watershed area (km^2)	0.00	-0.03 to 0.03	0.11

I did not detect a substantial effect of floodgate openness on response ratios of captures or biomass for the three most common fish groups captured – three-spine stickleback, juvenile cyprinids, and sunfishes. The log-response ratio for prickly sculpin (*Cottus asper*) captures, however, indicated that relatively few sculpins were captured above floodgates that seldom opened compared to areas where they opened for longer periods (Table 3). If floodgates never opened, the model would estimate the upstream number of prickly sculpins at approximately one quarter of that found downstream, but if floodgates opened 80% of the day, on average there would be little to no difference in sculpin numbers above and below floodgates.

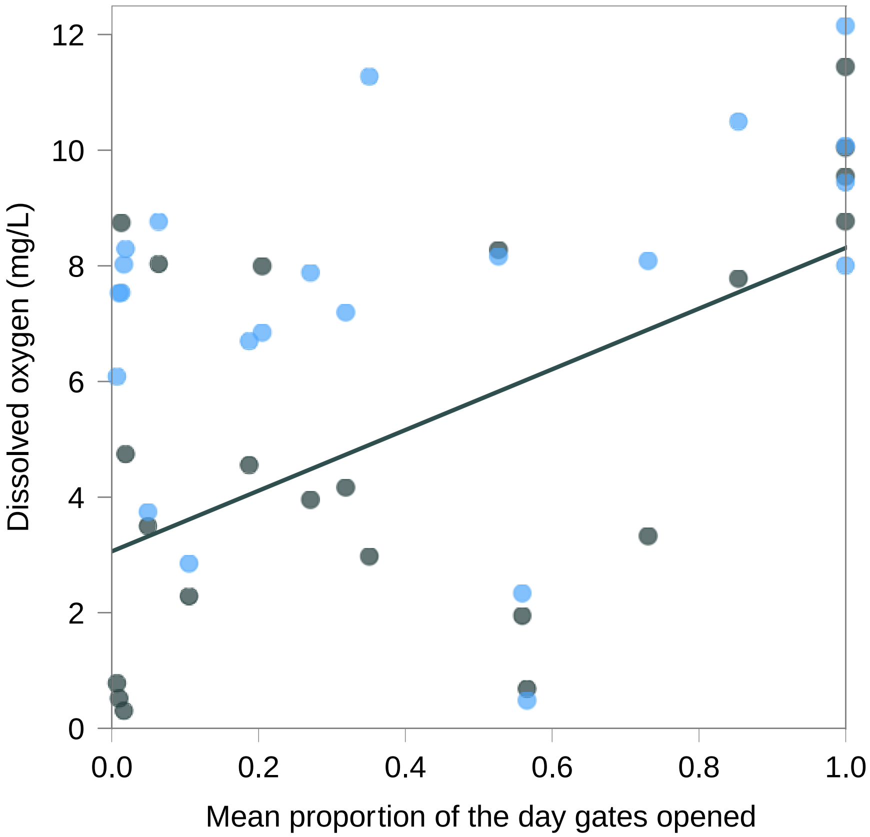

Figure 6 **Dissolved oxygen concentrations above/below floodgates and operations**

Dissolved oxygen concentrations (mg/L) measured ~15 m upstream (grey) and downstream (blue) of the floodgates plotted against the mean proportion of the day floodgates opened. The plotted line is based on a single linear model comparing upstream dissolved oxygen concentration with floodgate operations and is meant for visualization purposes.

Water quality parameters (dissolved oxygen, temperature, conductivity, and salinity) were visualized against floodgate operations and site characteristics (Table A3).

Temperature, conductivity, and salinity above and below floodgates did not appear to vary with floodgate operations. Dissolved oxygen concentrations were on average lower above floodgates than below (Figure 6), with concentrations averaging at 4.11 (s.d. = 2.91) mg/L above floodgates and at 6.77 (s.d. = 2.79) mg/L below floodgates. Linear modelling indicated that upstream dissolved oxygen concentrations were greater on average where floodgates opened more frequently or in sites without floodgates (Figure 6, Table 4). Models including floodgate openness ranked highly based on delta-AIC scores and model averaging estimated a parameter weight of 0.93, indicating a high degree of support for an effect of floodgate operations on upstream dissolved oxygen. Based on the model averaged parameter estimate for floodgate openness (Table 4), dissolved oxygen concentrations were on average 5.9 times lower in reaches above floodgates that never or rarely opened compared to sites where there are no floodgates or where floodgates opened more frequently. Linear models and AICc model averaging did not indicate much support for an effect of floodgate operations on downstream dissolved oxygen concentrations (Table 4).

Table 4 Summary of AICc model averaging output for upstream dissolved oxygen

	Parameter	Parameter Estimate	95% Confidence Interval	Parameter Weight
Upstream Dissolved Oxygen	Intercept	3.89	0.52 to 7.26	NA
	Mean Proportion Open	5.89	2.03 to 9.75	0.93
	Distance Upriver (km)	-0.04	-0.09 to 0.01	0.40
	Watershed Area (km^2)	0.03	-0.04 to 0.11	0.11
	% Watershed with Develop Land Use	-2.28	-8.83 to 4.26	0.10
	Number of floodgates	-0.11	-1.3 to 1.08	0.09
Downstream Dissolved Oxygen	Intercept	7.59	4.32 to 10.86	NA
	Number of floodgates	-0.65	-1.43 to 0.14	0.42
	Mean Proportion Open	2.42	-1.05 to 5.89	0.33
	Watershed area (km^2)	0.02	-0.05 to 0.09	0.17
	Distance Upriver (km)	0.00	-0.05 to 0.05	0.15
	% Watershed with Develop Land Use	-0.53	-6.56 to 5.50	0.14

4 Discussion

These results demonstrate considerable variation in floodgate operations in the Lower Fraser River area of British Columbia, Canada, and that these operations can be related to their impacts on fish biodiversity and water quality. Floodgate operations varied substantially across sites, with most floodgates opening for less than one quarter of the day on average. Differences in fish communities above and below floodgates were more pronounced where floodgates were closed for more time. Furthermore, in sites where floodgates seldom opened, upstream fish communities had relatively fewer native species than at sites where floodgates opened more often. These findings provide evidence that impacts to fish communities can vary with the time that gates are open. Accordingly, there may be opportunities to mitigate impacts to tidal creek fish communities by altering floodgate operations.

4.1 Floodgate Operations

I found substantial variation in the opening patterns of floodgates throughout the region, with several floodgates remaining closed for weeks and others opening daily. While some floodgates opened for more than 50% of the day on average, almost half of the floodgates in this study opened for less than 20% of the day on average (Figure 2). Some of this variation may reflect the local scale at which floodgates are typically managed, with different designs and management routines employed in different locales (Bass 2010). The seasonal patterns of floodgate openings appeared to vary throughout the Lower Fraser region. For example, the three Fraser Valley sites typically opened for longer portions of the day but were closed during the freshet (Figure 3b). The four floodgates on the Pitt River, however, typically opened infrequently and for short periods of time (Figure 3c), while sites along the Coquitlam River opened for longer periods of time on average and appeared to vary most with tidal cycles (Figure 3d). Topography and floodgate elevation may be factors contributing to this spatial variation in operational patterns. For example, many floodgates are situated in areas built upon reclaimed wetlands (rather than on creeks or sloughs) that historically would have been inundated for much of the year, and therefore must remain closed to keep the reclaimed land dry. Much of the land along the Pitt River was formerly wetland (DFO 1999) and is situated at or within several meters of sea level, which could partly explain why Pitt River floodgates tend to open less. The observed spatial variation may also be related to differences in management and operations across jurisdictions. In British Columbia, municipalities or local diking districts typically manage their own flood control works under the oversight of a provincial dike inspector, resulting in a diversity of floodgate designs and management routines (LGL Limited et al. 2009, The Fraser Basin Council 2010). Although some of the variation in opening patterns has previously been noted, there are a limited number of sites with pre-existing data on floodgate operations (Thomson 2005). My study represents a key step towards understanding variation in the operation of floodgates across this economically and ecologically important region.

I found that Fraser River flow (i.e., mean daily discharge at Mission) was the most important factor determining observed floodgate operation (Table 2), and that floodgates were more likely to be closed during periods of high discharge in the mainstem. This pattern is likely due to the influence of the Fraser River freshet, a snowmelt-driven period of high flow in the spring and early summer, with typical daily mean discharge rates around 8000 m^3/s at its peak, compared to 700 m^3/s in low flow months (i.e. winter) (Levy and Northcote 1982). Indeed, many floodgates were closed during the freshet (i.e. for the first half of July 2014 and in 2015 for part of May and June). Historically, up to 20,000 hectares of wetland and slough habitat in the Lower Fraser were flooded annually, most likely during the spring freshet (Birtwell et al. 1988). Understandably, the spring freshet is a major concern for flood managers, such that several floodgates are manually closed for this period. However, this period is also when juvenile salmon redistribute themselves to tidal portions of watersheds to rear before leaving for the ocean (Levy and Northcote 1989, Levings et al. 1995). When floodgates are closed, juvenile salmon cannot enter tributary habitats, and may therefore be deprived of further opportunities to grow before entering the ocean. Furthermore, closed floodgates mean that smolts can only leave gated tributaries via pumps, where they are likely to be injured or killed (Thomson 1999). Thus, the temporal pattern of floodgate closures means that they can have disproportionately large impacts on juvenile salmon

The spring freshet, however, does not appear to influence floodgate operations in the same way throughout the Lower Fraser (Figure 3). The position of a tributary within the Lower Fraser (i.e. distance from the ocean) may have had some importance to floodgate operations (Table 2). Other work has noted that floodgates positioned closer to the ocean are more likely to be controlled by tidal cycles (LGL Limited et al. 2009). Although the Fraser River is tidal to ~115 km from the ocean (Levings et al. 1995), the strength of the tides diminishes at locations further upriver. The data showed a trend towards floodgates opening longer on average at sites further upriver, and this could reflect differences in the influence of the freshet and the tides.

The specifics of floodgate design and management are often discussed when considering how to alleviate impacts on fish passage and water exchange (Charland 1998, Giannico and Souder 2005). For example, lightweight side-mounted gates are typically recommended over cast iron top-mounted gates, as they tend to open wider and more readily with changing water levels (Thomson 2005). Manually operated sluice gates, such as those in Mountain Slough, have also been recommended as they can easily be left open except during periods of high flood risk (Giannico and Souder 2005). This study, however, did not find substantial support for an effect of gate type on floodgate opening times (Table 2). This result may be attributable to an underrepresentation of manual (n=2) and top-mounted gates (n=3), compared to side-mounted gates (n=13) in my study. Furthermore, these categories could not fully capture the variety of management schemes and floodgate designs in the Lower Fraser. For example, the top-mounted floodgates at Hatzic Slough were atypical in both design – being larger and possibly made from a lighter material – and management, as the Dewdney Area Improvement District chained the gates open in the late summer and early autumn.

The presence of pumps did not appear to systematically impact floodgate openings. Pumps are installed at floodgates to move water out of tributaries when the gates are closed for extended periods of time, such as during the freshet, but depending on the settings of the pumps, they can reduce floodgate openings throughout the year by reducing the head differential across the floodgates (Thomson 2005). Pumps were present at a majority of the sites in this study (n=13) and varied in their size, number, and ‘fish-friendliness’. There could be variation in the settings of pumps that could allow for floodgates to open more frequently, such that looking at ‘pumps’ or ‘no pumps’ as a categorical variable may be too coarse a scale to make generalizations about what they mean for gate openings. Additionally, pumps tend to occur at sites with larger, more developed watersheds (Appendix Figure A2).

4.2 Fish Communities

This study shows that the level of impact on fish in tidal creeks can vary with floodgate operations. Fish communities above and below floodgates were most dissimilar where floodgates rarely opened, but were more similar at sites that opened for longer periods of time or that did not have floodgates. While several studies have demonstrated that fish communities in gated creeks differ from those in unrestricted creeks (Kroon and Ansell 2006, Scott et al., In Press), this study shows that the level of these impacts can vary depending on floodgate operations. Past studies have suggested that opening floodgates for longer periods of time should relieve impacts by increasing fish passage and tidal exchange into tributaries (Pollard and Hannan 1994, Raposa and Roman 2003, Ritter et al. 2008). Following tide gate restoration projects in Australia and New Zealand that allowed floodgates to open more often, tidal creeks improved in water quality and upstream fish communities started to shift towards those found in un-gated creeks (Boys et al. 2012, Franklin and Hodges 2015). It is therefore likely that opening floodgates more often would reduce disruptions to tidal creek fish communities.

Where floodgates rarely opened, native species richness was on average 32% lower above the floodgates compared to downstream. This corresponds to an average difference of one fewer native species above closed floodgates. Where tributaries did not have floodgates, however, there were no differences in native richness between upstream and downstream sections, as predicted. Floodgates have been associated with reduced native fish diversity in tidal creeks in the Lower Fraser (Scott et al., In Press), and around the world (Pollard and Hannan 1994, Halls et al. 1998, Kroon and

Ansell 2006). Boys et al. (2012) found that fish and crustacean communities above floodgates became more similar to those at reference sites within two years after creating fish passage windows in the surface of two tide gates. They also found significant changes in community composition after opening tide gates for just a few hours approximately once a week. These results provide evidence that opening floodgates more often could lessen impacts to native fish biodiversity by allowing more tidal exchange and opportunities for fish passage.

This study did not detect any relationship between floodgate operations and the richness, abundance, or biomass of non-native fish species. In contrast, Scott et al. (In press) found that non-native species were more abundant in areas upstream of floodgates than in creeks without floodgates. This previous study examined fish communities from creeks in the region throughout the spring and summer seasons and thus captured data on fish communities over a broader temporal range. Further research could investigate how non-native species are utilizing and moving through gated and un-gated habitats to determine how floodgate operations influence non-native fishes.

Three-spined stickleback, juvenile cyprinids, and prickly sculpin were the three most commonly captured native fishes in this study. Neither sticklebacks nor juvenile cyprinids showed any differences in abundance in relation to floodgate operations. Three-spined sticklebacks are often abundant in tidal creeks in the Pacific Northwest, including those with tide gates (Tonnes 2006, Greene et al. 2012, Scott et al., In Press). Prickly sculpins were more abundant in creeks where floodgates opened more often or where there were no floodgates. Where floodgates never or rarely opened, however, the upstream sculpin abundance was on average one quarter of that found below the floodgates. Sculpins may be particularly vulnerable to altered connectivity in river systems (Favaro and Moore 2015) and prickly sculpin abundances have previously been found to be lower in gated creeks than in non-gated creeks (Scott et al., In Press).

Due to the timing of sampling, this study was not able to quantify the impacts of floodgate operations on juvenile salmon. Overall, I captured 29 juvenile salmon, 11 of which were from un-gated sites (Appendix Table A1). Of the remaining 18 individuals, 14 were coho salmon captured upstream of the floodgates at Mountain Slough – a site where the floodgates are only closed during the freshet. Although tidal creeks and wetlands can be key rearing habitats for juvenile coho and Chinook salmon in the spring and early summer, most individuals are unlikely to remain in these habitats by late summer (Levy and Northcote 1982, Craig et al. 2014, Scott et al., In Press). Previous research in a subset of this study's sites found that creeks with floodgates had 2.5 times fewer salmon than sites without floodgates (Scott et al., In Press). Future studies could directly investigate how floodgate operations and designs impact passage of juvenile salmonids across the seasonal patterns of their life cycle.

Floodgate operations were associated with dissolved oxygen concentrations upstream of floodgates, but not downstream (Fig. 6, Table 4). As previously found in this region (Gordon et al. 2015), I observed lower dissolved oxygen concentrations above floodgates than in reaches below the floodgates (Fig. 6). I build on this result by showing that floodgate openness is linked to the severity of the hypoxia (Table 4). Although the application of these results is limited, as these data include only one pair of observations per site, it is likely that increases in water exchange from changes to floodgate operations would result in water quality improvements (Raposa and Roman 2003). For example, increasing opening times could relieve hypoxic conditions found above floodgates (Gordon et al. 2015) by restoring variable flows and tidal flushing to tributaries (Franklin and Hodges 2015). Additionally, hypoxic conditions above floodgates tend to be most pronounced in the late summer (Scott et al., In Press), so the impact of floodgate operations on water quality may vary seasonally. Further research is needed to understand how different operations might relieve hypoxic conditions above floodgates by, for example, investigating how water quality parameters respond to increased water exchange across floodgates. Additionally, future research could address how floodgate operations relate to dissolved oxygen concentrations and other parameters of water quality (e.g. nutrients) and whether these relationships vary seasonally.

Even where floodgates open regularly, they may still represent barriers to fish passage. The conditions at individual floodgates can restrict fish passage opportunities to a subset of the time gates remain open (Bass 2010). Fully open floodgates may still share many characteristics of culverts that represent barriers to fish passage, such as the potential to produce high water velocities or to become inaccessible to fish if installation heights do not match water levels (Haro et al. 2004, Bass 2010). For example, culverts and floodgates might become ‘perched’ at low tide if the gates are installed higher than low tide depth, thereby preventing fish from travelling upstream through an open gate (Novak and Goodell 2007, Bass 2010). Conversely, if floodgates are installed too low, floodgates may remain underwater for long periods of time and therefore be prevented from opening (Giannico and Souder 2005). Many floodgates are also fitted with grates or trash racks that could block larger fish from passing through the floodgates, especially when debris is pilled against the racks. Furthermore, the angle of floodgate opening could limit the size of fish that can pass through an open floodgate (Bass 2010, Greene et al. 2012). Future studies could investigate how much time fish passage is actually possible based on water velocity, gate opening angles, and the presence of other structural barriers. Such details could aid in crafting floodgate designs that would be better for fish passage.

4.3 Management Implications

Flood managers are faced with a combination of concerns regarding aging infrastructure, environmental protection, and projected sea level rise. As with other types of infrastructure, floodgates may require more maintenance and function less reliably as they age until they ultimately require replacement. In Oregon and Washington, it is believed that a majority of floodgates do not operate ideally due to a variety of maintenance issues ranging from rusty hinges and ill-fitting gates to debris blockages (Novak and Goodell 2007). Problems with aging infrastructure may coincide with the challenges of climate change adaptation. Climate projections predict a 1.2 m rise in sea level by 2100 for British Columbia (Bornhold 2008), and tide gates are predicted to be less effective at preventing flooding under sea level rise projections (Walsh and Miskewitz 2013). These challenges demand new infrastructure and flood management plans to prevent loss of property and livelihoods in Metro Vancouver. Indeed, a recent provincial study estimated that it will cost $9.47 billion to upgrade Metro Vancouver’s existing flood infrastructure to meet this sea level rise (Delcan 2012). Delcan assessed four strategies to adapt to new sea levels – protecting property with flood infrastructure, accommodating occasional flooding, managed retreat from flood-prone areas, and avoiding development in floodplains. In most areas along the Fraser River, the preferred option of local and provincial government representatives was to build more flood protection infrastructure given that allowing flooding will not be feasible in developed areas (Delcan 2012). These forthcoming flood infrastructure upgrades represent an opportunity to improve access to tidal creek habitat for native fishes while protecting people from floods. Recently, there has been increased interest in building fish-friendlier infrastructure in the Lower Fraser region (The Fraser Basin Council 2010). This study reveals opportunities to improve habitat for native fishes by altering floodgate operations.

Many floodgate and pumping station designs have been created to improve fish passage, some of which also allow for water exchange across floodgates (Charland 1998, Giannico and Souder 2005). Where there is sufficient available labour, the simplest option may be simply to chain a subset of floodgates open when there is no elevated flood risk although this poses a risk of human error; this is already employed at a few sites in the Lower Fraser. Another option is installing self-regulating tide gates (SRTs), which are designed to stay open for longer portions of the tidal cycle than traditional tide gates (Greene et al. 2012). Other designs involve installing a ‘pet door’ (i.e., a small orifice in the gate’s face) in a floodgate that allows fish to swim through even when the gates are closed, although this can be clogged with debris and requires regular maintenance (Giannico and Souder 2005). One of the more popular solutions for fish passage in the Lower Fraser is the installation of fish-friendly pumps.

Fish passage has been addressed at several sites, including ones in this study, by installing fish-friendly pumps that are less likely to entrain and kill fish on their way downstream via the pumps (Thomson 1999). The main purpose of these pumps is to allow fish passage from the tributary to the mainstem. This could be important for juvenile salmonids, since the pumps are typically the only method of water exchange during the Fraser River freshet, when high water levels force floodgates closed. While fish-friendly pumps play an important role in allowing juvenile salmon to leave the system during the freshet, they do not allow bi-directional fish passage. Tidal creeks can represent important nursery habitats for rearing and protection from predators, and this role necessitates bi-directional fish movement. For example, Chinook salmon using tidal creek habitat may originate from other systems and need to migrate into the tributary for a time (Levings et al. 1995). Furthermore, fish-friendly pumps will not solve water quality problems that likely arise from limited water exchange across the floodgates. Allowing increased water exchange could allow hypoxic water out of the system and flush the creek with more oxygenated water from below the floodgates. Depending on their settings, pumps may actually reduce floodgate opening times due to a reduced hydraulic head differential (Thomson 2005). A better solution might be to combine these fish-friendly pumps to aid in juvenile salmonid migration during the freshet with floodgate designs or management strategies that allow gates to open longer for the rest of the year.

4.4 Conclusions

Increasing floodgate openness could alleviate impacts on fish communities by increasing tidal exchange and by creating more opportunities for fish passage. This study demonstrates that not all floodgates operate the same, and that impacts on water quality and native fish communities may be less severe if floodgates open for longer periods of time. Tidal creeks represent important habitats for numerous fish species, including commercially important species such as salmon. Coastal floodplains are inhabited by millions of people and are incredibly important to human society, so it is often not feasible to remove floodgates completely. There is an opportunity to use data such as this to inform floodgate operations to improve habitat and connectivity for fish while still protecting developed areas from flooding.

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Appendix.

Supplemental Figures and Tables

Camera Placement Details

Figure A1. **Brinno TLC200 time-lapse camera in weatherproof housing**

Figure A2. **Cameras were placed inside a protective housing like the one pictured here and locked to flood box accessory structures (e.g. grates and railings). At this site and several others, floodgates are located beneath a grate. The camera lens was positioned to focus on the gate(s) through holes in the grate.**

Figure A3. An example of camera installation: Here the camera was locked to a railing above the floodgate. Ropes were used to angle the camera into a good position to focus on the floodgate below. At other sites, pieces of foam and zip ties were used to adjust camera angles.

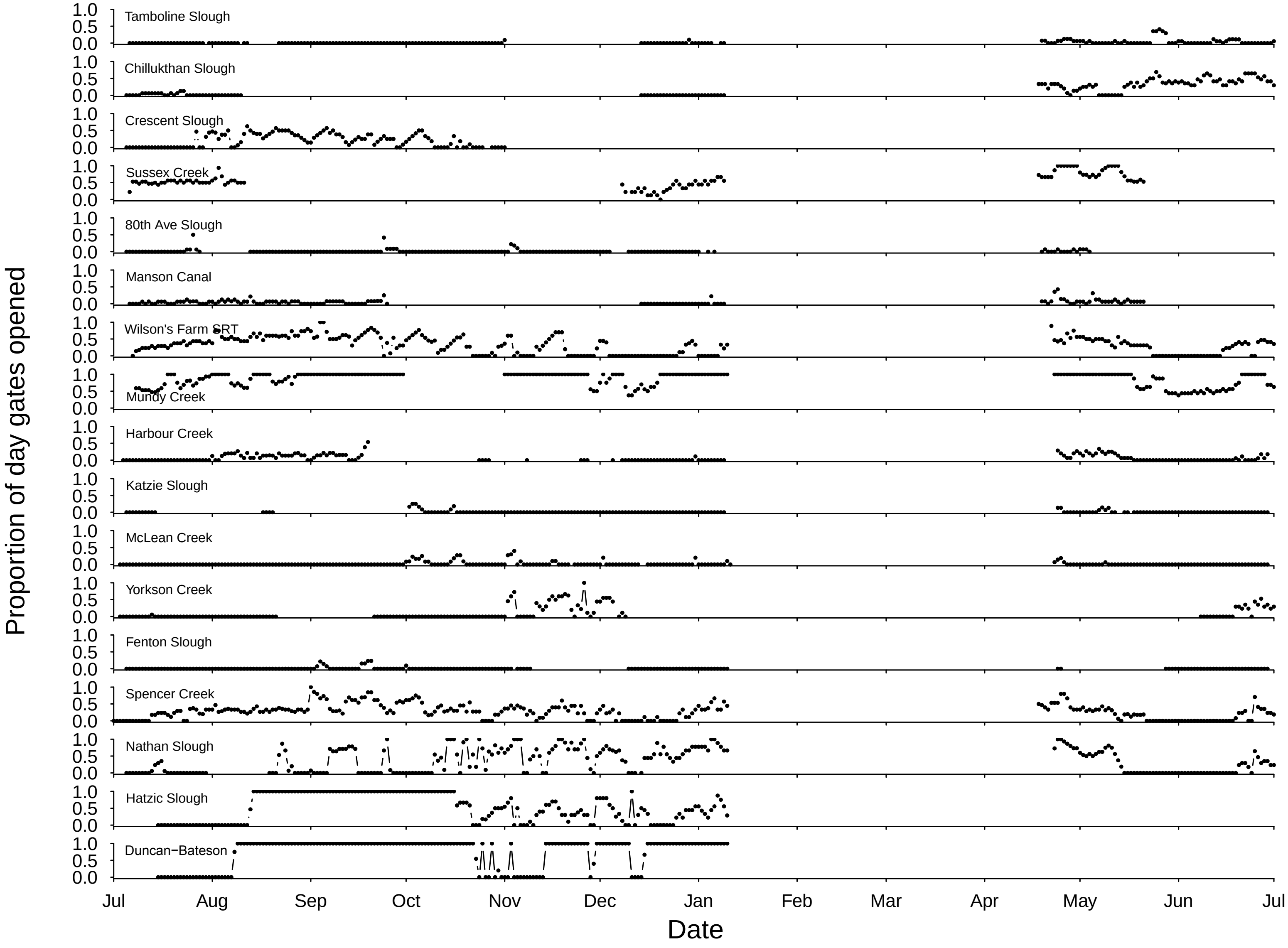
Proportion of day gates opened
Tamboline Slough
Chillukthan Slough
Crescent Slough
Sussex Creek
80th Ave Slough
Manson Canal
Wilson's Farm SRT
Mundy Creek
Harbour Creek
Katzie Slough
McLean Creek
Yorkson Creek
Fenton Slough
Spencer Creek
Nathan Slough
Hatzic Slough
Duncan−Bateson
1.0
0.5
0.0
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Date

Figure A4. **Time series of observed floodgate openings for each site from July 2014 through July 2015. Sites are ordered by increasing distance from the ocean. Blank periods are due to dysfunction, vandalism, or preventative removal in late winter.**

Fish Capture Data Summaries

Table A1 Summary of fish captures at each site listed by species

For each site, total fish captures upstream and downstream of floodgates are sorted by taxonomic family and species, Minimum and maximum fork lengths of captured fish are also given for each species and sampling location. The table is divided into two sections, one each for sites without and with floodgates.

Sites without floodgates		Family	Species	Number captured	Min. FL (mm)	Max FL (mm)
De Boville Slough	Downstream	Centrarchidae	Largemouth bass (*Micropterus salmoides*)	1	-	75
			Pumpkinseed *(Lepomis gibbosus*)	70	56	155
			Unidentified juvenile sunfish	6	51	66
		Cyprinidae	Northern pikeminnow *(Ptychocheilus oregonensis*)	2	74	75
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	3	21	27
	Upstream	Centrarchidae	Largemouth bass (*Micropterus salmoides*)	2	159	163
			Pumpkinseed (*Lepomis gibbosus*)	20	55	110
			Unidentified juvenile sunfish	2	58	69
		Cottidae	Prickly sculpin (*Cottus asper*)	2	74	98
			Juvenile sculpin (*Cottus* sp.)	1	-	< 20
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	42	16	68
Nathan Creek	Downstream	Catostomidae	Largescale sucker (*Catostomus macrocheilus*)	3	96	155
		Centrarchidae	Pumpkinseed *(Lepomis gibbosus*)	1	-	73
		Cottidae	Prickly sculpin (*Cottus asper*)	1	-	60
		Cyprinidae	Northern pikeminnow (*Ptychocheilus oregonensi*s)	12	49	97
			Peamouth chub (*Mylcheilus caurinu*s)	1	-	93
			Redside shiner *(Richardsonius balteatus*)	4	44	61
			Unidentified juvenile minnow	40	< 20	39

		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	6	16	69
		Salmonidae	Chum salmon (*Oncorhynchus keta*)	5	39	55
			Coho salmon (*Oncorhynchus kisutch*)	1	-	67
	Upstream	Centrarchidae	Pumpkinseed (*Lepomis gibbosus*)	1	-	71
		Cottidae	Prickly sculpin (*Cottus asper*)	1	-	62
			Juvenile sculpin (*Cottus* sp.)	1	-	15
		Cyprinidae	Peamouth chub (*Mylcheilus caurinus*)	3	90	102
			Northern pikeminnow (*Ptychocheilus oregonensis*)	7	50	67
			Unidentified juvenile minnow	3	23	32
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	7	21	73
		Salmonidae	Chum salmon (*Oncorhynchus keta*)	2	50	54
Silverdale Creek	Downstream	Catostomidae	Unidentified juvenile sucker	1	-	49
		Centrarchidae	Pumpkinseed (*Lepomis gibbosus*)	20	< 20	106
			Unidentified juvenile sunfish	17	23	109
		Cottidae	Prickly sculpin (*Cottus asper*)	10	51	161
		Cyprinidae	Northern pikeminnow (*Ptychocheilus oregonensis*)	1	-	128
			Unidentified juvenile minnow	4	36	44
		Ictaluridae	Brown bullhead (*Ameirus nebulosus*)	1	-	148
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	1	-	36
	Upstream	Catostomidae	Unidentified juvenile sucker	1	-	32
		Centrarchidae	Pumpkinseed (*Lepomis gibbosus*)	52	49	93
			Unidentified juvenile sunfish	27	26	64
		Cottidae	Prickly sculpin (*Cottus asper*)	6	59	104
		Cyprinidae	Unidentified juvenile minnow	17	20	38
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	4	< 20	44
		Salmonidae	Chum salmon (*Oncorhynchus keta*)	1	-	66
			Cutthroat trout (*Oncorhynchus clarkii*)	1	-	174

West Creek	Downstream	Cottidae	Prickly sculpin (*Cottus asper*)	8	59	84
			Juvenile sculpin (*Cottus* sp.)	1	-	80
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	4	22	42
		Salmonidae	Bull trout (*Salvelinus confluentus*)	3	210	408
			Mountain whitefish (*Prosopium williamsoni*)	1	-	110
	Upstream	Cottidae	Juvenile sculpin (*Cottus* sp.)	2	26	31
		Centrarchidae	Unidentified juvenile sunfish	2	28	37
		Cyprinidae	Unidentified juvenile minnow	55	12	29
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	5	20	27
		Salmonidae	Chinook salmon (*Oncorhynchus tshawytscha*)	1	-	80
			Coho salmon (*Oncorhynchus kisutc*h)	1	-	63

Sites with floodgates		**Family**	**Species**	**Number captured**	**Min. FL (mm)**	**Max FL (mm)**
80th Avenue Slough	Downstream	Catostomidae	Largescale sucker (*Catostomus macrocheilus*)	1	-	322
			Unidentified juvenile sucker	1	-	34
		Cyprinidae	Northern pikeminnow (*Ptychocheilus oregonensis*)	9	57	77
			Unidentified juvenile minnow	17	18	32
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	4	19	29
	Upstream	Catostomidae	Unidentified juvenile sucker	4	31	38
		Centrarchidae	Pumpkinseed (*Lepomis gibbosus*)	4	76	96
			Juvenile sculpin (*Cottus* sp.)	1	-	45
		Cyprinidae	Northern pikeminnow (*Ptychocheilus oregonensis*)	1	-	98
			Unidentified juvenile minnow	37	< 20	37
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	692	17	52

Chillukthan Slough	Downstream	Centrarchidae	Pumpkinseed (*Lepomis gibbosus*)	3	62	68
		Cottidae	Prickly sculpin (*Cottus asper*)	82	17	97
			Juvenile sculpin (*Cottus* sp.)	1	-	21
		Cyprinidae	Peamouth chub (*Mylcheilus caurinus)*	1	-	43
			Unidentified juvenile minnow	4	20	27
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	29	19	45
		Pleuronectidae	Starry flounder (*Platichthys stellatus*)	6	< 20	73
			Unidentified righteye flatfish	1	-	59
	Upstream	Catostomidae	Largescale sucker (*Catostomus macrocheilus*)	1	-	130
		Centrarchidae	Pumpkinseed (*Lepomis gibbosus*)	4	74	114
		Cyprinidae	Brassy minnow (*Hybognathus hankinsoni*)	1	-	64
			Common carp (*Cyprinus carpio*)	1	-	175
			Unidentified juvenile minnow	13	< 20	38
			Peamouth chub (*Mylcheilus caurinus*)	45	35	66
			Redside shiner (*Richardsonius balteatus*)	15	58	101
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	784	22	46
Crescent Slough	Downstream	Catostomidae	Unidentified juvenile sucker	1	-	30
		Centrarchidae	Pumpkinseed (*Lepomis gibbosus*)	16	50	81
			Unidentified juvenile sunfish	5	59	67
		Cottidae	Prickly sculpin (*Cottus asper*)	11	60	102
			Juvenile sculpin (*Cottus* sp.)	1	-	25
		Cyprinidae	Northern pikeminnow (*Ptychocheilus oregonensis*)	1	-	69
			Peamouth chub (*Mylcheilus caurinus*)	1	-	61
			Redside shiner (*Richardsonius balteatus*)	2	70	75

			Unidentified juvenile minnow	10	26	43
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	78	22	56
		Pleuronectidae	Starry flounder (*Platichthys stellatus*)	1	-	73
	Upstream	Centrarchidae	Black crappie (*Pomoxis nigromaculatus*)	2	< 20	87
		Cottidae	Prickly sculpin (*Cottus asper*)	1	-	91
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	13	< 20	64
Duncan-Bateson Slough	Downstream	Catostomidae	Unidentified juvenile sucker	11	29	41
		Cyprinidae	Northern pikeminnow (*Ptychocheilus oregonensis*)	4	89	147
			Redside shiner (*Richardsonius balteatus*)	2	67	72
			Unidentified juvenile minnow	55	< 20	34
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	6	20	56
	Upstream	Cyprinidae	Northern pikeminnow (*Ptychocheilus oregonensis*)	2	61	118
			Unidentified juvenile minnow	4	20	28
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	638	16	51
Fenton Slough	Downstream	Centrarchidae	Largemouth bass (*Micropterus salmoides*)	10	43	79
			Pumpkinseed (*Lepomis gibbosus*)	75	59	98
			Unidentified juvenile sunfish	14	28	66
		Cottidae	Prickly sculpin (*Cottus asper*)	5	68	141
			Juvenile sculpin (*Cottus* sp.)	3	25	27
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	17	30	40
	Upstream	Centrarchidae	Unidentified juvenile sunfish	4	22	31
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	1	-	47
Harbour Creek	Downstream	Centrarchidae	Unidentified juvenile sunfish	1	-	32
		Cottidae	Prickly sculpin (*Cottus asper*)	1	-	75
			Juvenile sculpin (*Cottus* sp.)	5	19	33
		Cyprinidae	Northern pikeminnow (*Ptychocheilus oregonensis*)	2	24	104
			Peamouth chub (*Mylcheilus caurinus*)	4	< 20	61

			Redside shiner (*Richardsonius balteatus*)	8	60	67
			Unidentified juvenile minnow	6	9	31
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	6	< 20	32
	Upstream	Centrarchidae	Unidentified juvenile sunfish	7	15	27
		Cottidae	Juvenile sculpin (*Cottus* sp.)	1	-	27
		Cyprinidae	Common carp (*Cyprinus carpio*)	1	-	24
			Northern pikeminnow (*Ptychocheilus oregonensis*)	71	22	33
			Redside shiner (*Richardsonius balteatus*)	3	24	26
			Unidentified juvenile minnow	743	< 20	28
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	5	27	30
		Unknown	Unknown juvenile fish	1	-	< 20
Hatzic Slough	Downstream	Catostomidae	Unidentified juvenile sucker	1	-	33
		Centrarchidae	Pumpkinseed (*Lepomis gibbosus*)	7	37	123
			Unidentified juvenile sunfish	98	17	37
		Cottidae	Prickly sculpin (*Cottus asper*)	1	-	44
			Juvenile sculpin (*Cottus* sp.)	1	-	28
		Cyprinidae	Northern pikeminnow (*Ptychocheilus oregonensis*)	23	26	67
			Peamouth chub (*Mylcheilus caurinus*)	7	37	45
			Unidentified juvenile minnow	62	< 20	41
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	1	-	23
		Unknown	Unknown juvenile fish	1	-	11
	Upstream	Centrarchidae	Black crappie (*Pomoxis nigromaculatus*)	29	45	73
			Pumpkinseed (*Lepomis gibbosus*)	4	36	57
			Unidentified juvenile sunfish	139	17	62
		Cottidae	Prickly sculpin (*Cottus asper*)	1	-	98
		Ictaluridae	Brown bullhead (*Ameirus nebulosus*)	1	-	35
Katzie Slough	Downstream	Centrarchidae	Pumpkinseed (*Lepomis gibbosus*)	1	-	81

		Cottidae	Juvenile sculpin (*Cottus* sp.)	19	20	32
		Cyprinidae	Unidentified juvenile minnow	43	14	26
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	4	21	39
	Upstream	Centrarchidae	Pumpkinseed (*Lepomis gibbosus*)	1	-	88
		Cyprinidae	Common carp (*Cyprinus carpio*)	1	-	44
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	2	36	36
		Ictaluridae	Brown bullhead (*Ameirus nebulosus*)	1	-	104
Manson Canal	Downstream	Cottidae	Juvenile sculpin (*Cottus* sp.)	1	-	17
		Cyprinidae	Unidentified juvenile minnow	12	11	42
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	1	-	24
	Upstream	Cyprinidae	Unidentified juvenile minnow	2	22	32
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	42	15	40
McLean Creek	Downstream	Centrarchidae	Pumpkinseed (*Lepomis gibbosus)*	17	45	78
			Unidentified juvenile sunfish (Centrarchidae)	10	19	129
		Cottidae	Prickly sculpin (*Cottus asper*)	4	59	70
			Three-spined stickleback (*Gasterosteus aculeatus*)	5	21	68
		Cyprinidae	Northern pikeminnow (*Ptychocheilus oregonensis*)	4	62	171
			Peamouth chub (*Mylcheilus caurinus*)	12	46	175
			Unidentified juvenile minnow	10	18	29
		Salmonidae	Chum salmon (*Oncorhynchus keta*)	1	-	51
	Upstream	Centrarchidae	Largemouth bass (*Micropterus salmoides*)	6	91	159
			Pumpkinseed (*Lepomis gibbosus*)	2	72	73
			Unidentified juvenile sunfish	1	-	77
Mountain Slough	Downstream	Catostomidae	Largescale sucker (*Catostomus macrocheilus*)	1	-	73
		Cyprinidae	Northern pikeminnow (*Ptychocheilus oregonensis*)	17	< 20	77
			Peamouth chub (*Mylcheilus caurinus*)	25	39	59
			Unidentified juvenile minnow	36	17	42

		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	160	21	40
	Upstream	Centrarchidae	Unidentified juvenile sunfish	1	-	52
		Cyprinidae	Northern pikeminnow (*Ptychocheilus oregonensis*)	3	58	70
			Unidentified juvenile minnow	7	< 20	33
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	820	20	41
		Salmonidae	Coho salmon (*Oncorhynchus kisutch*)	14	51	82
Mundy Creek	Downstream	Centrarchidae	Pumpkinseed (*Lepomis gibbosus*)	1	-	67
		Cottidae	Prickly sculpin (*Cottus asper*)	6	70	90
			Juvenile sculpin (*Cottus* sp.)	3	< 20	23
		Cyprinidae	Peamouth chub (*Mylcheilus caurinus*)	1	-	47
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	84	15	72
		Salmonidae	Chum salmon (*Oncorhynchus keta*)	2	43	58
			Coho salmon (*Oncorhynchus kisutch*)	1	-	77
	Upstream	Cottidae	Prickly sculpin (*Cottus asper*)	1	-	100
		Cyprinidae	Unidentified juvenile minnow	6	22	33
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	192	17	54
Nathan Slough	Downstream	Centrarchidae	Largemouth bass (*Micropterus salmoides*)	1	-	211
			Pumpkinseed (*Lepomis gibbosus*)	2	82	86
		Cyprinidae	Northern pikeminnow (*Ptychocheilus oregonensis*)	19	55	119
			Peamouth chub (*Mylcheilus caurinus*)	12	47	102
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	57	21	41
		Ictaluridae	Brown bullhead (*Ameirus nebulosus*)	1	-	186
	Upstream	Centrarchidae	Pumpkinseed (*Lepomis gibbosus*)	1	-	88
		Cyprinidae	Common carp (*Cyprinus carpio*)	3	26	70
			Northern pikeminnow (*Ptychocheilus oregonensis*)	3	65	80
			Unidentified juvenile minnow	1	-	29
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	49	22	56

Spencer Creek	Downstream	Centrarchidae	Largemouth bass (*Micropterus salmoides*)	1	-	123
			Pumpkinseed (*Lepomis gibbosus*)	8	72	104
			Unidentified juvenile sunfish	8	14	29
		Cyprinidae	Northern pikeminnow (*Ptychocheilus oregonensis*)	6	22	69
			Unidentified juvenile minnow	8	15	26
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	7	25	38
	Upstream	Centrarchidae	Unidentified juvenile sunfish	10	17	37
		Gasterosteidae	Three-spined stickleback (Gasterosteus aculeatus)	359	19	38
		Ictaluridae	Brown bullhead (*Ameirus nebulosus*)	2	50	131
Sussex Creek	Downstream	Cyprinidae	Unidentified juvenile minnow	75	8	40
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	43	13	38
	Upstream	Cyprinidae	Unidentified juvenile minnow	9	18	30
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	16	25	43
Tamboline Slough	Downstream	Catostomidae	Largescale sucker (*Catostomus macrocheilus*)	4	48	64
			Unidentified juvenile sucker	1	-	27
		Centrarchidae	Pumpkinseed (*Lepomis gibbosus*)	3	48	55
			Unidentified juvenile sunfish	2	36	43
		Cottidae	Prickly sculpin (*Cottus asper*)	16	45	78
		Cyprinidae	Peamouth chub (*Mylcheilus caurinus*)	1	-	123
			Unidentified juvenile minnow	3	15	23
		Embiotocidae	Shiner surfperch (*Cymatogaster aggregata*)	1	-	56
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	10	18	42
		Pleuronectidae	Starry flounder (*Platichthys stellatus*)	12	45	73
	Upstream	Cyprinidae	Pumpkinseed (*Lepomis gibbosus*)	1	-	104
			Redside shiner (*Richardsonius balteatus*)	6	75	95
			Unidentified juvenile minnow	7	24	32
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	136	< 20	42

Wilson's Farm Slough	Downstream	Centrarchidae	Largemouth bass (*Micropterus salmoides*)	1	-	60
			Pumpkinseed (*Lepomis gibbosus*)	22	56	87
			Unidentified juvenile sunfish	22	17	68
		Cottidae	Prickly sculpin (*Cottus asper*)	16	71	104
		Cyprinidae	Northern pikeminnow (*Ptychocheilus oregonensis*)	2	52	60
			Unidentified juvenile minnow	22	12	30
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	193	9	67
	Upstream	Centrarchidae	Pumpkinseed (*Lepomis gibbosus*)	62	72	124
			Unidentified juvenile sunfish	9	< 20	108
		Cottidae	Prickly sculpin (*Cottus asper*)	1	-	65
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	1	-	18
Yorkson Creek	Downstream	Centrarchidae	Pumpkinseed (*Lepomis gibbosus*)	3	43	58
			Unidentified juvenile sunfish	2	53	60
		Cottidae	Prickly sculpin (*Cottus asper*)	5	72	96
			Juvenile sculpin (*Cottus* sp.)	3	24	33
		Cyprinidae	Northern pikeminnow (*Ptychocheilus oregonensis*)	3	51	58
			Unidentified juvenile minnow	8	10	39
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	81	16	48
	Upstream	Centrarchidae	Pumpkinseed (*Lepomis gibbosus*)	4	50	76
			Unidentified juvenile sunfish	1	-	45
		Gasterosteidae	Three-spined stickleback (*Gasterosteus aculeatus*)	87	17	58

Summary of Data on Fish Captures and Floodgate Operations

Table A2. **Summary of floodgate operations (mean proportion of the day gates opened) and values based on fish sampling that were used to calculate the log-response ratios. Richness is calculated based on the number of species in that group, but including all minnows and all sunfishes pooled together due to the large number of unidentified juvenile individuals in these groups.**

Site	Mean proportion of the day gates opened	Up/Down-stream	Total Fish Captured	Total Biomass (g)	Total Richness	Native Fish Captured	Native Fish Biomass (g)	Native Fish Richness	Non-native Fish Captured	Non-native Fish Biomass (g)	Non-native Fish Richness
Sites without floodgates											
De Boville Slough	N/A (1.000)	Upstream	69	264.07	4	45	22.295	2	24	241.77	2
		Downstream	82	1006.62	4	5	8.07	2	77	998.55	2
Nathan Creek	N/A (1.000)	Upstream	25	57.28	5	24	50.46	4	1	6.82	1
		Downstream	74	180.27	7	73	167.81	6	1	12.46	1
Silverdale Creek	N/A (1.000)	Upstream	109	464.47	7	30	89.98	6	79	374.49	1
		Downstream	55	536.64	6	17	106.54	4	38	430.10	2
West Creek	N/A (1.000)	Upstream	66	14.94	6	64	13.8125	5	2	1.13	1
		Downstream	17	290.77	4	17	290.77	4	0	0.00	0
Sites with floodgates											
80th Avenue Slough	0.013	Upstream	739	285.39	5	735	222.93	4	4	62.46	1
		Downstream	32	34.93	3	32	34.93	3	0	0.00	0
Chillukthan Slough	0.187	Upstream	864	727.85	5	859	517.50	3	5	210.35	2
		Downstream	127	456.59	6	124	438.69	5	3	17.90	1
Crescent Slough	0.205	Upstream	16	34.30	3	14	24.86	2	2	9.44	1
		Downstream	127	254.44	6	106	138.68	5	21	115.76	1
Duncan-Bateson	0.731	Upstream	644	190.19	2	644	190.19	2	0	0.00	0
		Downstream	78	73.95	3	78	73.95	3	0	0.00	0
Fenton Slough	0.007	Upstream	5	2.79	2	1	0.74	1	4	2.05	1
		Downstream	124	920.75	4	25	57.66	2	99	863.09	2

Site	Mean proportion of the day gates opened	Up/Down-stream	Total Fish Captured	Total Biomass (g)	Total Richness	Native Fish Captured	Native Fish Biomass (g)	Native Fish Richness	Non-native Fish Captured	Non-native Fish Biomass (g)	Non-native Fish Richness
Harbour Creek	0.064	Upstream	832	60.57	5	823	59.40	3	8	1.17	2
		Downstream	33	25.46	4	32	25.16	3	1	0.30	1
Hatzic Slough	0.527	Upstream	174	133.29	3	1	5.96	1	173	127.33	2
		Downstream	202	100.10	5	96	22.97	4	105	77.13	1
Katzie Slough	0.010	Upstream	5	31.71	4	2	1.05	1	3	30.66	3
		Downstream	67	17.85	4	66	5.92	3	1	11.93	1
Manson Canal	0.049	Upstream	44	12.85	2	44	12.85	2	0	0.00	0
		Downstream	14	0.98	3	14	0.98	3	0	0.00	0
McLean Creek	0.017	Upstream	9	180.81	2	0	0.00	0	9	180.81	2
		Downstream	63	421.76	5	36	275.24	4	27	146.52	1
Mountain Slough	0.559	Upstream	845	302.12	4	844	300.47	3	1	1.65	1
		Downstream	239	79.08	3	239	79.08	3	0	0.00	0
Mundy Creek	0.854	Upstream	199	55.48	3	199	55.48	3	0	0.00	0
		Downstream	98	83.83	6	97	77.67	5	1	6.16	1
Nathan Slough	0.351	Upstream	57	64.23	4	53	40.22	2	4	24.01	2
		Downstream	92	490.93	5	88	208.94	2	4	281.99	3
Spencer Creek	0.271	Upstream	371	125.43	3	359	57.27	1	12	68.16	2
		Downstream	38	96.23	4	21	4.35	2	17	91.88	2
Sussex Creek	0.566	Upstream	25	6.63	2	25	6.63	2	0	0.00	0
		Downstream	118	13.78	2	118	13.78	2	0	0.00	0
Tamboline Slough	0.019	Upstream	150	109.23	3	149	79.24	2	1	29.99	1
		Downstream	53	191.80	7	48	174.70	6	5	17.10	1
Wilson's Farm Tide Gate	0.319	Upstream	73	1073.63	3	2	3.16	2	71	1070.47	1
		Downstream	278	353.69	5	233	170.58	3	45	183.11	2
Yorkson Creek	0.105	Upstream	92	60.76	2	87	39.04	1	5	21.72	1
		Downstream	105	73.45	4	100	56.51	3	5	16.94	1

Water Quality Observations

Table A3. Water quality measurements taken ~15 m upstream and downstream of floodgates at time of fish sampling

	Date Sampled	Upstream or Downstream	Water Temperature (°C)	DO (mg/L)	Salinity (ppt)	Conductivity (mS/cm)
Sites without floodgates						
De Boville Slough	08/05/2014	Upstream	26.79	8.75	0.05	0.115
De Boville Slough	08/05/2014	Downstream	23.86	7.98	0.03	0.062
Nathan Creek	08/01/2014	Upstream	24.11	11.42	0.09	0.198
Nathan Creek	08/01/2014	Downstream	24.02	12.13	0.09	0.201
Silverdale Creek	08/19/2014	Upstream	18.26	10.02	0.06	0.114
Silverdale Creek	08/19/2014	Downstream	18.21	10.05	0.06	0.112
West Creek	08/18/2014	Upstream	16.55	9.52	0.09	0.162
West Creek	08/18/2014	Downstream	17.72	9.42	0.08	0.140
Sites with floodgates						
80th Avenue Slough	08/12/2014	Upstream	20.25	8.72	0.05	0.093
80th Avenue Slough	08/13/2014	Downstream	19.64	7.51	0.05	0.099
Chillukthan Slough	08/11/2014	Downstream	22.90	6.67	0.65	1.306
Chillukthan Slough	08/12/2014	Upstream	21.08	4.53	0.53	0.985
Crescent Slough	08/06/2014	Upstream	21.91	7.97	0.19	0.383
Crescent Slough	08/06/2014	Downstream	20.19	6.82	0.24	0.481
Duncan-Bateson	08/26/2014	Upstream	19.68	3.30	0.11	0.208
Duncan-Bateson	08/26/2014	Downstream	21.92	8.06	0.05	0.092
Fenton Slough	08/15/2014	Upstream	21.69	0.75	0.13	0.255
Fenton Slough	08/15/2014	Downstream	21.19	6.06	0.06	0.121
Harbour Creek	08/27/2014	Upstream	19.67	8.01	0.05	0.091
Harbour Creek	08/27/2014	Downstream	20.53	8.74	0.04	0.089

	Date Sampled	Upstream or Downstream	Water Temperature (°C)	DO (mg/L)	Salinity (ppt)	Conductivity (mS/cm)
Hatzic Slough	08/24/2014	Upstream	23.84	8.25	0.05	0.108
Hatzic Slough	08/24/2014	Downstream	23.15	8.14	0.05	0.108
Katzie Slough	08/16/2014	Upstream	19.05	0.49	0.13	0.238
Katzie Slough	08/16/2014	Downstream	20.24	7.50	0.04	0.086
Manson Canal	08/13/2014	Upstream	18.58	3.47	0.09	0.172
Manson Canal	08/13/2014	Downstream	18.42	3.72	0.12	0.213
McLean Creek	08/05/2014	Upstream	19.10	0.28	0.07	0.140
McLean Creek	08/05/2014	Downstream	23.01	8.00	0.02	0.039
Mountain Slough	08/26/2014	Upstream	15.83	1.92	0.10	0.173
Mountain Slough	08/26/2014	Downstream	16.50	2.31	0.10	0.175
Mundy Creek	08/07/2014	Downstream	20.37	10.47	0.15	0.280
Mundy Creek	08/07/2014	Upstream	21.52	7.76	0.07	1.400
Nathan Slough	07/31/2014	Downstream	24.13	11.25	0.12	0.252
Nathan Slough	08/01/2014	Upstream	20.24	2.95	0.14	0.273
Spencer Creek	08/25/2014	Upstream	20.61	3.93	0.06	0.124
Spencer Creek	08/25/2014	Downstream	22.48	7.86	0.05	0.990
Sussex Creek	07/30/2014	Upstream	19.81	0.66	0.3	0.550
Sussex Creek	07/30/2014	Downstream	19.81	0.46	0.24	0.490
Tamboline Slough	08/21/2014	Upstream	20.81	4.72	1.11	1.985
Tamboline Slough	08/21/2014	Downstream	20.97	8.27	2.95	5.028
Wilson's Farm Tide Gate	08/07/2014	Upstream	21.56	4.14	0.03	0.062
Wilson's Farm Tide Gate	08/07/2014	Downstream	21.37	7.17	0.02	0.041
Yorkson Creek	08/04/2014	Upstream	21.19	2.26	0.12	0.244
Yorkson Creek	08/04/2014	Downstream	21.82	2.83	0.12	0.238

Results from Principal Components Analysis

Table A4. PCA eigenvalues

PC	Eigenvalue	% Variance
1	1.70953	42.738
2	1.25209	31.302
3	0.677668	16.942
4	0.360706	9.0176

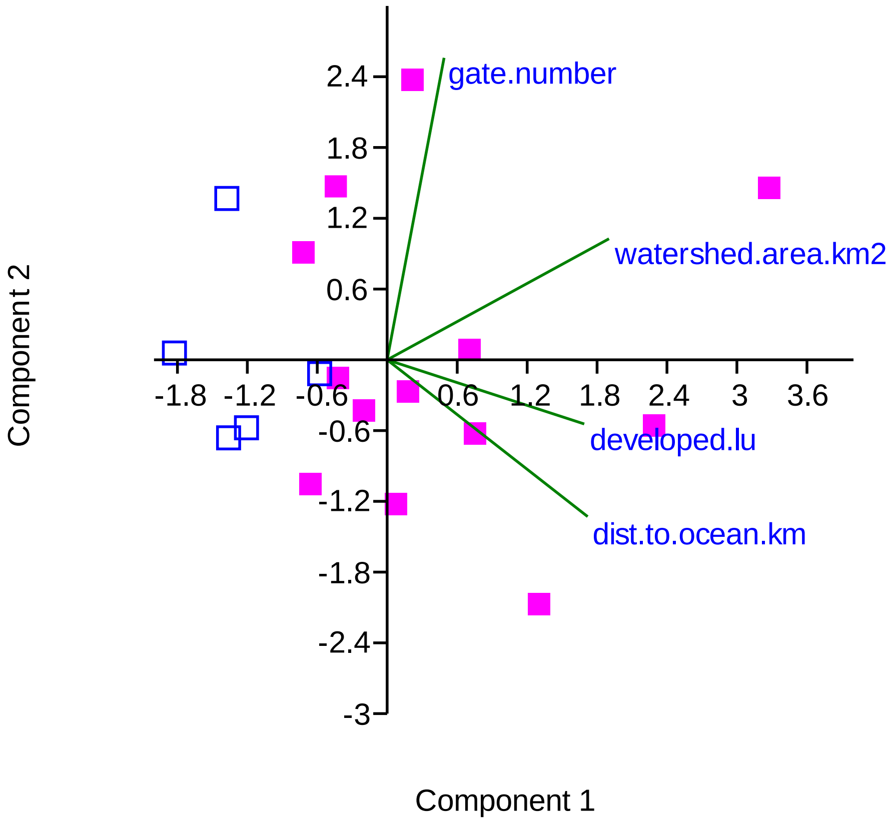

Figure A5. **PCA ordination plot of site characteristics by pump presence/absence**

Shown here is a Principal Components Analysis ordination plot displaying relationships between site characteristics. Points are colour-coded to represent the presence (filled squares) or absence (open squares) of pumping stations at a floodgate site. Green lines represent the loadings for the number of floodgates, the watershed area, the percentage of the watershed with developed land uses, and the distance from the ocean to the floodgate, labeled clockwise from the top.

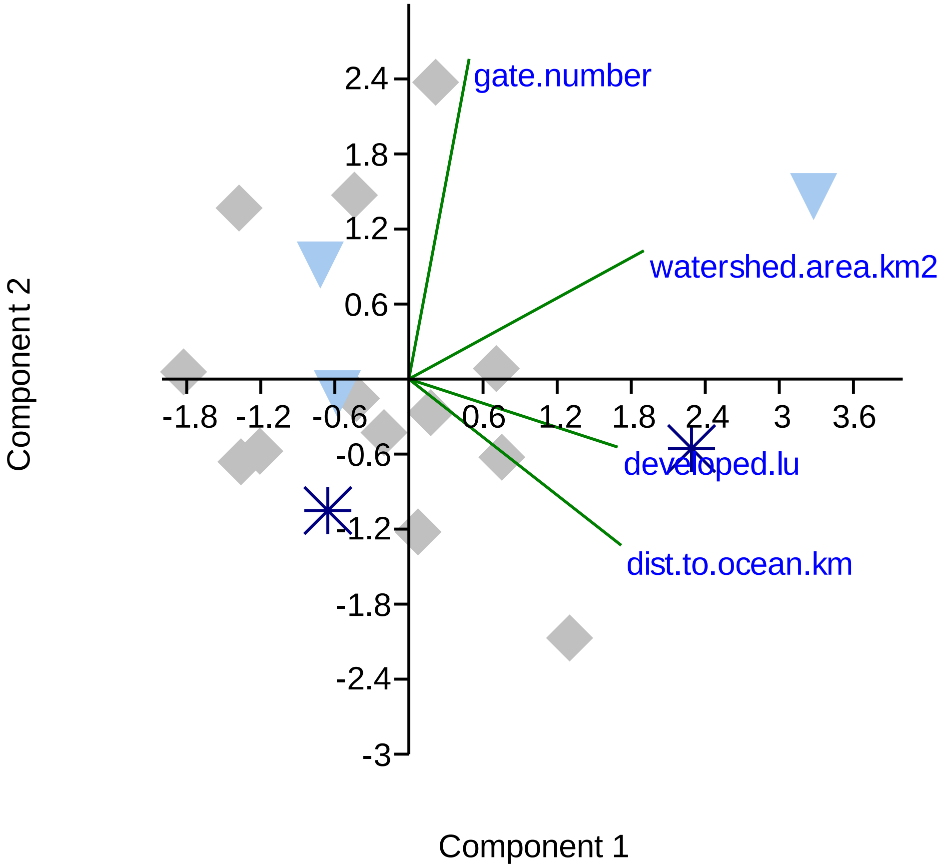

Figure A6. **PCA ordination plot of site characteristics by gate type**
Shown here is a Principal Components Analysis ordination plot displaying relationships between site characteristics. Points are colour-coded to represent three gate types: manual sluice gates (stars), side-mounted gates (diamonds), and top-mounted gates (triangles). Green lines represent loadings for the number of floodgates, the watershed area, % of the watershed with developed land uses, and the distance from the ocean to the floodgate, labeled clockwise from the top.

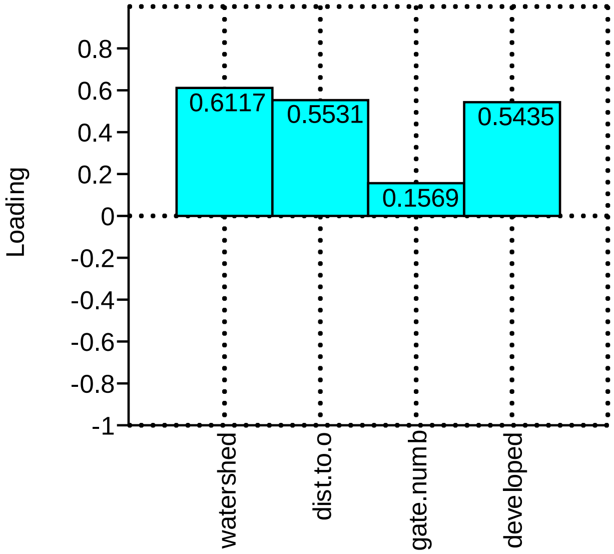

Figure A7. **Loadings for Principal Component 1**
These are the loadings for the first principal component of a PCA performed on site characteristics of floodgate sites.

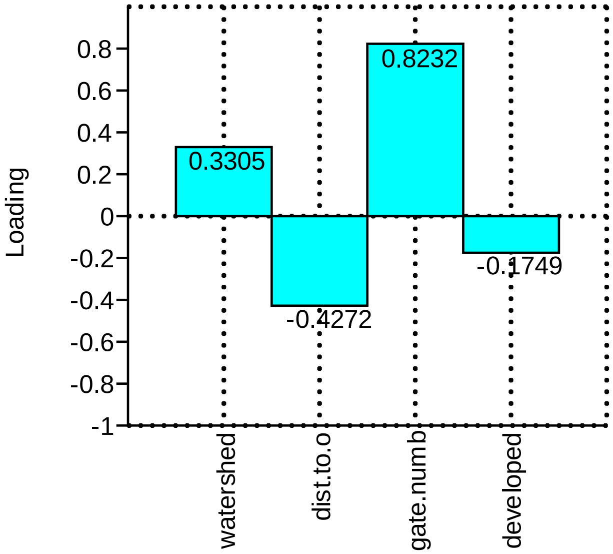

Figure A8. **Loadings for Principal Component 2**
These are the loadings for the second principal component of a PCA performed on site characteristics of floodgate sites.