Splendor Without Spoil: Restoring tidal channel habitat on Swishwash Island

by

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Abstract

Restoration of estuarine and tidal marsh habitats in Canada's Fraser River estuary is imperative for the conservation and recovery of select depressed Pacific salmon populations and the many species that depend on them. In the 1930's through to 1940's, dredge spoils were deposited on East Swishwash Island, permanently altering the small delta island's geomorphology and ecology. The purpose of this study was two-fold: 1.) Confirm and describe fish use of remnant tidal channel habitat on Swishwash Island, using juvenile Chinook salmon (*Oncorhynchus tshawytscha*) as a focal species and 2.) Quantify the historical tidal channel loss on East Swishwash Island and potential for restoration. Tidal channels and adjacent marshes were sampled for realized fish use, plant distributions, basic water parameters, and large woody debris (potential predator refugia). Remote data sets (historical and present-day) were used to quantify historic, current, and future tidal channel density scenarios. Swishwash tidal channels were utilized during the sampling period by Chinook salmon with comparable relative abundances and fork lengths. Tidal channel capacity and marsh habitat have been reduced by 50% on East Swishwash Island due to spoil deposition and marsh erosion. Based on reference conditions derived from undisturbed and historic marsh islands, restoring island elevations could facilitate the addition of 1 km of marsh edge while increasing tidal channel area on East Swishwash Island by nearly 200%. This would provide important habitat in a fragmented distributary of the Fraser River estuary to species of fish and wildlife, including 3 ecotypes of juvenile Chinook salmon.

Keywords: *Estuaries; Chinook; Oncorhynchus tshawytscha; rearing; restoration; mitigation; tidal channels*

Dedication

This paper is dedicated to my family and friends who have supported and believed in me and my endeavors. It is also dedicated to the late Dick Loomer, a local steward of Swishwash Island, and others like him who humbly try and reconcile humanity's relationships with nature.

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This project took place within the unceded territories of the Musquem, Tseil-Waututh, Tsawwassen and Sto:lo First Nations who have been stewards of the estuary since time immemorial. I would like to thank my supervisor Dr. Ken Ashley for accepting me as a student, providing the scope for this project, and for his experience and guidance during my study. Thank you to my committee for their thoughtful and thorough edits and comments. This work was supported by Mitacs through the Mitacs Accelerate program. I would like to thank Dave Scott, Misty MacDuffee and the Raincoast Conservation Foundation for having me as an intern and for their support and mentorship with this research. Thank you to Dave Harper and Ricky Hurley of the River's Institute for their patience in providing me with calibrated and maintained field equipment. Thank you to Dr. Gregory Hood for his time and input on this project. A big thank you to Allison Brennan for her work and support in developing my Mitacs application and assisting me with this process. Thank you, Jocelyn Woods and the Nature Conservancy of Canada, for allowing me access to Swishwash Island property and files and for your interest in this project. Thank you to Alyssa Purse, Tamie Bergsma, and Lori Sclechtleitner of the Ecological Restoration Swishwash undergraduate capstone group and Fish and Wildlife students for laying a strong foundation and baseline for this project from which to build. Thank you to Sean Galway from the Geomatics department at BCIT and Laurie Stott from Fish and Wildlife for assisting with LiDAR data sets and analyses. Thank you to my family and friends for support and my wonderful field assistants Oliver Denny, Mitchell Rogers, Heather Scott, Emma Halupka, Hans Cienfuegos, Katie Moore, Megan Winand, Dylan Cunningham, Jack Hall, and others!

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List of Acronyms

BC	British Columbia
DFO	Department of Fisheries and Oceans
ARP	Applied Research Project
BCIT	British Columbia Institute of Technology
BCP	British Columbia Packers LTD
LWD	Large Wood Debris
FRE	Fraser River estuary
LAC	Library and Archives Canada
NCC	Nature Conservancy of Canada
SFU	Simon Fraser University
LFR	Lower Fraser River
MFR	Middle Fraser River
UFR	Upper Fraser River
LiDAR	Light Detection and Ranging
PBS	Pacific Biological Station
PNW	Pacific Northwest

Chapter 1. Introduction

Swishwash Island is a small vestige of the highly productive Fraser River estuary (FRE) tidal marshes, of which an estimated 70-90% has been degraded due to various types of development (Levings 2004). Although never diked for agriculture, Swishwash Island has undergone large changes to its landscape and ecology. The most dramatic shift came with the deposition of sand and dredge on East Swishwash Island from 1930-1950 (Carter 2002). These dredge spoils buried a significant portion of marsh habitat, raised localized elevations of the eastern island, and permanently altered compositions and distributions of East Swishwash's biological communities. The spoils also infilled tidal channel habitat important for select species of out-migrating juvenile Pacific salmon (*Oncorhynchus* spp). In particular, populations of juvenile Chinook salmon (*O. tshawytscha*) express an acute sensitivity to reduced access to salt marshes and tidal channel habitats in estuaries (Healey 1980; 1982; Levy and Northcote 1982; Levings et al.1986; Magnusson and Hilborn 2003; Duffy and Beauchamp 2011; Flitcroft 2018; Davis 2019)

There are large benefits in restoring these ecosystems, both for depressed stocks of Fraser River salmon and the many species that depend on them (Levings and Nishimura 1997; Simensted and Cordell 2000; Adams and Williams 2004; Bottom et al. 2005; Rice et al 2005; Ellings et al. 2016; Davis et al. 2017; 2019). For this project I looked at fish-use, with a strong focus on Chinook salmon as a focal species, and other indicators of tidal channel structure on Swishwash Island and the FRE. I combined this analysis with georeferenced and analyzed historic and current spatial imagery of channel habitat on East and West Swishwash Island to quantify loss and restoration potential. This information will help inform 'Before' conditions of a potential paired 'Before After Control Impact' (BACI) study should restoration proceed. This will provide valuable information for monitoring and evaluating success of tidal channel development (Roegner et al 2008).

This report is divided into four chapters. Chapter 1 provides a background for ecological restoration of marsh tidal channels and the basis for using Chinook salmon as a focal species, within the context of the Fraser River estuary. In Chapter 2, I introduce my study site and provide a detailed description of my methods. In Chapter 3, I present the results of my collected data. Chapter 4 is a discussion highlighting some of my findings and recommendations for future tidal channel restoration projects and research in the Fraser River estuary.

Study Goal:

1.) Investigate fish use and structure of existing tidal channels on Swishwash Island and examine geomorphology in historical and current contexts, establishing the 'Before' of a BACI study design, to inform restoration, monitoring, and evaluation of success.

Study Objectives:

1.) Sample fish communities and water quality parameters in select tidal channels on Swishwash Island and compare with reference channels throughout the FRE Delta.

2.) Describe and quantify the dominant marsh vegetation communities, presence of invasive species, and identify rare species present.

3.) Measure Large Wood Debris and surface velocities in select channels on Swishwash Island as measures of channel capacity to support juvenile Chinook.

4.) Map and extract current and historic tidal channel geometries (area, length, edge, order, density) to assess Swishwash Island tidal channel opportunity for juvenile Chinook and make rigorous inferences for channel restoration design.

1.2. Estuaries

1.2.1. Background

Estuaries are a crucial source of biodiversity and productivity at land–sea interfaces across the globe (Lotze et al. 2006; Ellings et al 2016; Levings 2016). Sediments and nutrients are collected and transported via fluvial channels and mixed with those of marine environments in semi enclosed tidal bays (Levings 2016). The dynamic transport and exchange of waters, nutrients and sediments facilitates the geochemical processes and conditions that make estuaries among some of the most primary-productive environments in the world (Day et al. 1989). This productivity ecologically reverberates across trophic levels in ecosystems that support critical ecological functions (foraging, nesting, breeding, refuge, rearing and migration) for a variety of life-stages of fish and wildlife species (Day 1989; Schaefer 2014; Levings 2016).

In addition to benefiting wildlife, functioning estuaries provide many ecosystem services for people (e.g. nutrient cycling, water quality, disturbance regulation, food production, and socio-cultural benefits) and are valued hubs of transportation as direct and protected links to the sea (Rice et al. 2015). There have been major attempts at quantifying ecosystem services in monetary values by estimating relative contributions of biomes (De Groot et al. 2012; Costanza et al. 1997; 2014). Though these estimates are often not spatially explicit nor sufficiently dynamic due to simplicities in value aggregations, they can provide basic comparison for public awareness and land-use decision making (Costanza 2014). Of the 16 biomes ranked by Costanza et al (2014), estuaries and salt marshes were among the most economically valuable of any ecosystem (with tidal marshes second only to coral reefs). The 2012 average global monetary value of ecosystem services for estuaries and tidal marshes were estimated to be \$28,916 and \$193,845 $ha^{-1}yr^{-1}$ (US), respectively (Costanza et al. 2014). The intrinsic values associated with estuaries have made them major cultural and economic centers of societies and focal points of human activity throughout history (Lotze et al.2006; Levings 2016).

Today, disproportionate urbanization, agricultural development, and resource-extraction pressures have led to decline in estuarine habitat across the world (Ashley 2006; Lotze et al. 2006; Ellings et al. 2016; Levings 2016). Fluvial connectivity and dynamic nutrient, sediment, and bio-geo-chemical processes are permanently altered in lieu of flood prevention and river training infrastructure, channel dredging, and storage of wood and dredge spoil (Hood 2004; Levings 2016). These impacts are further exacerbated by continued diminishment of water and sediment quality through industrial and nonpoint-source pollution and erosion pathways, increasing rates of climate change, and continued introduction and expansion of invasive species (Day et al. 1989; Levings 1982; 2016; Bottom et al. 2015; Ashley 2016). Today, estuaries are some of the most heavily used and threatened ecosystems in the world (Lotze et al. 2006; Levings 2016).

1.2.2. Pacific Salmon and Estuaries

Decades of focused study has put to rest the misconception that estuaries are mere conduits that act as bottlenecks or mortality sinks for out-migrating juvenile salmon. To the contrary, current understanding is that the productive salt water oligohaline gradient of estuaries is not only important for ontogenetic development, imprinting, and physiological transitioning but provides productive and dynamic rearing conditions that leads to enhanced survival to varying degree depending on species and population (Healey 1980; 1982; Levy and Northcote 1982; Simenstad 1982; Nielson et al. 1985; Magnusson and Hilborn 2003; Duffy and Beauchamp 2011; Davis 2019). Though it is difficult to isolate mechanisms linking estuarine conditions to survival, rigorous studies have provided ample evidence that the productive feeding, low velocities, and water parameter conditions can contribute to an overall fitness and size at ocean entry, thought to be an important determinant of the crucial stage of early marine survival (Healey 1980; 1982; Levy and Northcote 1982; Levings et al.1986; Duffy and Beauchamp 2011; Davis 2019).

As juvenile anadromous salmon (*Oncorhynchus* spp.*)* reach the terminus of their rivers and enter the estuary, size, complexity, and biota of their environment expands into a mosaic of changing habitats (Healey 1982; Bottom et al. 2005; Levings 2016). The classification of these tidal habitats is based on different configurations of flat and channel features of vegetation, salinity, and sedimentary gradients (Levings 2016). Growth and production of salmonids in northwest estuaries are largely based on detrital food chains, as their major prey source tends to be detritus feeders (Healey 1980;1982; Bottom 2015; Levings 2004; 2016). Sources of detritus along the estuarine tidal gradient vary but include the emergent vegetation in tidal marshes, eelgrass meadows, and algae (Levings 2016). The physical configuration and ability to efficiently produce or retain detritus largely determines a habitat's value for juvenile rearing (Healey 1980; 1982; Levings et al 1991; Simenstad 2002). Marsh tidal channels, intertidal nodes of distributaries, and leading edges of deltas are considered prime habitat with marsh edges being primary ecotones for foraging and refugia from predation (Simenstad et al. 2002).

There can be high energy requirements for juvenile salmon as they traverse the estuarine landscape. Though structural elements such as Large Woody Debris (LWD), sloughs, and tidal channels of intact estuaries can buffer seasonal variations in river flow, salmon must continually adjust to tidal changes in salinity gradients, water depths, and habitat accessibility (Bottom et al. 2015). The ebbing and flooding of tides may direct movement of rearing salmon fry between low tide refuge and marsh habitats respectively (Healey 1982, Levy and Northcote 1982). With average residencies reaching upwards of 30 days in some populations of Chinook, an availability of aforementioned structures and suitable low tide refugia immediately adjacent to marsh habitats is a likely factor of salmon production and survival in estuaries (Levy and Northcote 1982; Bottom et al. 2005).

All anadromous species of salmon are dependent on estuaries as they transit marine and freshwaters, but the degree and relative importance varies with the species, population, and location (Simenstad 2002; Bottom et al 2005; Levings 2016). Anadromous Pacific salmon express a strong fidelity for spawning sites in natal streams, leading to potentially rapid and complete reproductive isolation (Dittman and Quinn 1996; Levings 2016; Quinn 2018). This isolation contributes to adaptation to the local conditions expressed through a high variation in life-history types between species, systems, and populations (Quinn 2018). Generally, of the five semelparous species of Pacific salmon, pink (*O. gorbuscha*) and sockeye (*O. nerka*) salmon spend less time in estuaries, while coho (*O. kisutch*), chum (*O. keta*), and Chinook (*O. tshawytscha*) maintain populations that have adapted to a range of immediate (days), intermediate (weeks), or prolonged (month+) residencies (Levings 2016; Flitcroft 2018).

The interspecific occupation of estuarine habitats by juvenile salmon is partitioned temporally and spatially and depends on fish size, tidal stage, and season (Healey 1982; Healey 1980; Levy and Northcote 1982; Bottom et al 2005). Generally, subyearling fry with fork lengths (FL) less than 30-60 mm occupy shallow habitats along shorelines (e.g. tidal marshes and flats) (Levy and Northcote 1982; Simenstad et al. 1982; Bottom et al 2005). These distributions shift to deeper habitats away from shorelines (e.g. shoals and distributary channels) as fish develop to the fingerling and smolt stages (60-100 mm FL). Juveniles with FL upwards of 100 mm tend to use both shallow and deep habitats (Healey et al. 1982; Levy and Northcote 1982; Bottom et al 2005).

High levels of intraspecific variation have been observed in species of anadromous salmon and can act as a portfolio effect, providing resilience to changes along the habitat continuum (Carlson and Satterwaite 2011). Anadromous salmonids have thrived and persisted in their broad range of dynamic habitats because of this diverse suite and plasticity of life-history types. Of the anadromous species, variation in intraspecific use and phenotypic reliance on estuaries is most common in populations of coho and Chinook (Flitcroft 2018). Considering the variety in life-histories across species and populations, it is recommended that the full historic extant of a respective estuaries' habitats, species, and life history types contribute to restoration goals and monitoring strategies (Simenstad and Cordell 2000; Bottom et al. 2005; Roegner et al. 2008).

1.3. The Fraser River Estuary

1.3.1. Description

The Fraser River basin spans 232,000 km^2 across south-central British Columbia, essentially draining one quarter of the region (Church 2016). The river flows 1,370 km from its montane head waters to the Salish Sea, incorporating 12 major sub-basins and 34 sub watersheds (Figure 1.1). The annual hydrograph of Fraser River is unimodal, with low flow during winter and high flow in spring and early summer due to snowmelt (Church 2016). Freshet refers to the period of high discharge and suspended sediment transport, which generally occurs from May through July (Milliman 1980). During this period, discharge at Hope (150 km upstream of the mouth) ranges between 6,000 and 12,000 m^3 with sediment loads of approximately 25 million metric tonnes per year (Milliman 1980).

Figure 1.1. Map of the Fraser River basin system, 2018.
Note. Modified from: Murray A. (2016) Fraser River Delta: Southern British Columbia (Canada). In: Finlayson C., Milton G., Prentice R., Davidson N. (eds) The Wetland Book. Springer, Dordrecht

As the Fraser River reaches the Fraser Lowlands in its approach of the Salish Sea, the gradient rapidly declines. As velocity of the river drops, the river begins to deposit its load, first as gravel, then sands, then mixed mud, silt, and sands at the tidally dominated mouth (Mclaren and Ren 1995). Approximately 3.5 million tonnes are deposited in the lower reaches annually (Mclaren and Ren 1995). Over the past 10-11,000 years bp, sediment deposition and retention has led to the formation of the Fraser River estuary (FRE), the largest estuary on the Pacific coast of Canada (Schaefer 2014).

The FRE is classified as a stratified drowned river valley (Levings 2016). The tidal regime is classified as mixed, semi-diurnal with approximate mean and maximum annual ranges of 3 m and 5 m at the delta front (Kostaschuk and Best 2005). Estuaries are often delineated by the reach of the oligohaline gradient or the area of mixing salt and fresh waters, however, some classifications also include tidal freshwater areas and the foreshore plume (Rice et al. 2005). Estuarine boundaries are variable as salinity and tidal determinants shift spatially and temporally across gradients (Rice et al. 2005). In the FRE, the salt wedge that flows beneath the less dense freshwater reaches to just downstream of the bifurcation of the two major North and South Arm distributary channels (see Mitchell Island for the North Arm and Annacis Island for the South) during periods of low river discharge (Miliman 1980; Dashtgard et al. 2012) (Figure 1.2). Tidal influence of fresh water channels and marshes extend up to Mission. During freshet, the wedge retreats to the lower limits of the distributaries and in trained channels can recede beyond channel boundaries (Dashtgard et al. 2012). Predominant wind directions are from the northwest and southeast with greatest fetch distances of 50 km to the northwest.

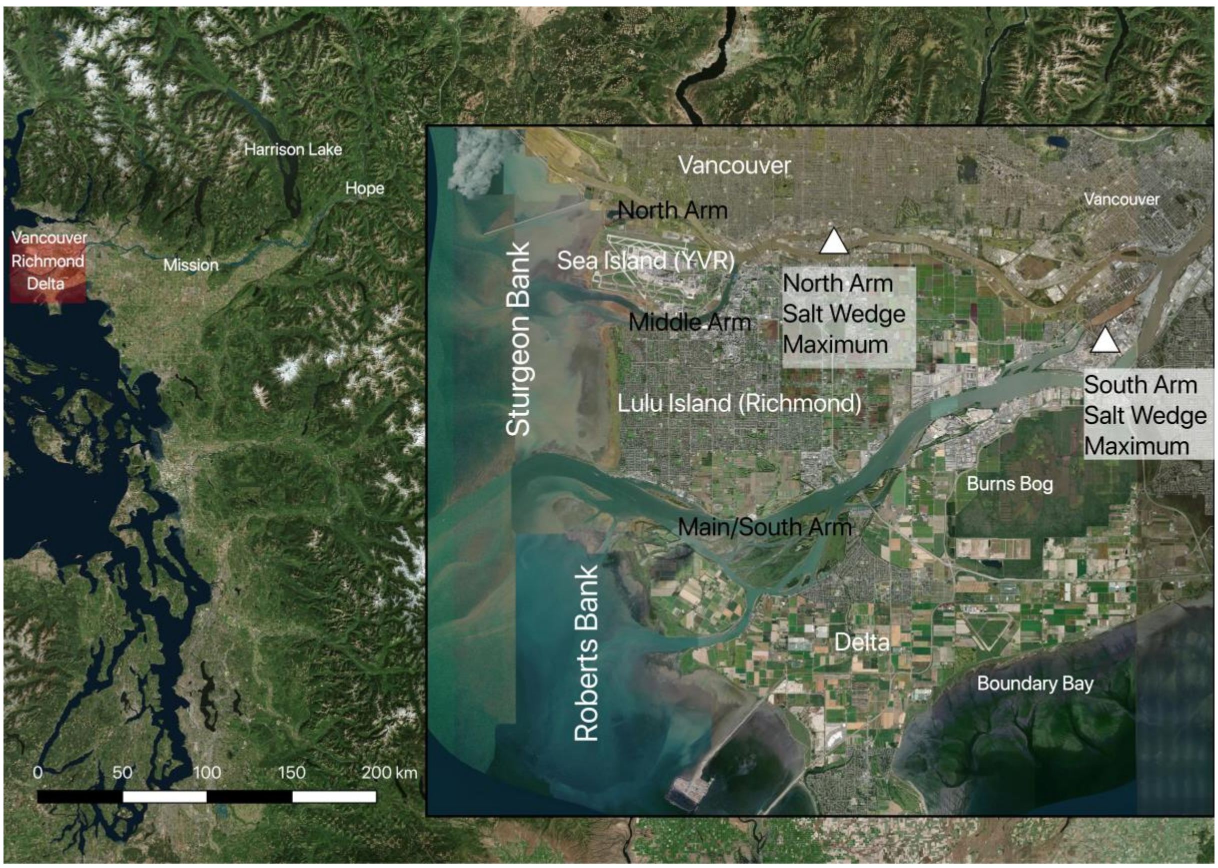

Figure 1.2. Fraser River estuary with mixing zones and maximum reaches of salt water influence in North and South Arm distributaries, 2018.

1.3.2. Biological Significance

The FRE is a globally significant centre of biodiversity and critical component of the ecology of the Pacific coast of North America. This importance is recognized through several national and international designations, most significantly an area of 20,682 ha of FRE delta was designated as a Ramsar Wetland Site under the UN Convention of Wetlands of International Importance (Ramsar 1982; 2012; WHSRN 2004; IBA 2018). The highly productive network of marshes, mudflats and tidal waters is centrally located along the Pacific flyway and is recognized as critical habitat for millions of migrating birds. Somewhat less conspicuously, hundreds of millions of migrating juvenile salmon (over 50% of British Columbia's total production) spend anywhere from a couple of days to months rearing in the estuary as they disperse to marine environments (Adams and Williams 2004).

The Fraser River system supports all seven of the local species of *Oncorhynchus* and contains some of the largest runs and highest diversity in stocks of any system in the world. Production of Chinook in the Fraser River is historically the largest in western North America and is made up of genetically distinct populations that are grouped for management based on combinations of their diverse exhibition of life histories and run timing (DFO 1995). There are three broad life history patterns or 'Types' including, 'Immediate', 'Ocean-type', and 'Stream-type' that are based on rearing behavior after emergence (generally occurring from March to late May and peaking from late April to May). These type-patterns are also indicative of marine migration routes and distributions (DFO 1995).

The 'Immediate' type is a distinct and rare form of 'Ocean-type' Chinook that travel directly to the estuary as fry after immergence (DFO 1995). A single stock, made up of Harrison River and transplant populations, form this group. This is the largest Chinook stock in the Fraser River and Canada. Immediates largely use the southern migration route exiting the Salish Sea through Juan de Fuca Strait but tend to remain in southern BC playing an integral role in the local ecology of the region. Ocean-type stocks originate mostly from the Shushwap Lake watershed and rear in freshwater for 60-150 days before entering the estuary as smolts. This type migrates through coastal waters as far as south east Alaska through the northern Johnstone Strait route. Stream-types are usually associated with upper reaches of the Fraser and North Thompson tributary and rear in freshwater habitats for one year before entering the estuary and marine environments as yearling smolts in their second spring of life. This type heads for the offshore waters of BC and Alaska, mainly utilizing the southern route (DFO 1995).

1.3.3. Tidal Marshes

One of the important natural resources of the FRE are its remaining tidal marshes (Schaeffer 2004). These systems are both direct contributors to detritus-based food webs and sites of extensive detritus trapping and decomposition (Hood 2018). As the marsh landscape floods under tidal influences, fish gain limited access and feed on the invertebrates in various life-stages that live and die in the vascular wetland vegetation (Hood 2018). In addition to productive foraging opportunities, tidal marsh systems provide corridors and refuge along migratory pathways for juvenile Pacific salmon (Bottom 2015). Particularly important marsh corridors are Lyngy's sedge (*Carex lyngbei*) dominated tidal marshes that fringe distributary channels and sloughs in tidal flood plains and deltas (Bottom 2015). These marshes are submerged partially for approximately half of most tidal days and provide sheltered corridors for movements throughout the estuary.

Tidal marsh development occurs along the drowned river valley's former flood plain. This area has transitioned over geological timescales, to an estuarine embayment (Gonor et al. 1988). As velocities slow and mud and sand are deposited from fluvial channels and marine environments, elevations rise, and vascular vegetation is able to establish (Adams and Williams 2004). This vegetation further slows velocities, stabilizes sediments, raises elevations and expands suitable area for plant colonization and establishment. Hutchinson (1982) described plant communities of Lulu Island foreshore marshes and delineated communities into three elevation zones of successional sequence that is often used today: 1.) The Low Elevation Zone is immediately above unvegetated tidal flats and is dominated by *Schoenoplectus pungens* and *Bolboschoenus maritimus*. 2.) The Middle Elevation Zone is dominated by *C. lyngbei*, *Triglochin maritimum*, and *B. maritimus* and the 3.) The High Elevation Zone community dominated by *Agrostis exarata*, *Distichlis spicata* and *Typha latifolia* (Hutchinson 1982; Adams and Williams 2004). These maritime community compositions are driven largely by elevation and its relation to inundation and salinity levels, however, sediment size, moisture, herbivory (particularly by Canada geese, *Branta canadensis*) and plant competition (e.g. invasion by introduced species) are also thought to have strong effects on community assemblage and structure (Adams and Williams 2004).

1.3.4. Marsh Tidal Channels

Marsh tidal channels are important geomorphic wetland features of the estuary (Hood 2002a; 2002b; 2007a). These dendritic waterways taper as they extend from wide mouths to distal terminal branches of high marsh areas (Levy and Northcote 1982). The geomorphological characteristics of tidal channels are regulated by processes that dissipate tidal energy, but tidal prism and freshwater inflow are also factors (Coats 1995). Channels can reach up over 100 m in length, are often deeply incised (.1-3 m), and less than 1 m in width (Levy and Northcote 1982). As conduits for water, sediment, nutrients, detritus, aquatic organisms, and wildlife, these structures essentially connect the nearshore environments and processes to those of the highly productive marsh (Levy and Northcote 1982; Hood 2002a; 2002b; 2007a; Levings 2004; 2016; Ellings et al. 2016). Ebbing tides and marsh topography combine to significantly increase prey availability for fish consumption by trapping, concentrating, and transporting invertebrates from the marsh surface into rivulets and tidal channels (Hood 2018; Simenstad 1983). This retention of drift insects and their resultant availability to foraging juvenile fish, increases as a function of slough system morphometry (Hood 2002a). High nutrient and organic inputs and deposition are a natural function of the low surface velocities and high edge to area ratios of small channels, and distal reaches of higher order channels (Hood 2002a; 2007a).

In addition to increased foraging potential, the deeply incised, sinuous tidal channels or creeks emphasize estuarine conditions thought to enhance growth and survival of juvenile migrants, offering physiological refuge from high velocities of larger order channels and refuge from predation (via deeply incised channels, overhanging banks, vegetative canopy, and imbedded large woody debris) (Simenstad 1983; 2002; Levings 2016).

1.3.5. Large Woody Debris

Large Woody Debris likely plays a variety of dynamic roles in tidal marsh ecology as a primary component of disturbance and habitat structure for plants and animals

(Gonor 1988; Hood 2007b). As LWD is deposited and settles on marsh surfaces, during flood tides and high river stages, it disturbs marsh vegetation, promoting marsh edge through erosional features such as water filled depressions, channels, and rivulets (Hood 2007b). It can further assist in tidal channel formation via aggregation pathways by damming flows between marsh islands and promoting sedimentation deposition between them until they are connected by a blind channel headed by the initial LWD complex (Hood 2016). In addition to contributing to detrital food webs, LWD provides microenvironments and habitat structures for plants and wildlife such as shelter for fish from high velocities and predators, and a substrate for species to spawn on such as Pacific Herring (*Clupea paltasi*) (Shaefer 2014). In undisturbed tidal marsh systems, the delivery and retention of LWD is driven by tidal and fluvial processes (Gonor 1988). These processes both transport and deposit LWD to marshes and determine salinity regimes that drive rates of organic decomposition (e.g. affecting distribution of marine wood-boring animals that decompose wood much sooner than counterparts in terrestrial or freshwater environments) (Gonor 1988).

There are also major anthropogenic drivers of delivery and retention of LWD in Pacific Northwest (PNW) estuaries that have greatly altered the amount and type of LWD in the marsh (beyond the alterations to fluvial and salinity processes). Large scale industrial logging has greatly reduced LWD available for recruitment to fluvial and tidal channels that deliver wood to estuaries. LWD that does enter these pathways are viewed as threats to infrastructure and transportation and managers implement systems of diversion or removal. In 1979 a debris trap was commissioned for the Fraser River between Agassiz and Hope (Thonon 2006). The trap is designed to reduce downstream travel of woody debris during spring freshet and captures 25,000 to 100,000 m^3 of mostly natural origin wood annually (Thonon 2006). This has greatly altered the amount and type of LWD that exists in the FRE.

1.3.6. Marsh restoration

When considering restoration, it is important to recognize that within the FRE and other urban systems there are constraints on what physical and chemical processes can be improved or restored given the irreversible alteration and fragmentation of the greater landscape and different rehabilitation goals and resources of local management jurisdictions (Simenstad and Cordell 2000). Tidal marshes of the lower FRE have been highly modified over the last 125 years by human activities (Shaefer 2004). The construction of dikes, docks, developments, and roads, installation of tide gates and alterations such as dredging, and filling have destroyed habitat and disconnected large areas of emergent wetlands from tidal inundation (Levings 1997; 2016). This has resulted in the loss of 70-90% of productive tidal wetlands and the important transitional and rearing habitat historically utilized by diverse and evolutionarily significant units of salmonids (Levings 2004; Schafer 2004).

The FRE and surrounding areas sustain a human population of over 2.5 million that is projected to grow to 4 million by 2040 Canada (Metro Vancouver 2016). Residential, commercial, and industrial developments and associated uses constantly interact with the natural environments of the estuary and undermine its ability to support the diverse needs of populations of fish and wildlife (Adams and Williams 2004). Environmentally sustainable development within the estuary depends strongly upon the legislative clout afforded by the federal Fisheries Act. The Department of Fisheries and Oceans enforces this legislation. In 1986 its national fish habitat policy and the guiding principle of 'no-net-loss' was adopted and sustained until the shift in 2012 to no ‘harm to fish’ or the productive capacity of fish habitat. Despite this and other legislated protection (e.g. Species At Risk Act, Migrating Birds Act, and Ocean Act), estuarine habitat is continually at risk of port expansions, fossil fuel storage and shipping facilities, lower distributary sediment dredging, and accrual of wrack deposits from logging boon storage that creates anoxic benthic conditions (Kisrtitz 1996).

Wetland creation and restoration, as a highly visible indication of active management, have become increasingly common and accepted offsets for damages and losses sustained by tidal marshes in the FRE (Levings 1997). Controversy surround these efforts, however, as there is great uncertainty in what constitutes a success (Levings and Nishimura 1997; Simenstad and Cordell 2000; Zedler 2000; Lievesley and Stewart 2017). This uncertainty is partly based on a lack of empirical study and understanding of the dynamic linkages between the structure (conditions) and function (processes) of these systems as well as what are relevant timescales for marsh restoration (Simenstad, and Cordell 2000; Zedler and Lindig-Cisneros 2002). Lievesley and Stewart (2017) used ‘native plant coverage’ and ‘area compensated’ as two criteria in their evaluation of past compensation projects in the FRE. Vegetation is recognized as a key indicator of ecological conditions in a restored environment and floristic measurements can be used to document plant succession following the implementation of restoration actions (Zedler 2001). They found that although 65% were rated ‘good’ in meeting target areas, only 50% were rated ‘good’ in native species coverage relevant to reference systems (Lievesley and Stewart 2017).

Success is further clouded due to misunderstandings revolving around tidal marsh function (ecological processes), and structure (ecological conditions) (Zedler and Lindig-Cisneros 2002; Simenstad and Cordell 2000). The linkages between structure and function is crucial as many wetland restoration projects are mandated with the target for functional equivalency between built or restored and natural (reference) systems, while monitoring and success metrics are often structural (Zedler and Lindig-Cisneros 2002). The assumption that equivalent structure implies equivalent function has been suggested as fundamentally flawed in the literature (Zedler and Lindig-Cisneros 2002). A restored marsh’s development often proceeds along complex paths that are difficult or impossible to predict (e.g. time had little effect on compensation success for projects in the FRE) (Lievesley and Stewart 2017). High inter-annual variation and lack of directional change suggest that a trajectory model based on steady recovery of a system’s function with intervened repair of structure in a short time (5-10 years), could be misleading in the restoration of these systems (Zedler and Lindig-Cisneros 2002).

Landscape studies and site-specific assessments that consider issues such as connectivity, heterogeneity, disturbance and access on relevant time-scales and incorporate life-history stages of a population or species are necessary to further understanding of how best to restore wetlands and specifically tidal marsh channels (Simenstad et al. 2002; Zedler and Lindig-Cisneros 2002). In combination with site-specific long-term assessments, manipulative experiments are required that test for specific functional linkages to structural elements in marsh tide channel habitats. Restoration treatments allow for manipulations of entire ecosystems and with careful design, provide rare opportunities to test theories used in restoration ecology (e.g. community assembly) and improve future practice of ecological restoration (Hobbs 2007). However, the dynamic nature of estuarine environments and migratory life-history of many focal species make rigorous experimental design difficult, costly, and resource intensive (Simenstad and Cordell 2000; Roegner et al 2008).

Estuarine ecological restoration and mitigation efforts in the PNW are often based on the recovery of brackish marsh systems due to the disproportionate historic loss of these systems, the relative ease at which they can be restored through the removal of barriers to inundation, and their inherent value as contributors to detrital food webs (Simenstad 2000; Rice et al. 2005; Ellings et al 2016). Gregory Hood (2002a; 2002b; 2017a) has been developing the use of allometric scaling in delta islands to predict various metrics of tidal channel geometries and biological communities. This tool can be used for physical geometries and is being tested as tool for biological relationships as well with strong implications for restoration (Hood 2002a; 2002b; 2017a).

There is strong desire by the public to restore habitat for declining Pacific salmon populations. In the Pacific Northwest, salmon are commercially valuable, cultural and ecological keystone species, and have many populations that are threatened, endangered, or extinct (Garibaldi and Turner 2004). There is also strong evidence to suggest that both the loss of these habitats and their recovery can have an impact on the survival of salmon populations in the Pacific Northwest (Healey 1982; Simenstad et al. 1982; Macdonald et al. 1988; Levings and van Densen 1990; Magnusson and Hilborn 2003; Davis 2019). There have been many attempts at building and restoring marsh and tidal channel habitat for juvenile salmon species in attempts to help their recovery, with mixed results (Kisrtitz 1996; Levings and Nishimura 1997; Simenstad 2000; Simenstad et al. 2002; 1982; 2016; Grey et al. 2002; Rice et al. 2005; Roegner et al. 2008; Ellings et al 2016; Woo et al 2018; Davis 2019)

Chinook as a focal species

Of the anadromous species of Pacific salmon, Chinook use marsh and tidal channel habitats most extensively both spatially and temporally (Levy and Northcote 1982; Healey 1982; Bottom 2016; Levings 2016; Hood 2018). Chinook access the uppermost marsh through the small, distal reaches of tidal channels, are among the last species to exit channels on an ebb and have been documented to show channel fidelity and return to specific tidal channels networks over time (Levy and Northcote 1982; Healey 1982; Hering 2015; Hood 2018). Select Chinook populations experience a protracted residency and utilization of estuarine environments relative to other juvenile species (upwards of 30 days in the FRE) with evidence to suggest that populations have evolved to utilize these environments and their dependency is inferred to be inherent on them for survival (Levy and Northcote 1982; Magnusson and Hilborn 2003; Macdonald et al 1988; Healey 1980; 1982; Davis 2019). The importance of marsh tidal channels is a significant element in the recovery and future resilience of this cultural and ecological keystone species (Levy and Northcote 1982; Simenstad and Cordell 2000; Garibaldi and Turner 2004; Levings 2004; Ellings et al. 2016; Hood 2018; Woo et al. 2018; Davis 2019).

Hood (2018) documented the fish abundance in tidal channels relative to marsh habitats. He found that relative densities averaged 63x higher for Chinook; 19x higher for chum, and 20x higher for three-spined stickleback (*Gasterosteus aculeatus*) in channels compared to marsh. When densities were extrapolated to a landscape scale where marsh area is greatly vaster relative to channel area, he determined chum and stickleback abundance was 1.6x and 1.5x higher for marsh pans (Hood 2018). However, Chinook's strong preference for tidal channel habitats was still present with 2.3x higher abundance in channels. The author posits potential temporal dynamics that could affect these findings (e.g. geese herbivory or seasonal changes in marsh canopy height that limits or improves fish access) (Hood 2018).

Restoration of marsh tidal channel systems using Chinook salmon as a focal species illustrates the aforementioned difficulty in acquiring functional measurements that are relevant and realistically collected on the temporal and spatial scales required (Simenstad and Cordell 2000; Rice et al. 2005; Ellings et al. 2016). Measuring the impacts of restoration on the growth and survival of salmon populations for project evaluation and comparison is challenging. Population densities are highly variable across space and time and are subject to variable outmigration success and adult return rates, both of which are impacted by broad-scale climactic and environmental factors outside of restoration influence (Roegner et al. 2008; Simenstad and Cordell 2000). Levings 2016). Fish sampling data alone cannot determine directional effects of restoration especially in larger watersheds where restoration treatments are small relative to the system. Furthermore, fish sampling data are often structural measurements that fail to illuminate how fish benefit and utilize restored habitat for which more functional measurements are required (Simenstad and Cordell 2000).

Though a manipulative experiment, linking structural and functional elements, are outside the scope and time of this study, the literature does offer alternatives to measurements of function of tidal channels through structural measurements separated into two categories: those of ‘Opportunity’ and ‘Capacity’. Opportunity is described as the spatial and physical metrics of habitat accessibility while Capacity is defined as the biological conditions for prey resources and salmonid growth (Simenstad and Cordell 2000; Simenstad 2002). Measuring tidal channel Opportunity and Capacity for juvenile Chinook can be gathered relatively easily and help to guide restoration design, goals, monitoring, and evaluation across projects and systems (Coats et al. 1995; Zeff 1999; Simenstad and Corrdell 2000; Zedler 2000; Simenstad 2002; Roegner et al. 2008; Ellings et al. 2016; Davis et al 2017; 2019; Chirol et al 2018; Woo et al. 2018). For this study I have used metrics of Capacity (fish use, vegetation, water quality, velocity, and LWD) and Opportunity (marsh area and tidal channel area) as measures to evaluate and monitor function of tidal channels before and after restoration.

Chapter 2. Methods

2.1. Study Site

Swishwash Island is a small (55 ha) delta island located at the mouth of the FRE (49° 10' 51.6036'' N, 123° 11' 48.7896'' W). The island is currently managed as a conservation area by the current landowners, the Nature Conservancy of Canada (NCC), within the traditional unceded territories of the Musquem, Tseil-Waututh, Tsawwassen and Sto:lo First Nations. The island is positioned between two larger, developed islands: Sea Island and the Vancouver International Airport to the north and Lulu Island and the City of Richmond to the south. Low-lying areas of the island are tidally flooded with brackish waters, dividing it into East and West Swishwash Island.

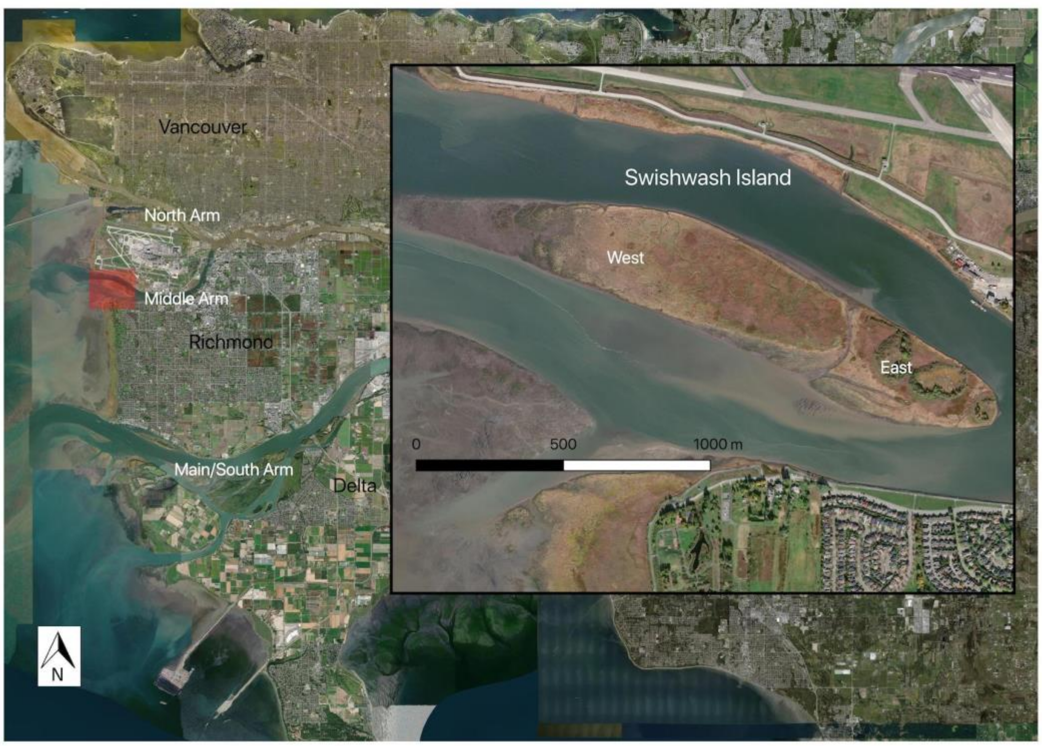

Figure 2.1. Study site Swishwash Island, delineated into East and West Swishwash Islands, in the Middle Arm of the Fraser River estuary, British Columbia, Canada, 2018.

2.1.1. Impacts

Middle Arm

The Middle Arm is heavily urban and developed distributary reach of the Fraser River (Figure 2.2). This distributary is the smallest of four distributary channels and delivers 3-5% of the Fraser River's discharge into the Salish Sea. The Middle Arm is no longer used for commercial or industrial shipping and is only opportunistically dredged by the Port of Metro Vancouver. As a result, most vessels harboured in the Middle Arm transit the river through the North Arm and there is very little recreational or commercial boat traffic that frequent water near Swishwash Island. A Department of Fisheries and Oceans (DFO) Coast Guard base is located directly across from Swishwash Island and routinely drills its vessels including a large hovercraft that produces a substantial wake (approximately 1m). There are also a large number of sea-planes that use the waters immediately upstream of Swishwash as an aquatic runway and contribute to the significant level of low flying air traffic associated with the Vancouver International Airport (YVR).

YVR is a 'Salmon Certified' airport and has mandated water quality standards and monitoring as a part of this certification. Fueling and de-icing practices have been identified by the airport as potential stressors to connected waterways (i.e. the North and Middle Arms of the FRE) and they have implemented a variety of measures to mitigate these (e.g. rain gardens and contaminant threshold water quality monitoring) (YVR Environment Management Plan 2014). Rubber particulates and associated chemicals have recently been identified in the literature as a major stressor and mitigation measures and monitoring for this should be implemented in addition to other potential contaminants (Copper, Cambium, hydrocarbons) expectantly produced from the runways and parking lots (Walsh et al. 2005; Peter et al. 2018).

Figure 2.2. Urbanized landscape of the international Vancouver Airport and City of Richmond surrounding Swishwash Island in the Middle Arm of the Fraser River estuary, 2018.

Historically, Sea and Lulu Islands were densely filled with sloughs, tidal channels, and marsh lands (Figure 2.3). Today the surrounding landscape has been replaced by dense urban, commercial, and industrial development. The remaining tidal marsh in the Middle Arm consists of a patchwork of small fringe marshes (many of which are unmonitored built offsets) that exist on the toes of dykes protecting development infrastructure (Figure 2.2). Floating infrastructure, (e.g. docks and barges for wood and spoil processing, boats and planes, fueling stations, and float homes) leach contaminants and excess nutrients into water and sediments. They also disturb plant photosynthesis through structural shading. These disturbances further fragment and impede on the ecological integrity of these remaining marsh lands.

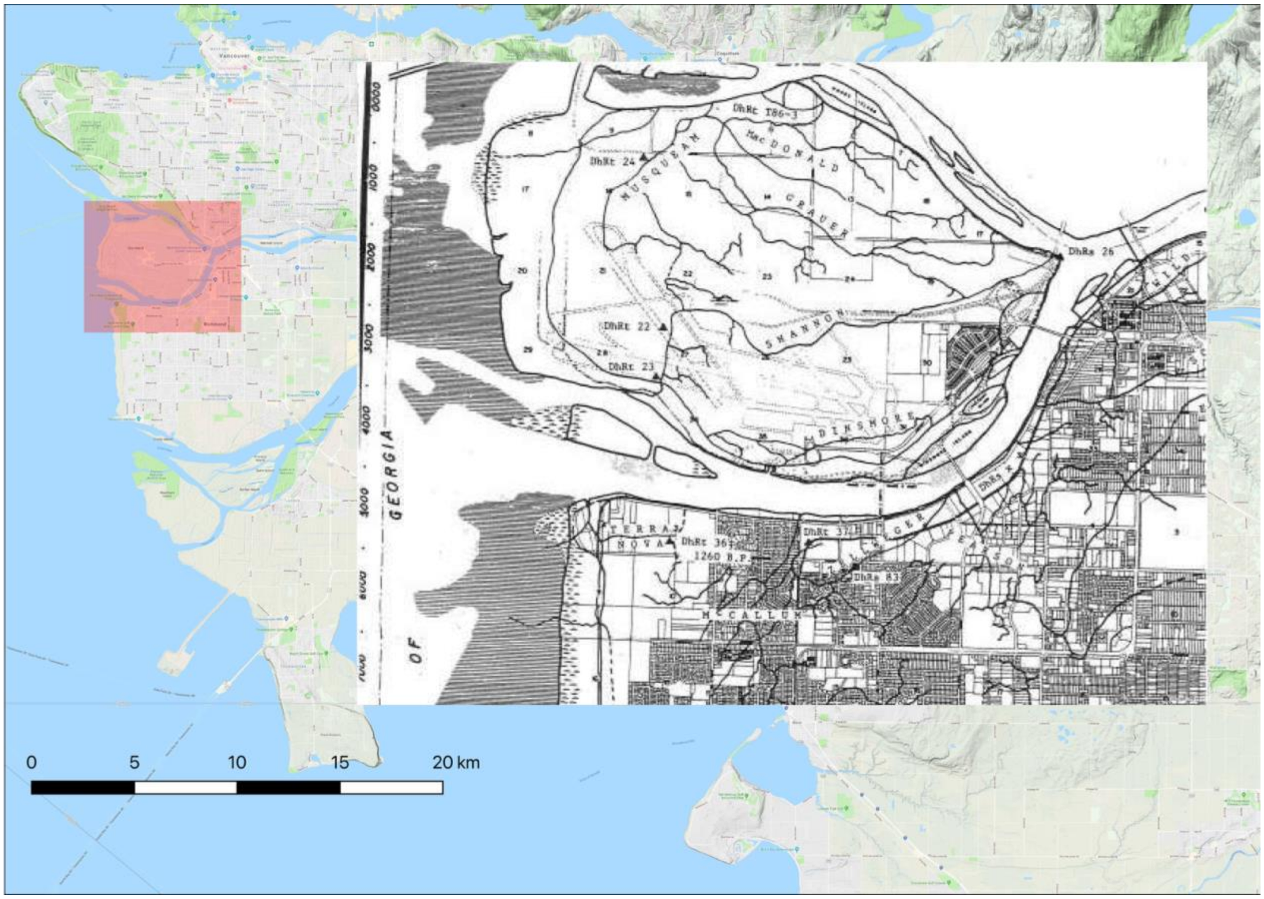

Figure 2.3. Historic (19th Century) tidal channels and sloughs of Sea and Lulu Islands mapped by archeologists in 1987 that were mostly lost to road networks and drainage structure by the onset of the First World War (Richmond Archives 2019).

Swishwash Island

Unlike many islands within the FRE's delta, Swishwash Island is not diked. It has nonetheless undergone significant anthropogenically driven changes over the past century, with persistent effects impacting biological and geomorphological structure and processes. A salmon cannery, built in 1890, operated in various capacities on the East Swishwash Island complex. Historical aerial images and a fire insurance application show a cannery building and several small outbuildings, a dock, tent structures and what appears to be a small berm of sand and aggregate to protect seasonal tent housing from flooding along the north marsh edge (Carter 2002). The Sea Island cannery was originally built and owned by Alexander Ewen and Daniel Munn under the name 'Bon Accord'. It was commonly referred to as 'Munn's' cannery as there was already a Bon

Accord Cannery in Port Mann (City of Richmond Archives, accessed Feb. 2019). The Middle Arm surrounding the cannery was described as 'shallow' with only low draft vessels being able to transit the waters. The insular processing plant changed hands a number of times over the years and shifted between capacities as a cannery, cannery labor housing, fish site, and there is record of it being propositioned as a saw mill (Richmond Archives 2019). It was eventually bought by the New Jersey company BC Packers. In 1918, as was common for canneries, a fire broke out and most of the infrastructure burned to the ground. With the advents in refrigeration technology and decline in fisheries leading to the collapse of the canning industry there was little motivation for the owners of BC Packers LTD (BCP) to rebuild. The island was acquired by the NCC in effort to protect remaining habitat in the FRE.

Figure 2.4. Relic footprint of Sea Island Cannery and current dredge spoil distribution that are persistent stressors on East Swishwash Island, 2018.

Historically the geomorphology of East Swishwash was much different than today. A complex of smaller islands with significantly more tidal channel and marsh habitat existed. The geomorphology of the smaller islands suggests a trajectory that would potentially see them joined with major channel distributaries between them (Hood

2016). This dynamic process was likely interrupted with what was the most dramatic shift to the island's geomorphology and ecology. In the 1930's through to the 1940's a series of dredge spoils were deposited on the East Swishwash Island complex under ownership of BCP (Figure 2.5). It is unclear whether these dredge spoils were deposited deliberately to raise elevations of the island for some unknown venture (e.g. sawmill) or simply as an avenue for spoil storage or disposal. It is evident these dredge spoils altered the topography and sediment distributions and raised mean elevations approximately 2 m across roughly 2.6 ha of marsh habitat (Carter 2002). Marsh vegetation was buried and inherently unable to recolonize as marsh plant distribution is highly controlled by elevation, inundation, and sediment type. Existing tidal channels were either directly infilled or modified by close proximity to the larger, sandy sediments. The in-filling created drier, more upland habitat areas on the eastern portions of the islands that were resistant to tidal inundation and exchange.

Figure 2.5. Historic (1930) East Swishwash Island geomorphology (black and white) compared to present day, 2018.

Note. Current geomorphology of East Swishwash with dredge spoils (circled in blue) and a point (black stars) to compare with the inset historical geomorphology taken pre-dredge spoil deposition (1930). (UBC Collections 2018).

2.1.2. Current Conditions

Since acquiring the property NCC has largely left the area to re-wild. Today, East Swishwash Island exists within an alternative stable state with very different biological communities existing on raised elevations and nutrient poor soils. Thin rings of soil surrounding the dredge spoils at their outer edges have been enriched by flooding and now support a dense vegetation mix of mostly invasive species including, cottonwood (*Populus trichocarpa*), scotch broom (*Cytisus scoparius*), and Himalayan blackberry (*Rubus armeniacus*). With the exception of a few grass and sedge species such as the native big-headed sedge (*Carex macrocephala*), invasive reed canary grass (*Phalaris arundinacea*), and thin patches of cryptogamic of mosses and lichens, little grows in the center of the dredge spoils. Conifers like Douglas-fir (*Psuedotsuga menziesii)* and Sitka spruce (*picea sitchensis)* have been planted by NCC staff and volunteers with little success in the dry, nutrient poor soils (Figure 2.6).

Public access to the island is limited to volunteer events that largely involve invasive species removals and native species planting. Bio inventories that identify and map the species and their distributions have also been implemented as part of the island's management plan. These inventories have documented wildlife use of the spoils including extensive use by great blue herons and denning coyotes (*Canis latrans*). Occurrences of birds of prey such as bald eagles (*Haliaeetus leucocephalus*), short-eared owl (*Asio flammeus*) and northern harrier hawks (*Circus hudsonius*) have also been recorded (Carter 2002). The insularity and limited access of the site is a rarity within the lower mainland and estuary and any habitat patches remaining in the urban environment are heavily utilized by wildlife species as a safe haven. These alternative ecosystem values to nesting birds and wildlife require further ecological assessment of cost/benefit ratios. Based on the management and popular media surrounding the island there is a shifted baseline in public understanding and attempts to excavate soils, of what is viewed as a 'pristine' environment, to elevations conducive to flooding could potentially trigger backlash without a communication strategy based on science (Carter 2002).

Figure 2.6. Typical interior view (west) across the largest dredge spoil deposited on East Swishwash Island with nutrient starved Douglas fir and Sitka spruce trees, 2019.

2.2. Study Design

2.2.1. Near Field

Three channels were chosen on Swishwash Island as Near Field reference sites. The island was stratified into eastern and western Swishwash based on historic disturbance. Channels were selected as closest in size to those being sampled at other locations throughout the FRE currently and historically and typically ranged from 1-3 m in width at the mouth. There were three total candidates in the eastern strata and six in the western strata of Swishwash Island. Due to constraints in resources only three channels could be sampled and assessed in total. I selected two from the west strata away from the dredge piles and one from the east strata, situated between two dredge piles that had developed since the disturbance. The east channel was selected for exploratory testing for a spoil proximity effect. Candidate channels were assigned a number and randomly selected using Excel software.

2.2.2. Far Field

Six additional tidal channels were adopted from an ongoing larger study in four tidal channel complexes throughout the Lower FRE. Two of these complexes are in the North Arm located north of the study site and two complexes south of the study site on the northern and southern ends of Sturgeon Banks. These channels provided information on some of the variability that existed across sites in tidal channel water quality and fish communities.

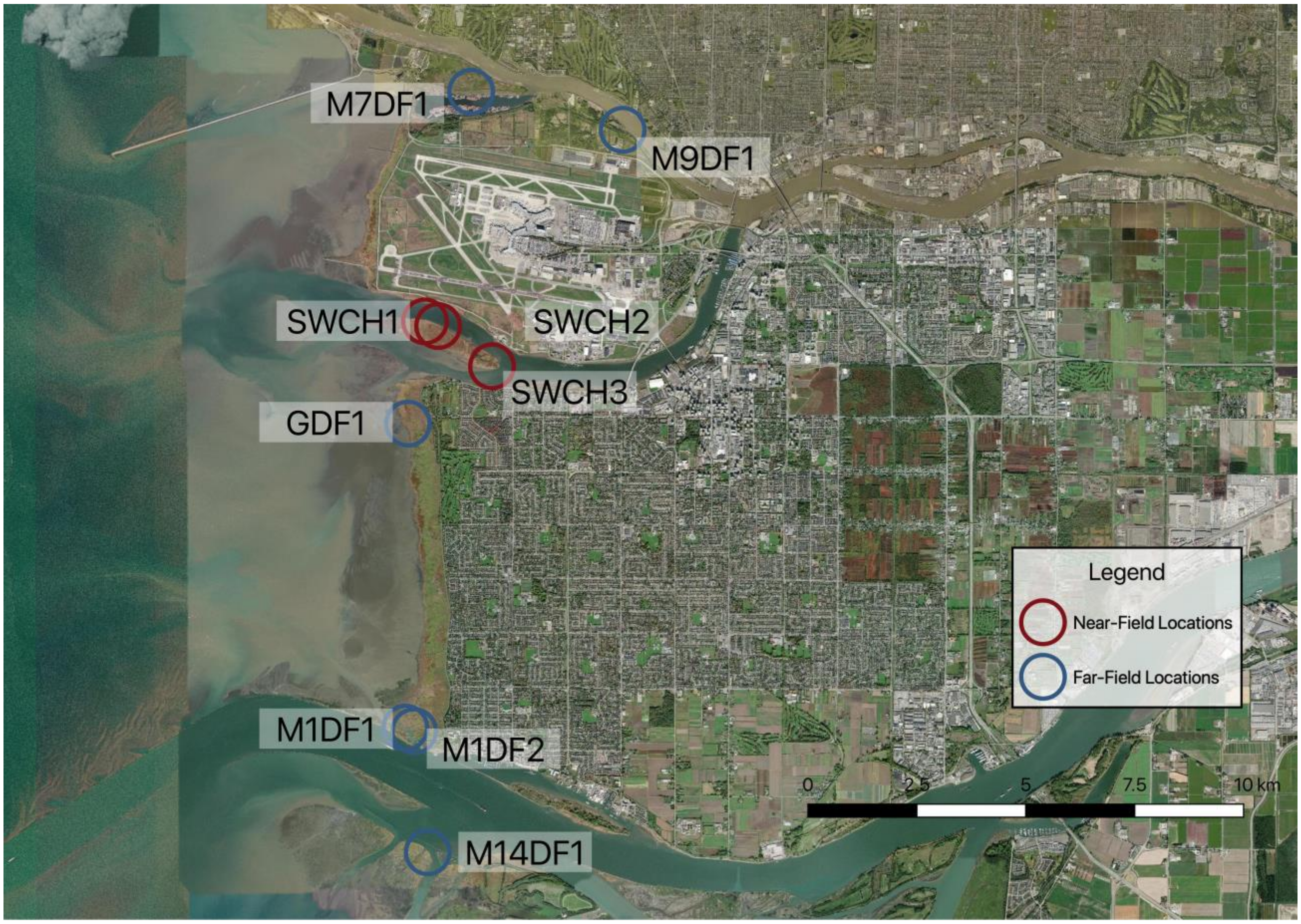

Figure 2.7. Near and Far Field reference channel locations for 2018 fish and water quality sampling.

Note. See Table 1. for channel locations and code names.

Table 1. **Channel code names and locations for Near and Far Field Tidal channels of the FRE listed in order from North to South that were sampled for this study in 2018.**

Code	Name	Lat.	Long.	Arm
M7DF1	Macdonald Slough (Far)	N49° 12.831'	W123° 11.409'	North
M9DF1	Macdonald Beach (Far)	N49° 12.529'	W123° 9.517'	North
SWCH1	Swishwash Channel 1 (Near)	N49° 10.591	W123° 11.578"	Middle
SWCH2	Swishwash Channel 2 (Near)	N49° 10.941'	W123° 11.775'	Middle
SWCH3	Swishwash Channel 3 (Near)	N49° 10.373'	W123° 11.792'	Middle
GDF1	Grauer Lands (Far)	N49° 10.156'	W123° 12.174'	Middle
M1DF1	Garry Point 1 (Far)	N49° 7.698'	W123° 12.205'	South
M1DF2	Garry Point 2 (Far)	N49° 7.670'	W123° 12.097'	South
M14DF1	Westham Island (Far)	N49° 6.690'	W123° 11.929'	South

2.3. Fish Sampling

A small modified fyke net, 1 x 1 m with 2.5 m long wings on each end and 0.65 cm mesh, was deployed in three Near-Field channel locations on Swishwash Island, and six Far-Field channel locations throughout the lower Fraser River estuary (Figure 2.7). Fixed locations were established as near to channel mouths as possible while still allowing for the best fit and longest submergence of the fyke net in these small tidal channels. The fyke is placed in the channel with wings staked to the sides of the channels creating a barrier that acts as a funnel as the tide drops and fish attempt to enter, disperse through, or exit the channel (Figure 2.8).

Figure 2.8. Typical small tidal channel with fyke net set in FRE. Wings are staked to the channel bank and are equipped with float and lead lines to funnel fish into the trap, 2018.

Nets were deployed at high slack and left until water levels reached 0.4 m or at 1.5 hours (whichever came first) on high-high tides of a mixed semi diurnal tide cycle. Channels were sampled at least twice a month from May-August as per the recommendations made by (Roegner et al. 2016). My sampling loosely followed established methods commonly used to capture juvenile salmon in this region (Levy and Northcote 1982). The method outlined in these studies was modified due to findings from a recent PIT tag study of rearing Chinook in the Cowichan River Estuary that found juvenile Chinook reside in channels for longer into the tide cycle than other salmon species, yet exit channels at approximately 0.5 m water levels (Hering 2015). Additionally, up to 20% of Chinook enter the channel during the ebb, limiting the functionality and efficiency of a one-way net left in channels until dry (Hering 2015). The fyke net has two openings and two sets of wings on upstream and downstream ends of the net box to catch fish entering the channel and exiting. Set times were recorded to help standardize catch rates against effort at all fyke locations.

Beach seining was conducted in the Middle Arm intertidal marsh areas adjacent to Swishwash Island. We used a 20 m long x 3 m deep beach seine with 6.3 mm stretch mesh deployed from a small boat using the round-haul method (Greer et al.1980; Levings 2016).

Fish sampling was conducted as a part of the Raincoast Fraser River estuary Connectivity Project and Study and under the standards and animal ethics of University of British Columbia Animal Care Committee and Canadian Council on Animal Care. Technicians were trained to keep fish in dark buckets with cool, aerated estuarine water. Fish were netted and gently placed in fish viewers for depth and FL measurements then placed in another oxygenated bucket before being released to where they were captured. This process was done as quickly as possible with minimal handling to reduce stress. A small subsample (n = 75) of Chinook was lightly anesthetized and a small tissue sample (caudal fin) was collected for DNA analysis. Fin clip samples were collected using the Pacific Biological Station's (PBS) DNA sampling protocol and stored on Whatman sheets. Whatman sheets were then submitted to PBS for microsatellite DNA analysis and the identification of juvenile salmon to the population or Conservation Unit level. Samples were stratified by fish-type then randomly sampled within; however large obvious stream-types were often selected producing a bias.

Analysis

Fork lengths (FL) of Chinook captured via beach seine on marsh edges adjacent to Swishwash Island on Sea and Lulu Island and fyke nets in Near and Far Field channel habitats from May-July were plotted using size frequency histograms using R Software and packages. Size bins were set at 10 mm frequencies. After plotting various size frequency histograms of Chinook, groups of stream types were removed from the data to achieve normality in distribution. Normality was qualified plotting quantiles and data in box plots with jitter. Statistical relationships of the mean fork length (mm) of juvenile Chinook salmon sampled from Near Field, Far Field, and Beach Seine locations for the months of May, June, and July were assessed using a one-way analysis of variance (ANOVA), followed by Tukey's test, using R (V.0.99.484, RStudio, Inc.; www.rstudio.com). A significance error rate of 5% with 95% confidence intervals was used for all analyses.

As sampling intensity differed throughout the season (May-August) and during sampling, a Catch Per Unit Effort (CPUE) standardization was used. Each fish sample was divided by the time (minutes) the net was set during the sample event of its capture to allow for comparison of relative abundances between channel locations. This CPUE was then plotted with months for Swishwash Island's Near Field channels to create a time series for the sample period.

2.4. Water Quality

Water quality measurements (temperature, salinity, dissolved oxygen, pH) were taken using a YSI Professional Plus multi parameter meter during fish sampling at both Near-Field and Far-Field locations. Temperature and DO have been graphed using R software relevant to Chinook rearing and estuarine thresholds from the literature.

2.5. Vegetation

Two transects per channel were established to estimate dominant plant communities for various elevations. Transects ran parallel to channels and perpendicular to main stem. A random number was generated between 1-10 m to determine a start point for transect away from marsh leading edge. After start location and heading determined, systematic sampling commenced with 20 m intervals. Every 20 m a random number would be generated between one and five to determine placement of the 1x1 m quadrat perpendicular from transect line away from channel; a second number would then be generated for a number between 5 and 20 to determine location of second quadrat. At each sample location, basal percent cover of species was determined to the nearest 5% and maximum stem height was measured.

Vegetation sampling and monitoring was designed to quantify changes in species percent cover with elevational gradient, identify any red-listed species, and determine invasive species present and coverage relative to native species. Sampling was concentrated on transects proximal to expected changes and for comparability between sites by targeting portions of the site with similar hydrology. Transects were also used to ground truth remote classification of vegetation communities.

2.6. Velocity

Velocities were gathered using a Hach FH950.0 hand held flow meter two hours into a 3 m tidal ebb at a suitable location (representative of reach) as close to channel mouth as possible at all Near-Field channels. A meter tape was run across channels and widths were divided by ten. Three Hach readings were taken 10 cm below the surface and averaged for each of the 10 increments. This was repeated 30 cm from the channel bottom and again in the middle of the water column. Readings were averaged for a surface, bottom and center column velocity.

2.7. Large Woody Debris

For estimates of LWD I walked each Near-Field tidal channel and estimated active LWD percent coverage per 100 m reach. This was done for three reaches for each channel. LWD was classified as greater than 2 m long and 10 cm in diameter.

2.8. Geomorphology

Using historic and current image data sets I quantified the amount of tidal channel and marsh habitat for historic and current Swishwash Island. I used this data to create an allometric scale that I then used to conservatively estimate how much tidal channel habitat to excavate with the removal of dredge spoils on East Swishwash Island. I included major (>3 order), minor (<3 order) channel lengths (perimeter/2) and channel areas. I also calculated channel density (Total Channel Area/Total Marsh Area) using the QGIS Geometry tool (version 3.4.2 Madiera).

Historical

I acquired national historic imagery of Swishwash Island from 1930 and 1938 from the UBC historical archive collections, that show the island before any spoils were deposited and after one small dredge was deposited respectively (Figure 2.9). I georeferenced this imagery using the georeferencing tool in QGIS. For my analysis of channel geometries for East Swishwash only one island was used for channel extraction. I chose the largest island in the north west quadrant of the small island complex of East Swishwash (Figure 2.9). This island was selected because it had the most developed channel structure, was the largest in size, and had the best resolution.

Channel geometries from this small island provided the minimum estimates of channel densities on my allometrically scaled gradient.

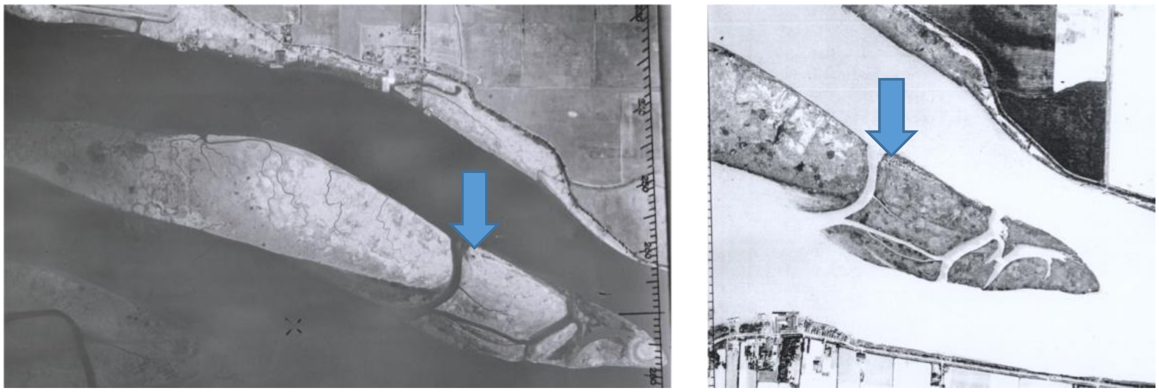

Figure 2.9. Historical (1938 left; 1930 right) images of Swishwash Island in the Middle Arm of the FRE used in analysis. Blue arrows denote the 'Historic' marsh island used for allometric scaling minimum (UBC Collections 2018).

Current

LiDAR data was collected for Swishwash Island from the City of Richmond in July 2017 at 15 points/m. LiDAR was processed and classified by Sean Galway in the BCIT geomatics department. I further cleaned the point cloud data using Cloud Compare software and then used ArcGIS to create a Digital Elevation Model (DEM) (Figure 2.10). I then used QGIS to map current channel features with cm precision and accuracy. I tested my model by loading my raster as a baseline map and channel lengths of East and West Swishwash. Ground truthing results were positive and I was effectively able to map primary and secondary channel structures. Accuracy of channels tertiary and beyond declined but was sufficient for my study purposes (i.e. channel area was not significantly affected). Channels that were not ground-truthed and for which I could not confidently delineate were not mapped to ensure conservative estimates. Geomorphology characteristics were collected for West Swishwash as the maximum channel density on my allometrically scaled reference for channel design.

Figure 2.10. Grayscale Digital Elevation Model of Swishwash Island produced 2018 from City of Richmond LiDAR (2017).

Synthesis

Using a channel density based on a scaling of reference marshes, tidal channels were digitally extended and created using QGIS to create a channel system on East Swishwash. Due to differences in photo quality between historic aerials and DEM raster, channel detection capabilities varied. However, underestimates of channel area potential pose less of a risk (relying on time to produce habitat) than over-estimates (cost of excavation labour wasted by infilling). As the historic images were being used to determine the lower extent of channel density and inaccuracies would only lead to underestimates of my range this bias seemed acceptable. The higher accuracy DEM was used with caution and channels that could not be confidently mapped (small, distal reaches in heavy vegetation) were excluded to ensure this maximum estimate was conservative.

Chapter 3. Results

3.1. Fish Results

Size Frequency

In my 2018 field season, 291 juvenile Chinook were captured in fyke and beach seine nets from May to August at Near and Far Field channels and marsh edge adjacent to Swishwash Island. Results indicated use of tidal channels from May-August is by juveniles predominately in the 40-60mm range with over 60% of individuals sampled in this size class (Figure 3.1.).

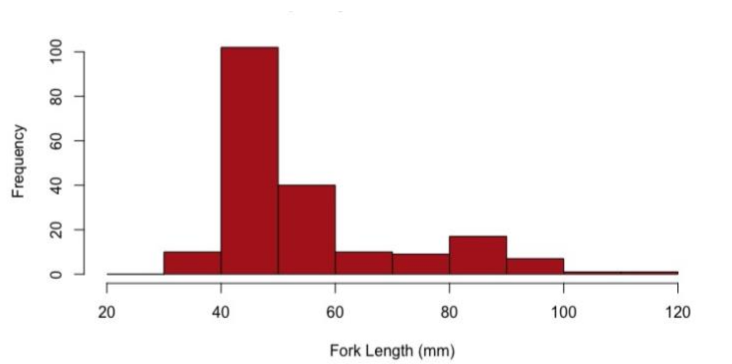

Figure 3.1. Juvenile Chinook salmon fork length size frequency histogram of all channels (Near and Far-Field) sampled in FRE in May-August, 2018 (n = 226).

Juvenile Chinook caught in beach seines had similar size frequencies to those caught in tidal channels however the predominant sizes were more evenly distributed between 40-60 and 60-80mm size classes (Figure 3.2).

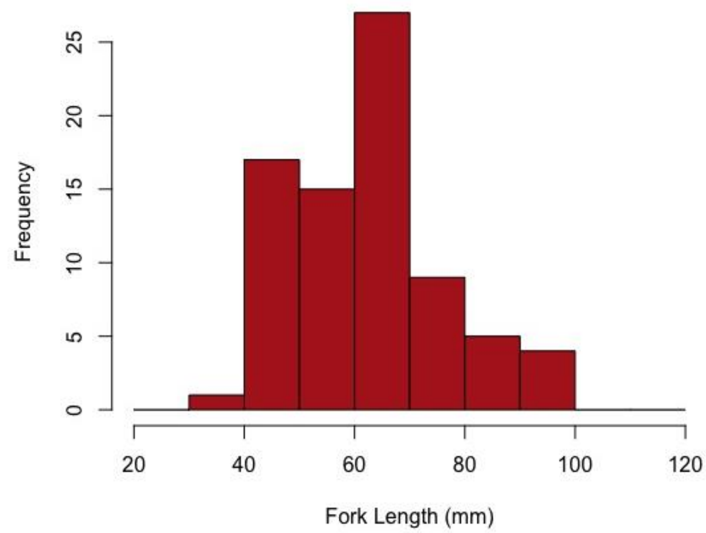

Figure 3.2. Juvenile Chinook size frequency histogram from Middle Arm beach seining locations sampled in May-August, 2018 (n = 65).

FRE channel data was further divided into Near and Far-Field channels and size frequency histograms for juvenile Chinook were constructed to check for major differences between Swishwash Island and FRE Chinook FL (Figure 3.3). The majority of Chinook utilizing Near and Far-field channels still fall within the 40-60 size class though Far-Field channels appear to be developing smaller, secondary mode in their distribution in the 80-100 mm class which is a result of a sampling of yearling stream-type Chinook populations.

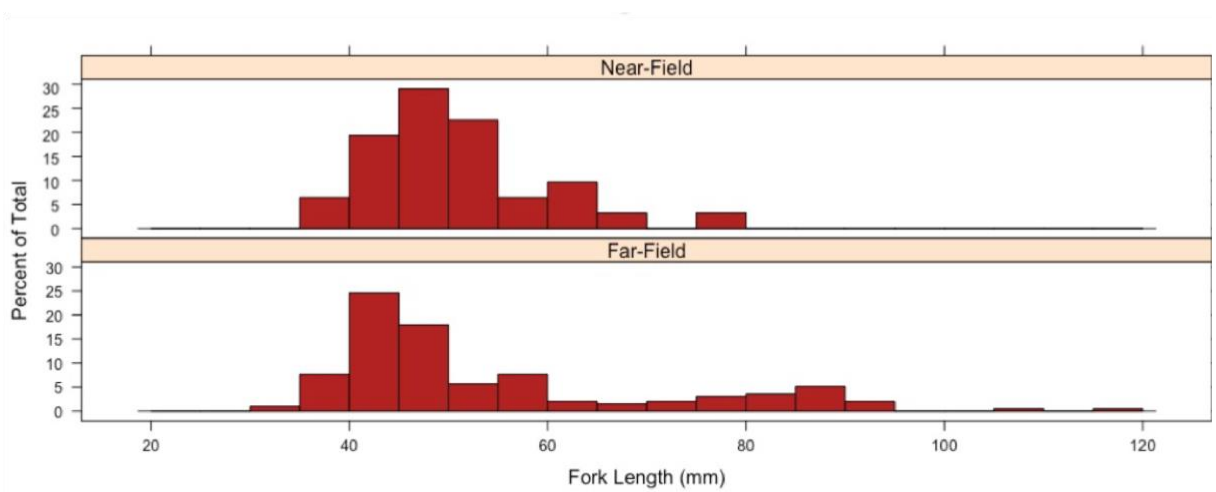

Figure 3.3. Size frequencies of juvenile Chinook captured in Near (n = 31) and Far-Field Tidal channels in the FRE May-August, 2018 (n = 195).

Results indicate that Chinook fork lengths for Near Field channels differed from Far Field channels in May (P = 0.011; df = 137) during the peak of migration and from Beach seined sites for June (P = 0.042; df = 66) and July (P = 0.012; df = 18).

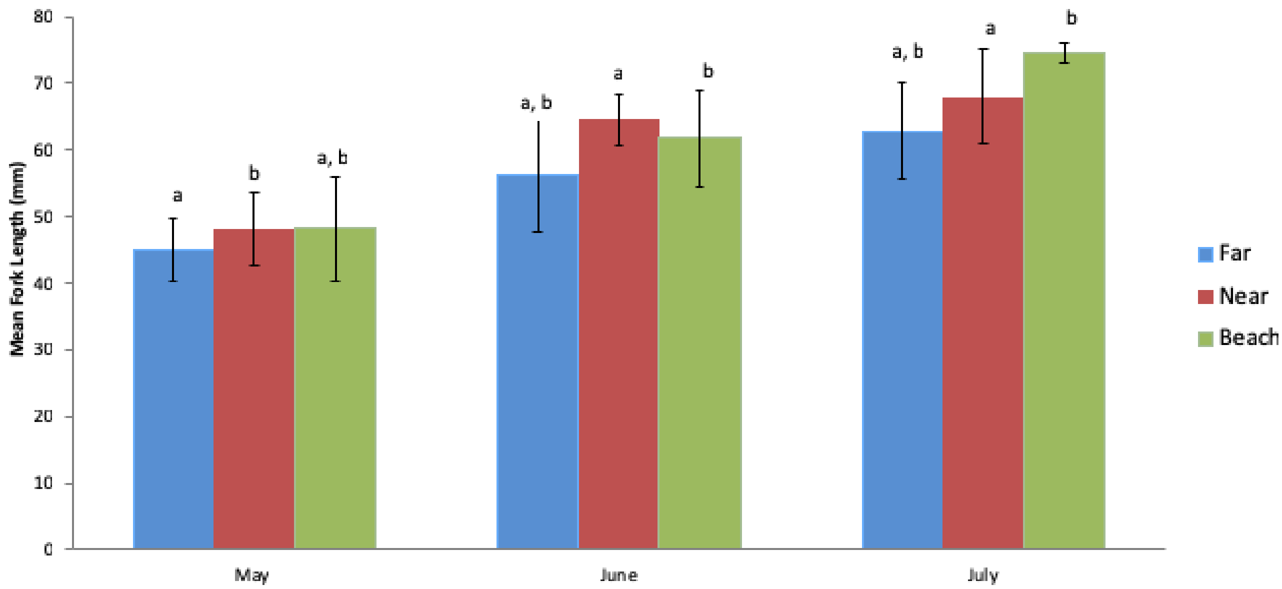

Figure 3.4. Mean (± standard error) fork length (mm) per juvenile Chinook measured each month at Far Field, Near Field, and Beach seine locations in the FRE in 2018. Letters indicate significant differences ($p < 0.05$) according to Tukey's HSD.

Catch Per Unit Effort (CPUE) and genetics

Relative Catch Per Unit Effort (CPUE) across tidal channel sites in Near and Far Field locations show that the highest Chinook CPUE in tidal channels occurred in the channel M1DF1 (Garry Point) adjacent to the FRE's largest distributary, the South Arm (Figure 3.5). Swishwash Channel 1 performed the greatest of the three channels on Swishwash Island however there was no significant different among channel sites for this measure of relative abundance.

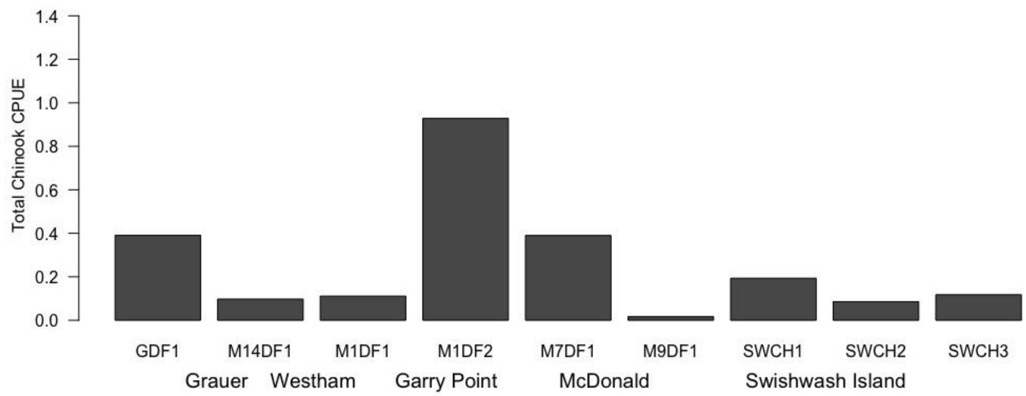

Figure 3.5. Channel CPUE of Chinook for relative density comparison between Near (Swishwash Island) and Far Field (Grauer, Westham, Garry Point, McDonald) channels in the FRE sampled from May-August, 2018.

Results from the PBS genetics lab of submitted genetic data (n = 78) indicate that all three ecotypes of juvenile Chinook utilize tidal channel habitats in the FRE to some degree during their migrations (Figure 3.6). Yearling stream types (n = 20) were biasedly selected for DNA analysis early in the sampling season due to conservation interest in their genetics and easy identification by size and results are not representative of a random sample.

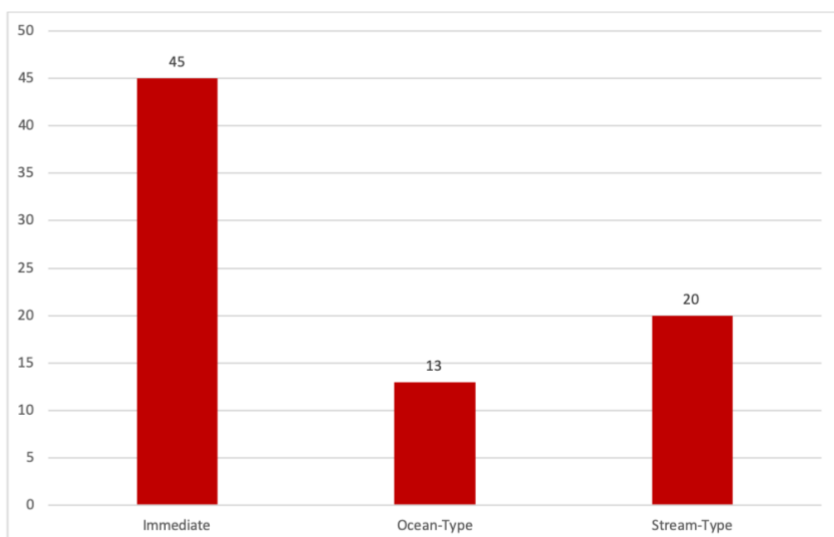

Figure 3.6. Juvenile Chinook life-history patterns (Immediate n = 45, Ocean-Type n = 13, and Stream-Type n = 20) utilizing Near and Far Field FRE channels in May-August, 2018.

Genetic sampling on Swishwash Island occurred only for the month of May due to availability of genetic sampling equipment. Chinook utilizing tidal channels were of three conservation units (CU) from the Lower Fraser River (LFR) and Middle Fraser River (MFR) and included all three ecotypes of juvenile Chinook including one stream type from the Lower Thompson River. See Appendix Table A1 for complete genetic results for all tidal channels.

Table 2. Swishwash Island Near Field genetic data for juvenile Chinook submitted to PBS lab for analysis, 2018 (n = 9).

Date	Site	Stock	CU	Region	Type
May 9	SWCH1	Harrison	3	LFR	Immediate
May 9	SWCH1	Chilliwack, Stave	6	LFR	Immediate
May 9	SWCH1	Chilliwack	6	LFR	Ocean
May 10	SWCH2	Harrison	6	LFR	Immediate
May 10	SWCH2	Harrison	6	LFR	Immediate
May 10	SWCH2	Lower Thompson	13	MFR	Stream
May 24	SWCH3	Chilliwack	6	LFR	Ocean
May 24	SWCH3	Chilliwack	6	LFR	Ocean
May 24	SWCH3	Chilliwack	6	LFR	Ocean

Time Series

Abundances peaked in early May and reduced dramatically as summer and the outmigration of juvenile salmon progressed. A second smaller peak occurred in Channel 3 in mid-June.

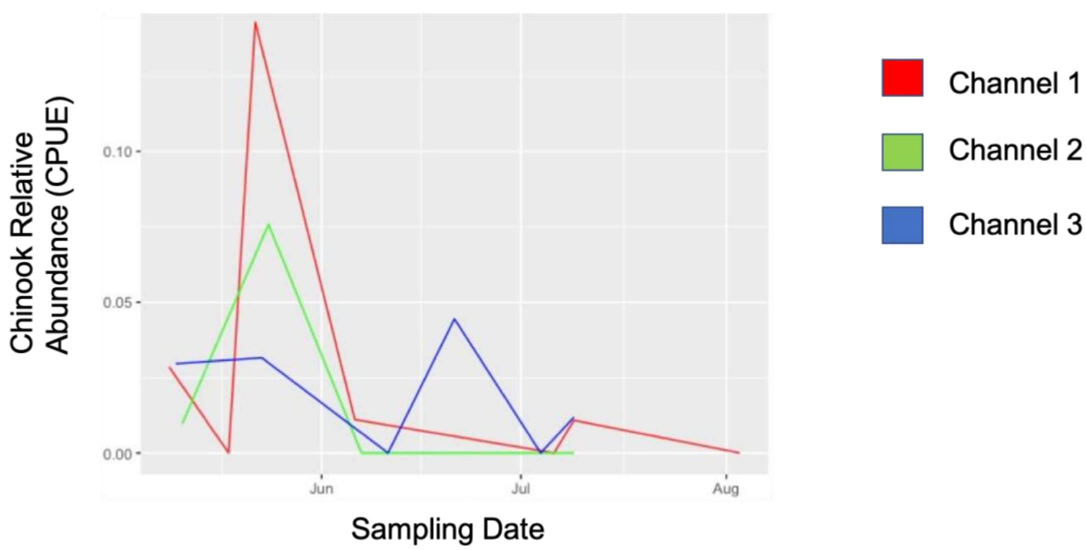

Figure 3.7. CPUE time series of juvenile Chinook salmon use of Near Field channels from May-August, 2018.

3.2. Vegetation

West Swishwash

Vegetation transects on the West Island conformed with previous vegetation classifications in the area (Hutchinson 1982; Adams and Williams 2004). A small low marsh zone of *Bolboschoenus maritimus* and *Schoenoplectus americanus* exists but due to erosion and rapid changes in elevation from sand to marsh it quickly transitions to being dominated by *C. lyngbei* with *Argentina pacifica, Sagittaria latifolia,* and *Triglochin Maritima* as a Middle Marsh Zone*.* Transition between middle to upper marshes occurs at 20-25 m from shoreline adjacent to Channel 1 (25 m) and Channel 2 (20 m). At this level the vegetation structure shifts with *Typha latifolia* becoming more dominant and the canopy height increases. Coherently species become present in high abundance. Purple Loosetrife (*Lythrum salicaria)* and false bindweed (*Convolvulus arvensis*) are present in all quadrats in middle to upper zones on West Swishwash.

East Swishwash

East Swishwash saw a similar distribution adjacent to Channel 3 however dredge spoils caused the transition to high marsh much more rapidly and dramatically. Transects had to be cut short due to an impassible crop of invasive species of cattail *Typha angustifolia* at approximately 40 m. It was in this small transition zone to the upper zone that I found a small isolated stand of Red listed Vancouver Island Beggar Ticks (*Bidens amplissima*) endemic to the region and thought to be extirpated from Swishwash (N49°10.618' W123°11.148').

3.3. Water Quality

Temperature

Temperatures of Near Field channels were similar to those found in Far Field channels with medians of 17 and 15°C respectively, with upper extremes of 20°C (Figure 3.8). An upper threshold of 25°C (red line) was plotted as an upper threshold of mortality and 15°C an optimal based on meta study (Levings 2016).

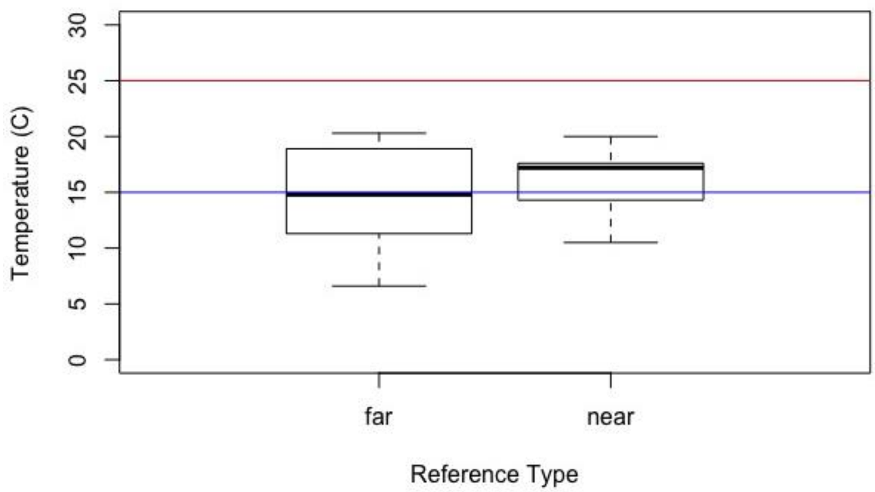

Figure 3.8. **Temperature of channels with optimal and upper threshold ranges recorded in Far and Near Field channels during fish sampling from May-August 2018.**

Dissolved Oxygen

DO in mg/L of Near Fields was sufficient for salmonid needs and exceeded those of Far Fields which suffered from some periodic low concentrations at some of its sites (GDF1). Range of DO and thresholds were plotted (Figure 3.9) with Far Field DO lower extreme and quartile at 5 mg/L.

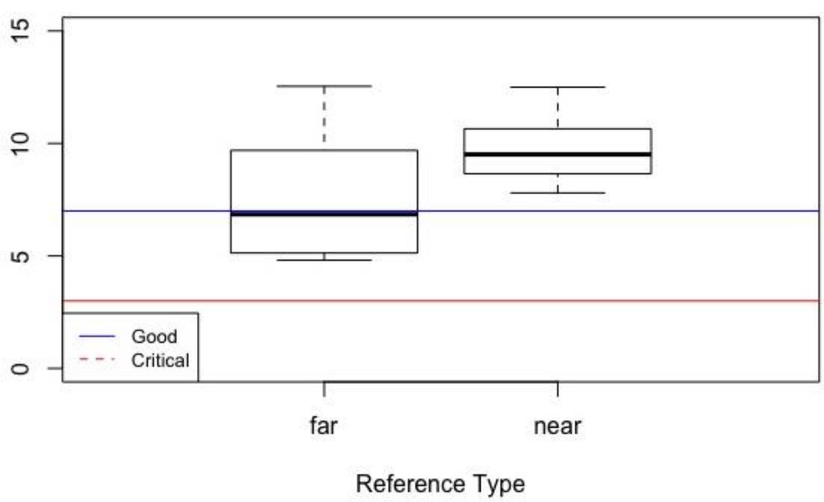

Figure 3.9. **Dissolved oxygen (mg/L) recorded at Far and Near Field channel locations from May-August, 2018 with thresholds indicating good conditions conducive to growth and survival and critical conditions negatively impacting growth, fitness, and survival.**

Salinity

Salinity ranged across sites and season with Near Field channels at Swishwash Island experiencing levels mostly within the 1-5 ppt range (Figure 3.10). Far Field salinities ranged much higher with the highest readings coming from channel sites on Sturgeon Bank and Westham Island in the late summer.

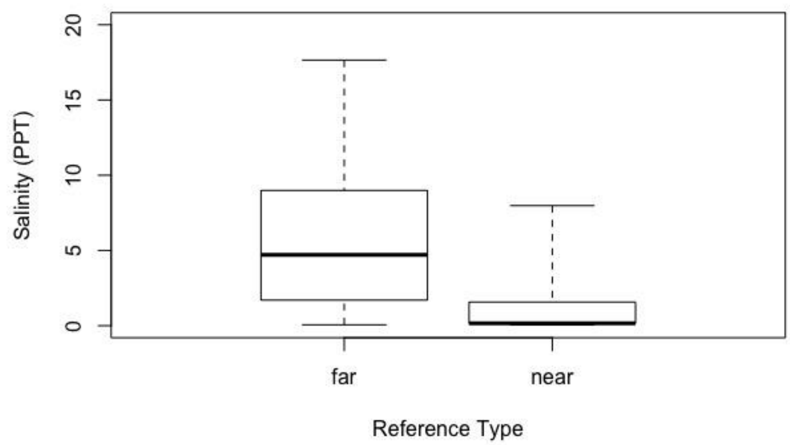

Figure 3.10. Salinity levels (PPT) of Near and Far Field channel locations in the FRE collected during fish sampling period May-August, 2018.

Velocity

Channel velocities collected for Near Field references ranged between .01 m/s and .06 m/s with highest velocities occurring in the center of Channel 2 just below mid-level depths.

3.4. Large Wood Debris

LWD percentages for reaches ranged from 0-85%. Lower reaches ranged from 0-15%, middle 10-35%, and upper 25-85%. Most LWD was transient and lying in or across channels as driftwood. The heads of Channels 2 and 3 were completely filled with wood of various size classes. A minority of LWD was more permanently lodged into channels and promoting scouring, pooling, and meandering. I observed these structures to be generally of natural origin (unlogged) and of a much larger size class than most of the LWD.

3.5. Geomorphology

Analysis of historical imagery shows that the east end of Swishwash Island is eroding with 2.5 ha of eastern edge eroding away since 1938 (Figure 3.11). This is alarming as historically (1930) the islands seemed to be aggrading (Hood 2016; G. Hood, Pers. Comm. 2019).

Figure 3.11. Historic (1930) Swishwash Island marsh structure overlain current, showing a steady recession. East Swishwash Island was the most heavily impacted losing 2.5 ha to erosion, 2018.

The current channel densities (channel area/marsh area m^2) of East Swishwash are well below those expected for a delta island of its size in the FRE as estimated from densities collected in this study (Table 3). The lower range estimate produced from the smaller area island from the historic (1938) East Swishwash complex is 1.75x greater than current densities while the upper range produced by current densities on West Swishwash (2017) is 3.7x greater than what exists (Table 3). I plotted a simple exponential line using the historic and contemporary marsh and channel areas (Figure 3.12). Using the contemporary island marsh area, I determined a total tidal channel area of approximately 1550 m^2 and drainage density of 0.011. This figure is almost 2x that of tidal channel area that exists on East Swishwash currently and is a conservative restoration target for East Swishwash Island if elevations are restored.

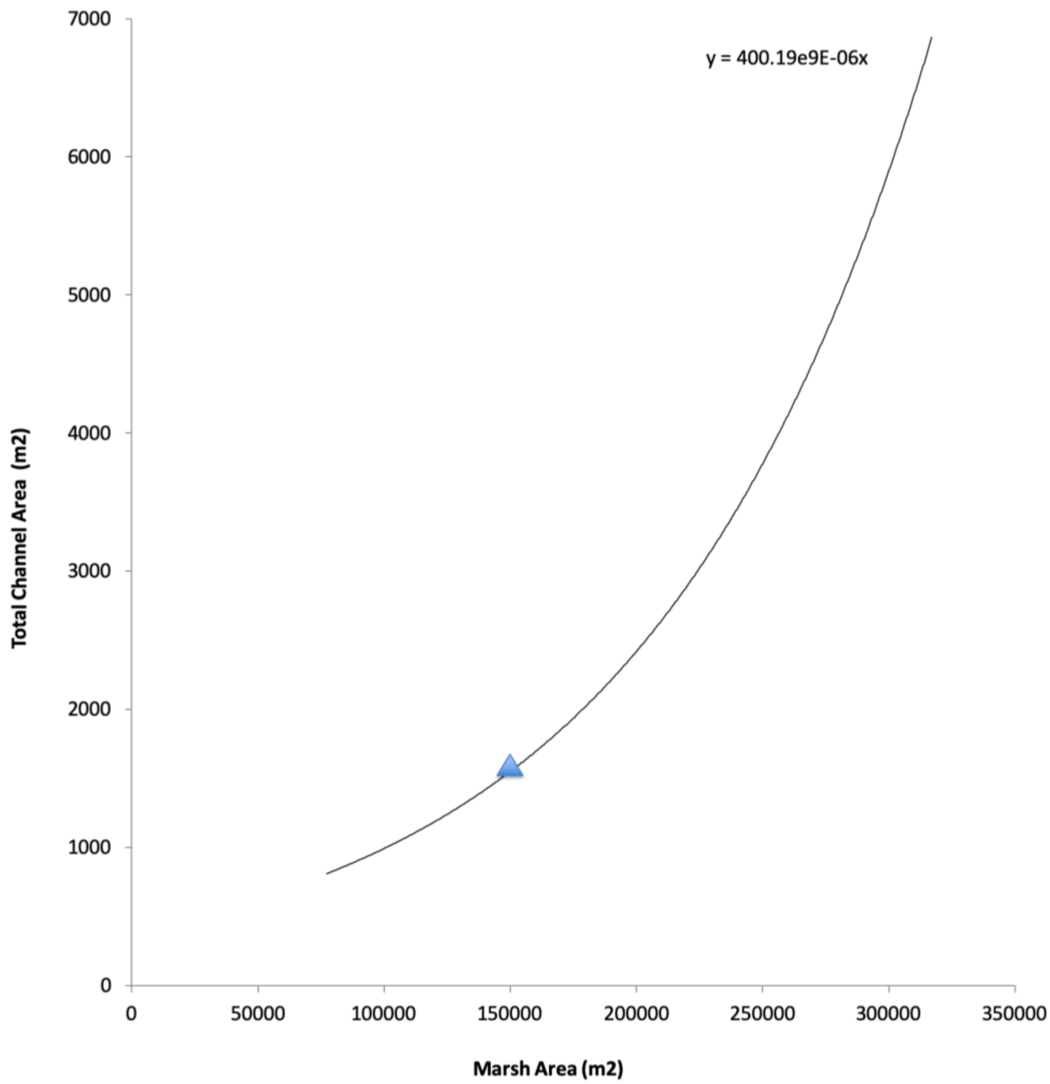

Figure 3.12. Scaling estimate for East Swishwash channel area to marsh area ($m^{2)}$ with future restoration potential plotted (blue triangle), 2019.

If dredge spoils were removed and elevations similar to West Swishwash created, the area could support an additional 675 m^2 of channel area and an additional 1 km of channel edge (Table 3). Digitization of the historic, current and proposed channel structures are reported and digitized in the table and figure below (Table 3 and Figures 3.13 - 3.15).

Table 3. **Channel metrics derived from QGIS digitization of Historic (1938), Current (2017) and Restored (proposed) conditions.**

Habitat and Channel Metric	Historic (1938)	Current (2017)	Proposed
East Swishwash			
Major Channel Area (m^2)	448	332	805
Major Channel Length (m)	722	462	863
Minor Channel Area (m^2)	361	546	760
Minor Channel Length (m)	574	640	738
Total Channel Area (m^2)	809	878	1550
Total Channel Length (m)	1296	1101	1600
Total Marsh Area (m^2)	77107	149183	149183
Drainage Density (m^2)	0.0103	0.0059	0.0110
West Swishwash			
Major Channel Area (m^2)	-	4903	-
Major Channel Length (m)	-	3821	-
Minor Channel area (m^2)	-	1964	-
Minor Channel Length (m)	-	2076	-
Total Channel Area (m^2)	-	6867	-
Total Channel Length (m)	-	5897	-
Total Marsh Area (m^2)	-	317067	-
Drainage Density (m^2)	-	0.0217	-

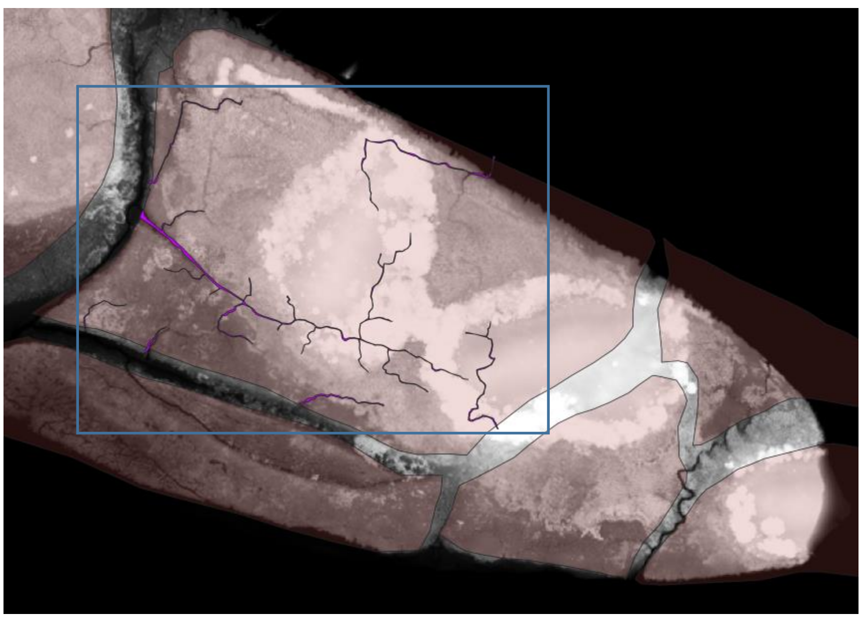

Figure 3.13. **Digitization of tidal marsh and channel features for historic island (1938) conditions (highlighted in blue box) used for minimum estimate of channel area density, 2019.**

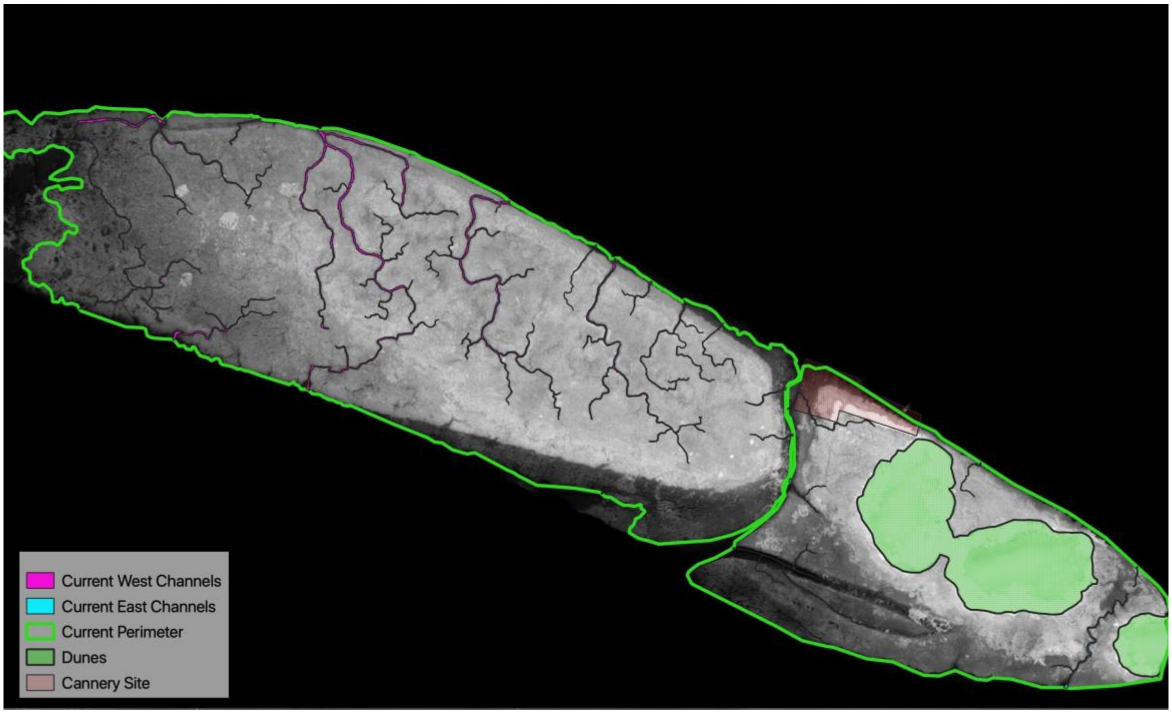

Figure 3.14. Swishwash Island current channel geomorphology, perimeter, dunes and cannery footprint digitized on DEM, 2019 (City of Richmond LiDAR 2017).

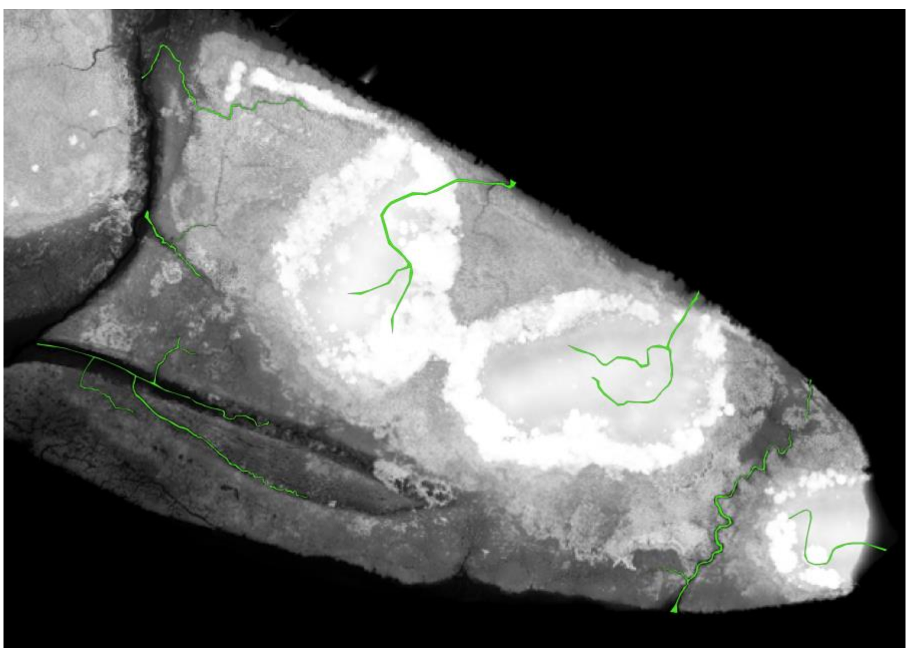

Figure 3.15. Swishwash Island proposed channel structure digitized on DEM. Based on estimates produced from interpolated exponential curve (Figure 3.12 and Table 3) produced in 2019. New channels should be excavated in areas targeted for spoil removal efforts.

Chapter 4. Discussion

4.1. Swishwash Island Tidal Channel Habitat

Chinook Utilization

Statistical differences between mean fork length distributions were observed for the month of May between Near and Far Field channels and for the months of June and July between Near Field and Beach locations. Higher FL's on Swishwash Island in May could be indicative of an 'island effect'. The mechanism of such an effect being that the insular habitat located in a main distributary stem, predispose larger individuals who have higher fitness and swim capabilities, to access and retain themselves in that environment. Smaller individuals that follow shallow, shoreline migrations are selected against residing in the distributary mouth and are less likely to cross deep waters. These smaller classes may not be as well represented in sampling efforts on Swishwash Island as a result of these deep, surrounding velocities. The month of May and peak freshet would heighten these effects because of a peak in discharge and velocity at a time when many juvenile salmonids are at their smallest (i.e. at their lowest swimming capacities) (Bottom et al 2015).

Velocity for the Middle Arm was not collected as a part of this study, however velocities of 3.1 m/s^2 were recorded in the mouths of distributary channels in the Columbia (Gonar 1988). Juvenile Chinook salmon sustained swimming speeds have been recorded as 0.25-0.65 m/s^{-1} for 80-125 mm size classes (yearlings) while smaller sub yearling Chinook (50–75 mm FL) have maximum sustained swimming speeds from 0.30 to .55 m/s^2 (Bottom et al. 2015). Though a standardization between beach seine and fyke net effort was not attempted, anecdotal observation of differences between juvenile salmon abundances between beach seine locations on marsh habitats on Sea and Lulu Island in the Middle Arm compared to the immediately adjacent insular tidal channel habitat of Swishwash Island would also support this island effect.

Catch Per Unit Efforts of Swishwash Island tidal channels were lower than some of the more predominant channels and tidal channel networks. This again may be indicative of this hypothesized island effect. Channels with the highest Chinook CPUE's (M1DF2, M7DF1, and GDF1) are located adjacent to significant low water refuges including Macdonald Slough, Garry Point (Sturgeon pit) and Grauer (Sturgeon Bank). Low-tide refuges, immediately adjacent to tidal channel complexes are increasingly recognized as crucial habitat features within the estuarine mosaic (Levings 1982; 2016; Simenstad 2002: Bottom et al 2015). With Chinook residing in estuarine environments for protracted periods with means upwards of 30 days in the FRE, and exhibiting channel network fidelity to some degree, these environments could have a significant impact on distribution and abundance of Chinook in tidal channel environments (Healey 1982; Levings 1982; Levy and Northcote 1982). Adjacent low water availability could be contributing to velocity effects on size distributions in the Middle Arm and Swishwash Island as there is little available refuge (from velocities and predators) and fish must retreat to the main distributary during ebbing tides.

Swishwash Island is not only insular in a geo-fluvial sense but also ecologically in terms of habitat connectivity and available refuge available for migrating salmon. The Middle Arm, and the severe encroachment and fragmentation of its marsh habitats, could potentially be a sink for juvenile salmon. The potential of Swishwash Island itself to be a sink habitat for salmon should also be considered. The woody tree and shrub species that have established on the periphery of the dune spoils have subsidized perching habitat on an outer delta island, where it is otherwise rare. Swishwash Island as a bastion of delta marsh void of access to people has also made it a valuable refuge for a variety of wildlife species including a family of otters in the north arm. Piscivorous avian species such as herons, mergansers, terns, and cormorants and river otters can have significant impacts through predations on small (40-100 mm) juvenile salmonids during their outmigration and rearing (Wood 1987; Dolloff 1993; Bottom 2015). Predation is likely enhanced with lack of effective LWD refugia structure in most tidal channel habitat on Swishwash Island for benthic feeding juvenile Chinook (Everett and Ruiz 1993; Bottom 2015).

LWD

The primary functions of LWD in Swishwash Island tidal channels are likely, structural refugia from predation, an important source of marsh disturbance, and a vital contributor to detrital food webs while refuge from velocity is secondary as channel velocities were found to be relatively low (.02-.06 m/s^{-1}). The LWD present in tidal channels were mostly driftwood or the occasional log escaped from a boon. This size and type of wood infills the headwaters of these small tidal channels at their highest distal reaches. Relative to the size and class of wood that would have existed in the marsh historically (old growth conifer trees with branches and root wads), structural dynamism of the LWD present has assumedly been reduced greatly with somewhat unknown ecological consequence (Gonar 1988; Hood 2007b). Gonar (1988) provides one of the few analyses of the role of wood in estuaries and reports that records from the 1850's document drift trees in Washington systems as large as 45 -75 m long by 5 m in circumference with root wads of approximately 6 m. It is clear that not only has the amount of wood entering and retained in tidal marshes been dramatically reduced but the size class and structure as well.

Vegetation

Swishwash Island vegetation adjacent to tidal channels closely follows zonation described for Lulu Island and the estuary previously (Hutchinson 1988; Adams and Williams 2014). On West Swishwash invasive species such as, purple loosestrife and hedge bindweed, occur in high abundances at approximately 20 m from the marsh edge. A major potential effect of invasive species in relation to juvenile salmon are the effects on detritus-based food webs and phenology (Levings 1982). Levings first studied this in the FRE in 1982 by measuring decomposition rates of purple loosestrife, providing important information on the auto-ecology of the species in local contexts. He compared these decomposition rates with its native competitor Lyngby's sedge. Lyngby's sedge is a relatively slow decomposer and provides detritus to food webs into spring with important timing syncs with juvenile salmon and other species' migrations. Levings found that purple loosestrife was a much faster decomposer and its inputs to the food-web had passed by early winter (Levings 1982). Hedge bindweed was observed in high densities in summer transects however on a field trip in mid-March the following year, the species' biomass had all but disappeared (author anecdote, 2019).

A thick patch of invasive cattails on East Swishwash is present in vegetation adjacent to Channel 3. It is likely they colonized after disturbance from dredge spoils as it is known to outcompete Lyngby's sedge after a disturbance (Hood 2013). Though there has been little study on the benefits of different vegetation communities for juvenile salmon through detrital food webs, Hood (2018) does show that canopy height can have an effect on foraging times in his study on salmon utilization of channel and marsh habitats. As flood tides occur juveniles are able to access the vegetation from above. As the tide recedes, they retreat back to lower habitats, channels, or marsh. Very few fish swim through vegetation without a channel or rivulet. Logically, the dense foliage and high canopy structure of marsh vegetation (such as cattail) will limit foraging times in marsh habitats (Hood 2018; 2013). Effective treatments include repeated mowing (twice a growing season) of the stalks used as a 'snorkel', and drowning the vascular plant with inundations (Hood 2013)

Water Quality

Measures of water quality on Swishwash Island were conducive to juvenile salmonid growth and activity. DO levels were higher on Swishwash Island relative to Far Field locations. However, DO at some far field locations were at thresholds low enough to affect growth (Hermann et al. 1962; Levings 2016). Low oxygen levels were especially apparent at the GDF1 (Grauer Lands at North Sturgeon Bank). The anecdotally large accumulation of wood at this site and in channels could be dropping oxygen levels (speculation). However, the biomass of invertebrates in these channels was anecdotally high as well. Further study into the tradeoffs between the oxygen consumed and food provided by invertebrate communities produced by LWD is required. Salinity, measured during freshet, was low at Swishwash Island. The salt water wedge was undetected in tidal channels on Swishwash and water was flushed regularly from the channels with the tidal cycles. Water entering channels was largely from the surface with high oxygen and low salinities. Salinity is expected to increase in the Fraser River with smaller freshets and higher evaporative temperatures due to climate change and could become a potential future stressor on Swishwash Island and other foreshore marsh habitats (Rand et al. 2006).

Water temperatures reached 20°C in tidal channels during July in the 2018 migration and has approached threshold levels for salmonid species and life-histories. Climate change will have a profound effect on salmon life histories (Ashley 2006; Rand et al. 2006; Crozier 2008; Beechie et al 2012). In the Pacific Northwest temperatures are projected to increase by between 2 and 6°C by 2070-2099 and summer flows are expected to decrease by 35-75% (Beechie et al. 2012). Experiments are needed that gauge the potential genetic and plastic responses to climate change (e.g. spawning and migration timings, developmental rates and growth, and disease and thermal tolerances

(Rand et al. 2006; Crozier et al. 2008). Furthermore, as climate change is likely to have varied effects specific to populations with extensive local adaptations and life-history diversities, monitoring and continued study of responses on a genetic level will become a growing field within ecological restoration (Carlson and Satterthwaite 2011; Crozier et al. 2018).

4.2. Geomorphology

Tidal channels scale allometrically with marsh area (Hood 2002a; 2002b; 2007a). Using a channel density of West Swishwash to infer structure of East Swishwash channel densities isometrically would likely produce an over density of channel area, failing to restore dynamic equilibrium, and potentially cause erosion and channel infilling. Tidal channel design utilized historic and current channel morphology optimizing the area that would be made available by the removal of spoils to ensure as little habitat as possible is disturbed and this project remains based in ‘restoration’ and not ‘creation’.

4.3. Restoration Potential

Since 1938, 7.5 ha of East Swishwash Island (roughly half the current area of the island) has been buried beneath dredge spoil or subsequently eroded away. The two are not necessarily independent as tidal channels that were infilled provided a vital mechanism for distributing tidal energy which can be a powerful force of erosion (Coats 1995). Similarly, the dredge spoils would have killed the underlying marsh vegetation undermining the capability of vegetation to stabilize soils. With so much change on local and landscape scales within such a dynamic system, it is difficult to isolate cause and effect. However, the FRE is at a point where every m^2 of this vital resource is important. There is opportunity to restore 5 ha of marsh habitat and increasing tidal channel area by nearly 200% and 1 km of tidal channel edge habitat on a protected, relatively undisturbed delta island within a highly developed matrix. Dredge spoils would have to be removed, elevations similar to those found on West Swishwash restored, and the site planted.

4.4. Restoration Recommendations

It is my recommendation that tidal channel and marsh habitats be restored on East Swishwash. Though there is further research to be done, the benefit of these habitats is clear and significant. With failing stocks, fishery closures, and emaciated Southern Resident Orcas (*Orcinus orca*), the time to restore these habitats is now. Despite the growing popularity and support of salmon restoration projects, public support should not be assumed. The public perception of the alternative stable state of East Swishwash as a 'pristine' and 'natural' wildlife preserve could be the project's second biggest barrier next to financing. A robust communications strategy should be developed and implemented well in advance of restoration with further research and ecological calculus conducted. Further bio-inventories are required to thoroughly survey the site for nesting birds and denning wildlife. Rare plants should be mapped and salvaged if possible. I would also recommend that close monitoring of erosion rates be established for the East and Northern edges of East Swishwash. A fluvial or estuarine geomorphologist should be contracted, and stability measures implemented if needed. NCC is aware of invasive species on the island and has plans for mitigation in their management plans. Invasive cattail, *T. angustifolia,* should be positively identified and controlled, with mowing a recommended treatment (Hood 2013).

Salmon monitoring should continue in tidal channels and marsh habitats on East and West Swishwash and adjacent shorelines. I recommend the use of the modified fyke net for tidal channel sampling but with wings and float lines that are wider to capture the height ranges experienced in these highly entrenched channels. If this expanded wing also included the front and back of the nets with float lines on top and lead lines beneath, this would greatly increase capture efficiencies across channel types and tidal ranges. Otherwise I recommend installing screen doors at channel sites and fitting fyke nets in established channel stations at low tide to ensure a good fit.

Careful consideration of restoration of tidal channels to East Swishwash provides a unique opportunity to experimentally study function of different elements. Excavated channels could be designed to be very similar in structure yet maintained for stark differences in LWD, deep pool habitats, or vegetation types. This could provide in-situ conditions to test the function of these elements that with paired functional measurements of juvenile Chinook could yield impactful results.

4.5. Future Research and Limitations

My project was limited by time. A single field season to try and capture habitat use of such a dynamic species is extraordinarily difficult and as a result, structural measurements were collected to infer function. Landscape dynamics were considered as much as possible however should continue to be considered in restoration of Swishwash Island. Equipment was also a major limitation and the various efficacy of sampling across sites needs to be tested. I recommend getting as many nets as possible and continuing the monitoring of fish use of channels and testing the efficacy of sampling at each site for a stronger comparison.

The effects of trained and diked systems on the physiological abilities of rearing fish to remain in the estuarine habitats ecological restoration of marsh habitats is largely unknown in the FRE system and beckons the question: are fish being evacuated from estuarine conditions prematurely into the Salish Sea, and if so, what effect does that have on their survival? This study confirms the use of tidal channels by Chinook salmon and offers information should an effort be made to restore channel habitat to East Swishwash. However cryptic effects such as those of an ‘island effect’ or other large landscape level stressors may have significant impact on potential success and may, in part, need to be addressed first. Significantly, low tide habitat and landscape connectivity need to be addressed through habitat identification, creation, and restoration.

There are currently efforts underway to restore marsh and tidal channel habitat and to enhance connectivity in the FRE with dike breaching’s and bathymetry mapping for identification of low water refuge areas by government, first nations, private, and non-profit organizations. Allometric scaling is a very powerful tool in marsh restoration that forgoes the complicated, data intensive and timely effort of calculating tidal prisms (Hood 2002a; 2002b; 2007a). A database for the FRE of scales of fractal geometries would assist with monitoring and target evaluation for habitat restoration, compensation, and enhancement projects. There are a group of islands in the South Arm (South Arm Marshes) that would be suitable candidates (G. Hood, Pers. Comm. 2019). A centralized restoration database and protocol similar to those created for the Columbia should be established for the FRE for greater ease and ability to conduct, monitor, and compare restoration efforts across organizations and time periods.

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Appendix.

Table A1. Genetic results for juvenile chinook from PBS for all tidal channels in the FRE for 2018.

Date	Site	Stock	CU	Region
March	M1DF1	Harrison	3	LFR
March	M14DF1	Harrison	3	LFR
March	M14DF1	Harrison	3	LFR
April	GDF1	Harrison	3	LFR
April	GDF1	Harrison	3	LFR
April	GDF1	Harrison	3	LFR
April	GDF1	Chilliwack, Stave	6	LFR
April	GDF1	Chilliwack	6	LFR
April	M9DF1	Harrison	3	LFR
April	M9DF1	Harrison	3	LFR
April	M9DF1	Harrison	3	LFR
April	M9DF1	Chilliwack	6	LFR
April	M7DF1	Harrison	3	LFR
April	M7DF1	Harrison	3	LFR
April	M7DF1	Harrison	3	LFR
April	M7DF1	Harrison	3	LFR
April	M7DF1	Harrison	3	LFR
April	M7DF1	Chilliwack	6	LFR
April	DJG	Harrison	3	LFR
April	DJG	Harrison	3	LFR
April	DJG	Harrison	3	LFR
April	DJG	Chilliwack	6	LFR
April	DJG	Chilliwack	6	LFR
April	DJG	Chilliwack	6	LFR
May	M7DF1	Slim Creek	12	UFR
May	M7DF2	Slim Creek	12	UFR
May	M1DF2	Harrison	3	LFR
May	M1DF2	Harrison	3	LFR
May	M1DF2	Upper Cariboo	11	UFR
May	M1DF2	Quesnel	11	MFR
May	M1DF2	Holmes	12	UFR
May	M1DF2	McGregor	12	UFR
May	M1DF2	Slim Creek	12	UFR
May	M1DF2	Slim Creek	12	UFR
May	M1DF2	Slim Creek	12	UFR
May	M1DF2	Slim Creek	12	UFR
May	M1DF2	Slim Creek	12	UFR

May	M1DF2	Slim Creek	12	UFR
May	M1DF2	Slim Creek	12	UFR
May	M1DF2	Slim Creek	12	UFR
May	M1DF2	Slim Creek	12	UFR
May	M1DF2	Slim Creek	12	UFR
May	M1DF2	Slim Creek	12	UFR
May	M1DF2	Slim Creek	12	UFR
May	M1DF2	Slim Creek	12	UFR
May	F2DF2	Slim Creek	12	UFR
May	SWCH1	Harrison	3	LFR
May	SWCH1	Chilliwack, Stave	6	LFR
May	SWCH1	Chilliwack	6	LFR
May	SWCH3	Chilliwack	6	LFR
May	SWCH3	Chilliwack	6	LFR
May	SWCH3	Chilliwack	6	LFR
May	M14DF1	Chilliwack, Stave	6	LFR
May	M1DF2	Harrison	3	LFR
May	M1DF2	Harrison	3	LFR
May	M1DF1	Lower Thompson	13	MFR
May	M1DF1	Lower Thompson	13	MFR
May	SWCH2	Harrison	6	LFR
May	SWCH2	Harrison	6	LFR
May	SWCH2	Lower Thompson	13	MFR
May	M9DF1	Chilliwack	3	LFR
June	M14DF1	Harrison	6	LFR
June	M14DF1	Harrison	3	LFR
June	M1DF2	Harrison	3	LFR
June	M1DF2	Harrison	3	LFR
June	M1DF2	Chilliwack	6	LFR
June	M1DF2	Lower Thompson	13	MFR
June	M1DF1	Lower Thompson	13	MFR
June	M1DF2	Lower Thompson	13	MFR
June	M1DF2	Lower Thompson	13	MFR
June	M1DF3	Lower Thompson	13	MFR
June	M14DF1	Chilliwack	6	LFR
July	M1DF1	Harrison	3	LFR
July	M1DF1	Chilliwack	6	LFR
July	M1DF1	Lower Thompson	13	MFR
July	M1DF1	Lower Thompson	13	MFR
July	M1DF1	Lower Thompson	13	MFR
July	M1DF2	Lower Thompson	13	MFR
July	M1DF2	Lower Thompson	13	MFR

Figure A1. **Red-listed Vancouver Island Beggar Ticks observed during vegetation surveys on East Swishwash Island, 2018.**

Figure A2. **Invasive Species Quadrat demonstrating the effect of bindweed on height of vegetation. This species forms mats and weighs down cattail and Lyngby's sedge with little known effect 2018.**

Figure A3. **Stream type Chinook smolt, with healed missing piece of caudal fin indicating potential recapture, summer 2018.**

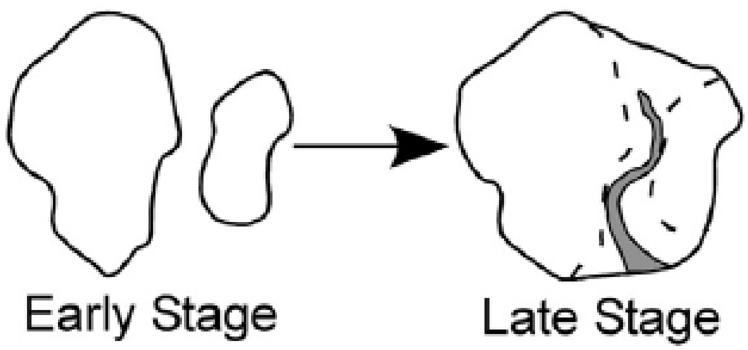

Figure A4. **Gregory Hood (2016) channel evolution through aggradation. It is this author's belief that historic East Swishwash Islands (1930) were aggrading and joining together before dredge spoils were deposited. This is counter to the current trajectory of high erosion along the leading east edge experience in past decades.**

Figure A5. **Sea Island Cannery circa 1900 operated on Swishwash Island among many other canneries in the FRE before it was decomissioned and burned down (Richmond Archives 2019).**

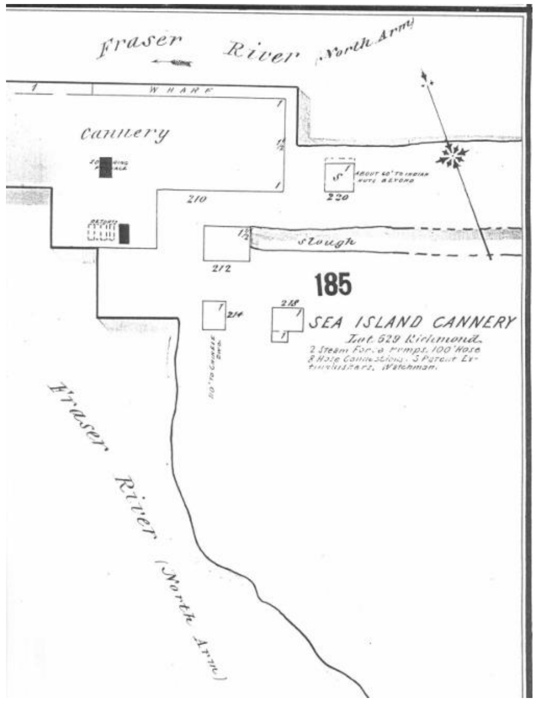

Figure A6. Sea Island Cannery Fire Insurance Application circa 1900 shows buildings of the cannery on Swishwash island as well as a slough that ran along a dyke to one of the out buildings (Carter 2002).

Figure A7. Informal housing/settlement for manual labour circa 1900 (Richmond Archives 2019).

Note. Note small dyke offering some flood protection for tents.

SFU SIMON FRASER UNIVERSITY
ENGAGING THE WORLD

TO: **Dr. Ken Ashley**
Adjunct Professor, SFU
Ken_Ashley@bcit.ca

FROM: **Dr. Allen Thornton**
Chair, UACC

SUBJECT: **Waiver for Animal Care Requirements on:**
"Swishwash Island Tidal Marsh Restoration"
Funding Source: Mitacs Accelerate
Application Ref. IT12728

DATE: **November 26, 2018**

Dear Dr. Ashley:

This letter is to confirm that Animal Care approval has been waived for the above noted research project for yourself and Kyle Armstrong.

It is understood that no vertebrates will be used for this research project, as data collected under an approved UBC protocol will be utilized. Therefore, for the purposes of your research, you do not require an Animal Care approval from the SFU UACC.

Please contact me should you have any further questions.

Sincerely,

Dr. Allen Thornton
Chair UACC

cc: ORS
cc: Kyle Armstrong (Student #: 301353007)

Figure A8 Waiver for Animal Care Requirements, 2018.