A typology of hydraulic barriers to salmon migration in a bedrock river

by

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Abstract

Salmon spend the majority of their life in the ocean, coming into inland rivers for the purpose of spawning. The Fraser River is one of the most productive salmon spawning rivers in the world, and is therefore paramount to understand where hydraulic barriers – reaches of river where fish migration is delayed due to high water velocity – exist. I explore locations in the Fraser River that are apt to be hydraulic barriers based on centerline velocity. Barriers are classified as either 1) plunging flows, where flow is deep with the highest velocities lower in the water column, 2) rapids, where flow is fast and shallow over bedrock steps, or 3) overfalls, where fast flow occurs over a step with a substantial drop in elevation. I find twenty-two sites that are potential hydraulic barriers, providing information on where salmon may be expending more energy and informing future spawning management efforts.

Keywords: Bedrock rivers; Pacific salmon; Hydraulic barriers; Fraser River

Land Acknowledgment

I would like to acknowledge that I live and work on the stolen traditional territories of the Musqueam (xʷməθkʷəy̓əm), Squamish (Sḵwx̱wú7mesh Úxwumixw), Tsleil-Waututh (səl̓ilw̓ətaʔɬ), and Kwikwetlem (kʷikʷəƛ̓əm) Nations. I would also like to respectfully acknowledge that the data for the research conducted during my masters was collected on the land and waters of the Nlaka'pamux (NɬeʔkepmxTmíxʷ), Stó:lō (S'ólh Téméxw), Stz'uminus, St'at'imc, (Stát̓imc Tmicw), Tŝilhqot'in Nen, Dënéndeh, Secwépemc (Secwepemcúl'ecw), and the Esk'etemc (Esketemculeucw) peoples. This is the land where I have had the privilege of learning and growing as a scientist through observations of river processes. It is important to take time to acknowledge the traditional territories and the Indigenous communities that care for the land, and have since time immemorial. As I move forward, I plan to honour traditional lands through my research and make meaningful connections with communities through data sharing and true partnership.

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Fraser River through Alexandra Canyon, looking upstream

Chapter 1.

Introduction

Hydraulic barriers are where high velocity flows impede upstream fish migration by forcing fish to swim anaerobically for extended distances. Barriers are often described in association with culverts, dams or other human-engineered structures that change the natural flow patterns of rivers (eg. Murchie et al., 2008; Meixler et al., 2009; Kemp & O'hanley, 2010; Bourne et al., 2011), but they may also occur as a result of high velocity forced by local river morphology or landslides that partially obstruct the channel. For example, on November 1, 2018 the western wall of French Bar Canyon in the Fraser River, British Columbia failed, depositing ~100,000 m^3 of rock into the channel. This created an overfall that was largely impassible for migrating salmon in 2019 and 2020, until rock removal and manipulation improved passage in 2021. The site was already challenging for upstream fish migration because canyon narrowing produced high velocity flow. Hell's Gate in the Fraser River is another widely known salmon migration barrier where waste rock from railway construction exacerbated high flow conditions at a narrow channel constriction, which became an acute barrier to upstream fish migration in 1913 due to a small rock slide, until it was blasted and removed (Jackson, 1950). At high discharges, both French Bar Canyon and Hell's Gate remain hydraulic barriers to fish migration.

How fish navigate zones of high velocity in rivers, whether caused by bank collapse, landslides, or channel morphology is not well understood (eg. Castro-Santos, 2004; Peake, 2004; Castro-Santos, 2005; Castro-Santos, 2006; Wang et al., 2016). With pressures from human exploitation of fish populations making them more susceptible to natural disasters (COSEWIC, 2016, 2017), it is imperative that salmon interactions with naturally occurring earth surface processes are investigated. Unfortunately, the flow dynamics in bedrock canyons, where hillslope failure is most likely to be coupled with river channels, have only recently been investigated in detail (Venditti et al., 2014; Hunt et al., 2018; Cao et al., 2022; Hurson et al., 2022). Previous work on velocity barriers in rivers has mainly focused on the presence of engineered obstacles to fish passage and the velocity over or through these structures (Murchie et al., 2008; Meixler et al., 2009; Kemp & O'hanley, 2010; Bourne et al., 2011). In order to understand where natural barriers are likely to occur, fish swimming capabilities must be considered in combination with river morphology. This has not been common practice as few data sets exist that contain detailed enough morphological data for bedrock rivers.

Morphology and flow through bedrock rivers are not well understood at the reach scale. Morphology is complex as it is controlled by rock structure and there have been only a few studies of flow dynamics in bedrock canyons (Dolan et al., 1978; Kieffer, 1989; Wohl et al., 1999; Venditti et al., 2014; Tomas et al., 2018; Carling et al., 2019; Hurson et al., 2022). Much of the work that has been done on bedrock rivers uses numerical models or experimental flume data to constrain factors that may influence flow as well as morphologic change (Wohl et al., 1999; Sklar & Dietrich, 2001; Egholm et al., 2013; Baynes et al., 2020; Zhang et al., 2020). Some of the first observations of flow through bedrock canyons come from the Grand Canyons of the Colorado River, Arizona (Leopold, 1969; Dolan et al., 1978) where accelerated flow through rapids has been observed to produce deep pools at the base of the rapid (Dolan et al., 1978). They hypothesized that high velocities at the exit of rapids was directed at the bed, creating deep scour holes. Along the same river it was also observed that, as flow was constricted by protrusion of alluvial fans into the river, velocities increased and rapids formed (Kieffer, 1989). Venditti et al. (2014) demonstrated the link between lateral constriction and pool formation by showing that plunging high velocity flows occur as rivers transition from alluvial to bedrock-bound and the channel is laterally-constricted. River constrictions lead to the development of the scour pools and subsequent downstream widening (Venditti et al., 2014; Hunt et al., 2018; Cao et al., 2022). Deeper scour pools are found where there is a greater degree of constriction, with cross sectional areas decreasing as flow enters the canyon (Venditti et al., 2014; Cao et al., 2022; Hurson et al., 2022; Wright et al., 2022). The observations made by Venditti et al. (2014) also showed a plunging high-velocity core as the water enters laterally-constricted canyons, resulting in a velocity inversion as well as upwelling along the canyon walls. How this complex morphology and three-dimensional flow structure in bedrock canyons affects fish migration is unknown.

Quantifying the passability of a velocity barrier, as well as the impact on salmon, has proven to be a challenge since modelled and measured water velocity values have been shown to differ substantially (Bourne et al., 2011). It is also hard to get critical swim speed measurements in the field (Castro-Santos, 2004). Thus, measurements are taken from laboratory experiments and often underestimate the actual abilities of fish that would be observed in natural environments (Peake, 2004). This underestimation is likely due to a combination of behavioural, physiological, and hydraulic issues associated with confining fish to a flume (Peake, 2004). Although this may seem counterintuitive, as one would expect it to be easier to swim in a lab environment as compared to a turbulent river, studies have shown behavioural refusal of fish to swim to exhaustion when confined (Tarby, 1981; Reidy et al., 1995; Swanson et al., 1998). Depending on the size of the fish and the width of the flume, the critical swim speed for a fish in a narrower channel (flume) can be lower than that of a fish in a natural river if the width of the flume constrains the tail beat amplitude of the fish (Webb, 1993). There are also other factors that will influence the ability of individuals and populations to pass velocity barriers, such as the number of attempts taken to pass a barrier and the rest period between attempts (Castro-Santos, 2004).

Typically, fish will swim at speeds that belong to one of three categories: sustained, prolonged or burst (Beamish, 1978). Sustained speeds are those that a fish is able to maintain for relatively long periods of time (>200 min) as the energy used is generated through aerobic metabolic pathways (Beamish, 1978). Prolonged swimming covers a range of speeds that require both aerobic as well as some anaerobic energy (resulting in fatigue after 20 s to 200 min), and burst swimming is short lived (<20 s) and solely requires energy created through anaerobic pathways (Beamish, 1978). Swimming at speeds that require anaerobic energy for long periods of time will result in fatigue, slowing upstream movement by forcing fish to rest (Parker & Black, 1959) and in some cases die (Black, 1958). Swim speeds are typically measured and recorded in units of body-length per time as the distance covered by a fish will often depend upon not only their species, but also their life stage and size (Castro-Santos, 2005). Although this may be useful for comparisons between species, it can be problematic and hard to apply to real world situations, such as predicting successful passage of high velocity river sections. Fewer studies have provided measures of swim speed in a format directly comparable to river flow velocities (e.g. m/s or cm/s), and those that do often do not directly correspond to those based on body-length (Kraskura, 2022). Individuals within species can have a range of body-lengths, so their absolute swim speeds (BL/s) do not correspond to the species-average; absolute swim speed (cm/s) is what is necessary to determine net upstream ground speed for individual fish.

Every year millions of salmon travel from the ocean to inland river systems along much of the Pacific Coast north of Mexico. The Fraser River is the most productive salmon rivers in Canada and one of the most productive rivers in the world in terms of species abundance and population variation (Marshall et al., 2017), making it extremely important to understand the types and locations of barriers to fish migration. There are a number of known hydraulic barriers in the Fraser River that have associated fishways to aid upstream migration, such as Yale Rapids, Hell's Gate Canyon, and Bridge River Rapids, but other locations are suspected to delay upstream migration at high flow as well (Hinch and Rand 1998). What constitutes a hydraulic barrier to fish passage – with regard to flow and morphology of the river – is not well understood. I explore this problem through an investigation of high velocities in the main canyon areas of the Fraser River. My specific research questions are:

1. Where are hydraulic barriers to upstream salmon migration in the Fraser River?
2. What is the channel morphology associated with the hydraulic barriers?
3. What is the spatial distribution of flow through hydraulic barriers?
4. What areas do adult salmon require anaerobic activity to navigate different types of barriers?

Chapter 2.

Methods

2.1. Study Site

The Fraser River is the longest river in British Columbia, flowing ~1375 km from Mount Robson to the Pacific Ocean and draining ~232 000 km^2. South of Dog Creek (51°35’0” N, 122°15’0” W), the river follows the Fraser Fault Zone as it flows between the Coast and Cascade Mountains (Roddick et al., 1979; Curran, 2020). The 375 km reach between Soda Creek and Yale (Figure 2.1) is familiarly known as the Fraser Canyon where the channel has three types of banks: non-bedrock, bedrock-constrained (bedrock on one bank), and bedrock-bound (bedrock on both banks) (Venditti et al., 2014; Rennie et al., 2018; Curran, 2020; Venditti et al., 2020; Wright et al., 2022). The non-bedrock sections are a mixture of glacial-fluvial terraces, colluvial deposits, and alluvial deposits. Of the 375 km that makes up the Fraser Canyon, 45% is non-bedrock, 29% is bedrock-constrained, and 26% is bedrock-bound (Wright et al., 2022).

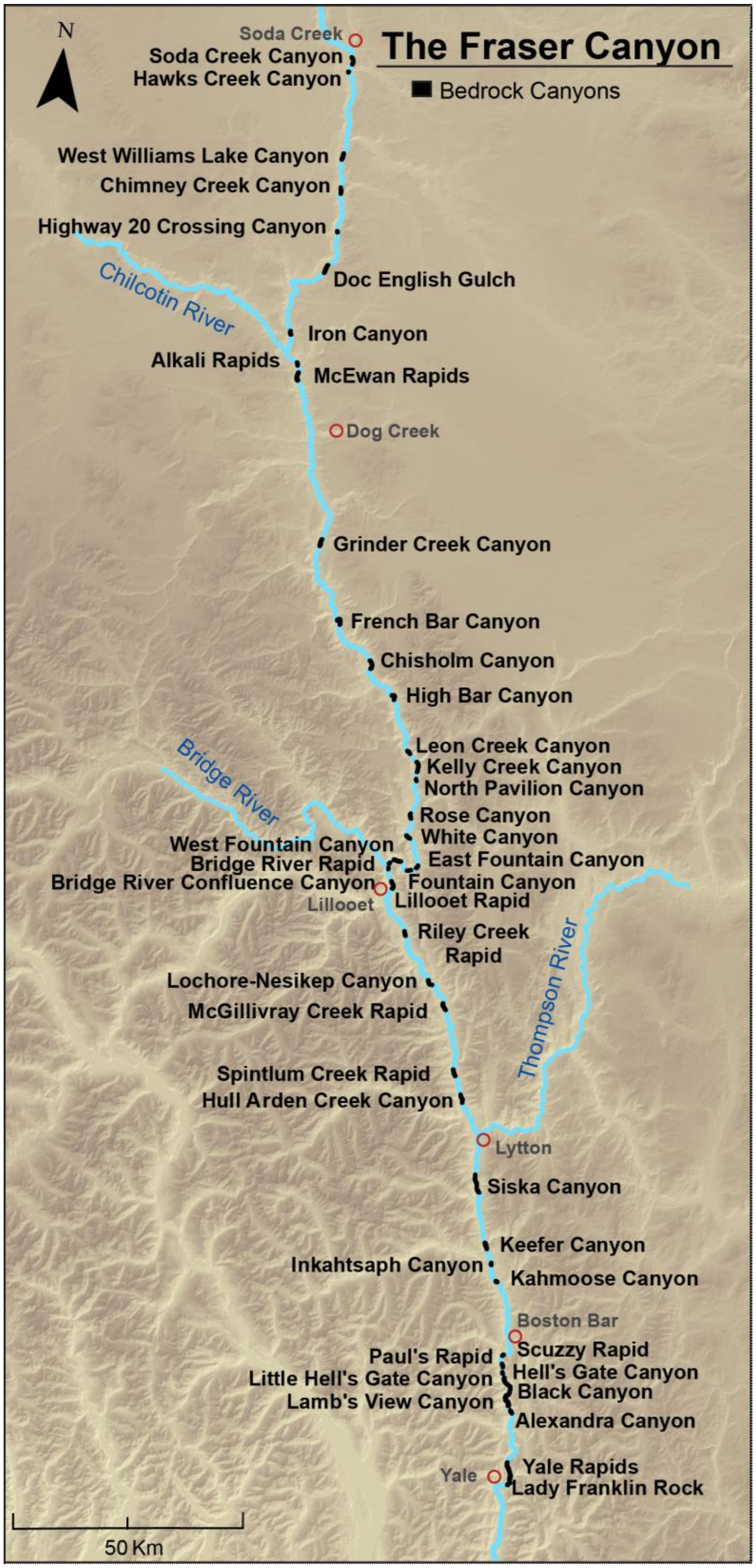

Figure 2.1. **Fraser Canyon, British Columbia, showing the locations of the individual named bedrock-bound canyons.**

The Fraser River is a largely snowmelt dominated river, experiencing the highest flows in the late spring and early summer when the snowpack from the surrounding mountains begin to melt (Figure 2.2). The flow begins to recede again towards the end of the summer, with reduced flows for the fall spawning season. Chinook (Oncorhynchus tshawytscha), Sockeye (Oncorhynchus nerka), Pink (Oncorhynchus gorbuscha), Coho (Oncorhynchus kisutch), and Chum (Oncorhynchus keta), salmon are all found in abundance in the Fraser River, with adults mainly returning to the river in the order above starting in early April and continuing to be present until the following January (Department of Fisheries and Oceans, 1998). Thus, different species and populations will experience different flow levels during spawning migration (Figure 2.2). As climate continues to change and flows vary from year to year, it becomes imperative to understand what river morphologies are creating the greatest barriers to salmon.

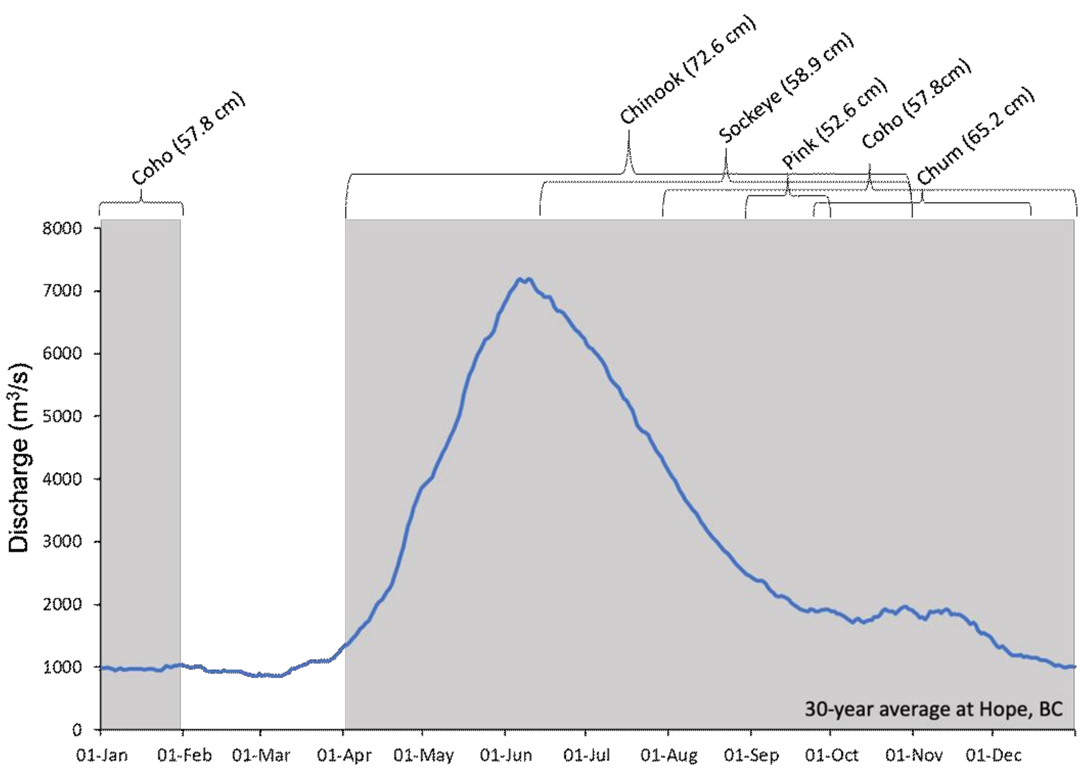

Figure 2.2 Hydrograph for the Fraser River at Hope, BC from Water Survey of Canada Gauge 08MF005. Expected return times for the lower Fraser are shown for the five salmon species of interest. Mean body-lengths are also noted.

2.2. High velocity identification

Zones of high velocity, which have the potential to create hydraulic barriers, were identified using data collected by an acoustic Doppler current profiler (ADCP) during a 2009 field campaign undertaken at just below the mean annual flow when the canyons are safely accessible (Venditti et al., 2014; Ferguson et al., 2015; Rennie et al., 2018; Wright et al., 2022). Locations were identified that have centerline velocity >3σ (standard deviation) above the mean for more than 10m, or are laterally constricted and apt to have high velocities but with missing velocity measurements. Those zones with missing data are where water velocities are too fast for ADCPs or highly aerated flow, both indications of high velocity. I further constrained areas with missing data by ensuring that they had velocities above the mean directly upstream and downstream of the data gaps. Locations identified based on criteria 1 are classified as high velocity zones and those identified based on criteria 2 are classified as 'suspected' high velocity zones.

2.3. Comparison of velocity to salmon swimming capabilities

Velocity data collected using large-scale particle image velocimetry (LSPIV) was used to predict how different types of flow and river morphology impact five species of salmon: Pink, Chum, Coho, Sockeye and Chinook. Sustained, prolonged, and burst swim speeds were calculated using known BL/s values of 2 BL/s for sustained, 4 BL/s for prolonged, and 10 BL/s for burst (Castro-Santos, 2005). Body-length specific values were then converted to m/s using three standard body-size measurements to make them comparable to river velocities (Table 2.1).

Body-length values for mature adults of the five species of interest ranged from 30 cm to 100 cm (Groot & Margolis, 1991). Body-length values of 52.6 cm, 65.2 cm, and 79.6 cm were used to represent small, medium and large fish. These values were calculated from species specific data in a recent review by Kraskura (2022), where size was measured alongside anaerobic swimming capabilities. Small represents roughly the mean body size of the smallest species, Pink salmon. Medium represents roughly the mean body length of all salmon species. The large represents some of the larger recorded body-lengths for all species.

Table 2.1. Swim speed values for Pacific Salmon based on standardized body lengths

Fish Size	Length (m)	Sustained – BL/s (m/s)	Prolonged – BL/s (m/s)	Burst – BL/s (m/s)
Small	0.526	2 (1.05)	4 (2.10)	10 (5.26)
Medium	0.652	2 (1.30)	4 (2.61)	10 (6.52)
Large	0.796	2 (1.59)	4 (3.18)	10 (7.96)

The most likely locations for velocity barriers in the Fraser Canyon were explored by comparing measured encounter velocities – the velocity of the water salmon are forced to swim against – with the passable encounter velocities (V_p) for the size class of interest. The passable encounter velocity is calculated as

$$V_p = U_x - \frac{L}{t} \tag{1}$$

with U_x as the swim speed reached by the fish for the each of the three swim types, L being the channel length (or swim distance), and t being the time that a fish can spend swimming at U_x. Since each swim speed can be maintained for different lengths of time, the value of t will depend on swimming type. Passable encounter velocities for swim types were calculated over 50 m channel segments as this was the maximum channel length that my calculated burst speeds could be sustained. If water velocities, measured every 10 m, were above V_p associated with sustained, prolonged, or burst swimming for ≥50 m, the reach was categorized as such.

Previous research tracking adult Sockeye salmon found that in high velocity areas of the Fraser River this species typically swim within one to three meters from the shore (Hinch & Rand, 2000). The encounter velocities being used in the calculations represent a depth-averaged centerline velocity and are thus an overestimate of the actual velocities that salmon would be swimming against as they traverse the river staying closer to the banks, avoiding the high velocity centerline. In order to compensate for this difference I investigated flow through distinct channel morphologies known to create high velocities (Wright et al., 2022) using imagery of the water surface that allow us to examine passable paths through morphologies at varying discharges.

2.4. Large-scale particle image velocimetry

Making observations of flow in the Fraser River is logistically challenging and is not practically possible in areas apt to be hydraulic barriers to fish at high flow due to safety concerns and instrument limitations. Therefore, I used LSPIV (e.g. Fujita et al., 1998; Fujita & Hino, 2003; Muste et al., 2008) to examine flow dynamics at known hydraulic barriers in the Fraser River. LSPIV uses sequential images of the water surface to measure patterns of water velocity vectors. LSPIV works by matching patterns found within a defined interrogation area from one image to the next using spatial correlation to determine velocity vectors based on the distance patterns move and time-step between the consecutive images. Patterns used for tracing must be visible in the footage but can come from artificially added tracers, or from naturally occurring flow structures. If movement along the water surface is visually obvious between consecutive images, it is unnecessary to use tracers (Jodeau et al., 2017).

Video footage for LSPIV was collected at high (June 17th, 2021), moderate (July 20th, 2021) and low (Sept 9th, 2021) flow in 2021 using a DJI Phantom 3 drone at Yale Rapids (49°35'17.84"N, 121°24'13.81"W) and Black Canyon (49°44’59.52” N, 121°25’19.70” W) (Table 2). Each measurement consisted of around 10 videos, 2 minutes in length, taken perpendicular to the flow. Videos were stitched together after processing to create continuous flow fields. Data for French Bar Canyon was collected with a DJI Phantom 4 drone in 2020 and 2022 (Table 2.2).

Table 2.2. High, moderate, and low flow discharge measurements.

Site	High Flow		Moderate Flow		Low Flow	
	Date	Discharge, m/s (% mean annual flow, % peak annual flow)	Date	Discharge, m/s (% mean annual flow, % peak annual flow)	Date	Discharge, m/s (% mean annual flow, % peak annual flow)
Yale Rapids	June 17th, 2021	~ 6300 (230%, 74%)	July 20th, 2021	~3950 (144%, 46%)	September 9th, 2021	~1550 (57%, 21%)
Black Canyon	June 17th, 2021	~ 6300 (230%, 74%)	July 20th, 2021	~3950 (144%, 46%)	September 9th, 2021	~1550 (57%, 21%)

French Bar Canyon	July 26th, 2020	~ 4790 (248%, 89%)	November 6th, 2020	~ 3310 (172%, 62%)	Mach 19th, 2022	~ 564 (29%, 11%)

Discharge is from the Water Survey of Canada (WSC) Hope Gauge (08MF005) for Yale Rapids and Black Canyon, and from WSC Big Bar Gauge (08MD013) for French Bar Canyon. Mean annual flow (for the 30-year period between 1990 and 2020) for Yale Rapids and Black Canyon is ~ 2740 m^3/s, and the peak annual flow is ~ 8550 m^3/s. Mean annual flow for French Bar canyon (for the 30-year period between 1942 and 1972, when the station was last running before being reinstated in 2018 after the landslide) is ~ 1930 m^3/s, and the peak annual flow is ~ 5370 m^3/s.

Video processing used Fudaa-LSPIV, a free online open source software (Le Boursicaud et al., 2016; Le Coz et al., 2016; Jodeau et al., 2017; Theule et al., 2018; Zhu & Lipeme Kouyi, 2019). I chose Fudaa-LSPIV as it was open source and publicly accessible. I chose to use videos two minutes in length in hopes of averaging out errors between single image pairs as well as surface turbulence.

2.4.1. Validation

LPSIV measurements have been shown to underestimate flow when compared with direct flow measurement techniques (e.g. Bradley et al., 2002; Kim, 2006; Tsubaki et al., 2011; Dobson et al., 2014; Tauro et al., 2017). Velocities obtained from LSPIV in September of 2021 were compared with ADCP measurements from September 2009 to test validity of the measurements because flows were relatively similar: 1540 – 1590 m^3/s and ~1620 m^3/s respectively. LSPIV surface measurements were compared with the top bin ADCP measurements, which are ~1 m below the surface. Four sites where ADCP data was available through the entire site were selected for this analysis including Black Canyon (49°44’59.52” N, 121°25’19.70” W), Whirlpool Rapid (49°49'4.35"N, 121°26'17.87"W), Scuzzy-to-Paul’s Rapid (49°48'14.72"N, 121°27'30.99"W), and Devil’s Tooth Rapid (49°34'1.99"N, 121°23'58.53"W).

Chapter 3.

Hydraulic barrier identification and classification

3.1. Potential hydraulic barrier identification

I identify potential hydraulic barriers as reaches where velocity exceeds mean + 3σ. Measured depth-averaged, mean velocity $\overline{U}$ through the Fraser Canyon was 2.47 m/s during the 2009 ADCP survey and σ = 0.67 m/s, making my threshold for high velocity zones 4.48 m/s (Figure 3.1). With 4.48 m/s exceeding prolonged swim speeds for all the fish sizes (Table 2.1), this is an acceptable starting place for identifying locations of high velocity that may be problematic for upstream movement of adult salmon. Twenty-two locations have been identified as high velocity zones, 16 where $\overline{U} >$ 4.48 m/s and 6 where I suspect $\overline{U} >$ 4.48 m/s (Figure 3.2). The high velocity zones are

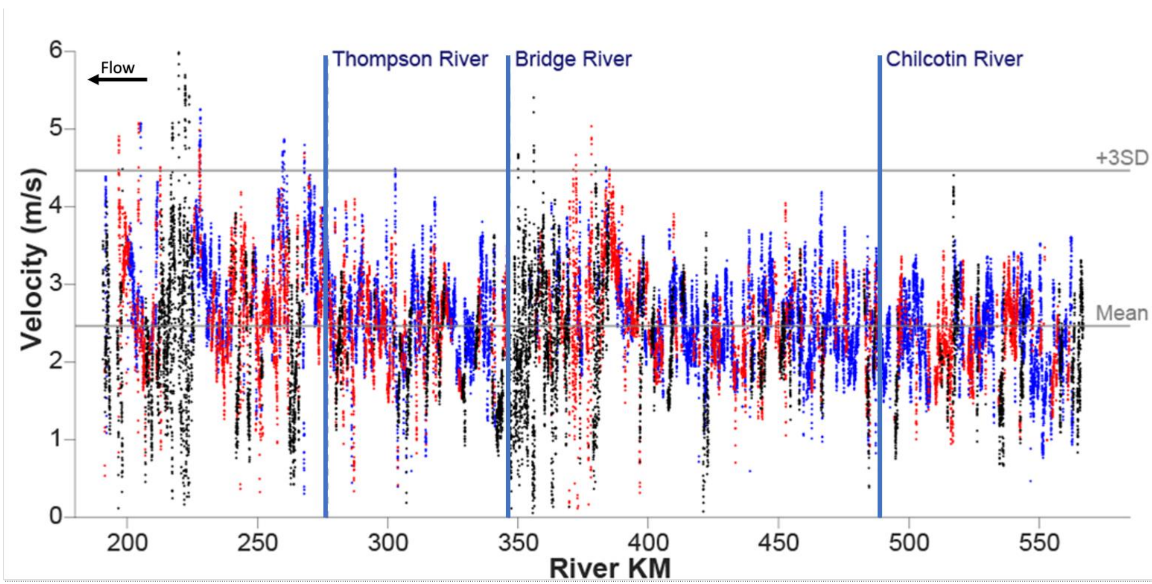

Figure 3.1. Along-stream velocity profile of the Fraser Canyon showing locations where velocity exceeds the mean by three standard deviations. The three major tributaries that enter the river through this reach, increasing discharge, have been labeled. Bedrock-bound, bedrock-constrained, and non-bedrock sections of the river are plotted in black, red and blue respectively. Velocity measurements were collected September 2009.

concentrated in two locations in the Fraser Canyon: between French Bar Canyon to Fountain Canyon (Figure 3.2a), and between Siska Canyon to Yale Rapids (Figure 3.2b). There are no notable high velocity zones, based on my criteria, between Lillooet and Lytton. The high velocity locations occur in non-bedrock, bedrock-constrained and bedrock-bound sections of the river, but suspected high velocity zones only occur in bedrock-constrained and bedrock-bound sections.

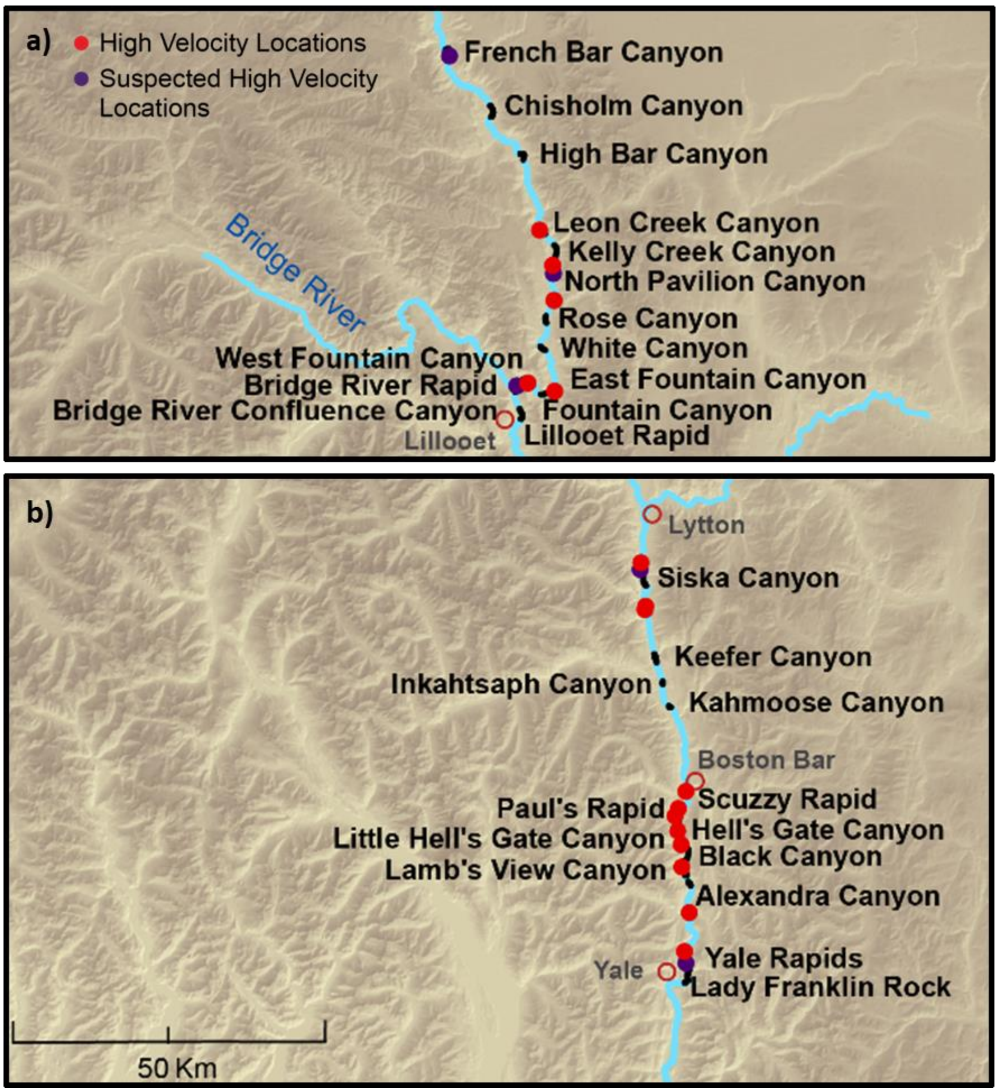

Figure 3.2. High velocity and suspected high velocity reaches in the a) central and b) southern sections of the Fraser Canyon. Locations have been classified as either high velocity or suspected high velocity based on ADCP velocity measurements taken during a 2009 field campaign.

3.2. Potential hydraulic barrier classification

The 22 potential hydraulic barriers occur in reaches with three distinct morphologies: 1) Constriction-pool-widening (CPW), 2) Bedrock Steps, and 3) Overfall Steps. The flows associated with these morphologies are plunging flows, rapids, and overfalls, respectively. Plunging flows occur anywhere a bedrock river is laterally constricted, by either bedrock or alluvial/colluvial deposit encroachment, leading to incision of a deep pool and subsequent downstream channel widening (Figure 3.3a). Plunging flows have a high velocity core that develops near the surface of a laterally constricted flow that then travels towards the bed creating a velocity inversion and the scour necessary for pool development (Venditti et al., 2014; Hunt et al., 2018; Cao et al., 2022; Li et al., 2022; Hurson et al, 2022). Plunging flows are most common in bedrock canyons, where CPW morphologies are common features, but may also occur anywhere a channel is laterally constricted by bedrock, colluvium or alluvial deposits (Leopold, 1969; Dolan et al., 1978). Rapids are observed in locations where flow is fast and shallow over steps made of bedrock or other bed features protruding upwards into a substantial portion of the water column. Steps can either be across the entire width of the channel or only a portion of the channel (Figure 3.3b). When flow is shallow enough that the bedrock steps influence surface hydraulics, a rapid is observed. An overfall is an extreme version of a rapid where flow is fast over a shallow section with a sudden and substantial change in elevation. Overfall steps are an extreme version of bedrock steps, occurring when the steps are large enough that there is a substantial elevation change observed (Figure 3.3c). At these locations flow ‘overfalls’ the steps like in a waterfall, but flow does not separate from the bed topography (i.e. water is not free falling), resulting in turbulent aerated surface flow as well as flow plunging to the bed directly below the overfall.

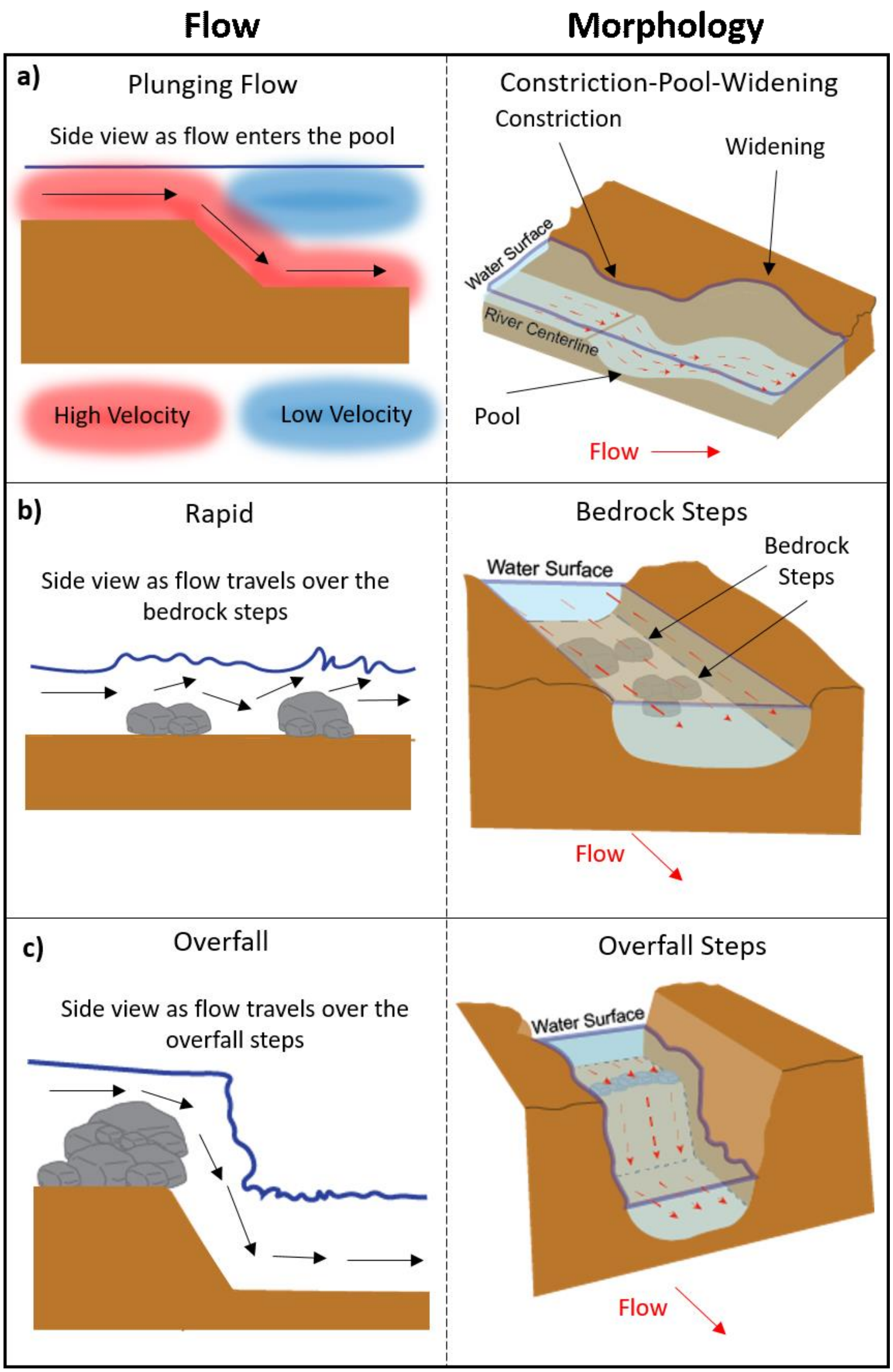

Figure 3.3. **Conceptual model of flow types and the related morphologies that create hydraulic barriers: a) Plunging flows are created by constriction-pool-widening sequences, b) Rapids are created by one or more bedrock steps, and c) Overfalls are created by overfall steps.**

It is important to recognize that plunging flows, rapids, and overfalls, and their associated morphologies are not mutually exclusive. For example, in French Bar Canyon, there is a series of rapids, with an overfall and a strong plunging flow downstream. Nevertheless, there are end members of these classifications that include Black Canyon, Yale Rapids, and the landslide in French Bar Canyon (Figure 3.4). Black Canyon is a site with a known and documented plunging flow (Venditti et al., 2014) where velocities exceed 5 m/s through a narrow constricted reach before decelerating through a series of deep pools carved by the plunging flows (Venditti et al, 2020). Plunging flows form a V-shape with strong boil generation along the sides, due to

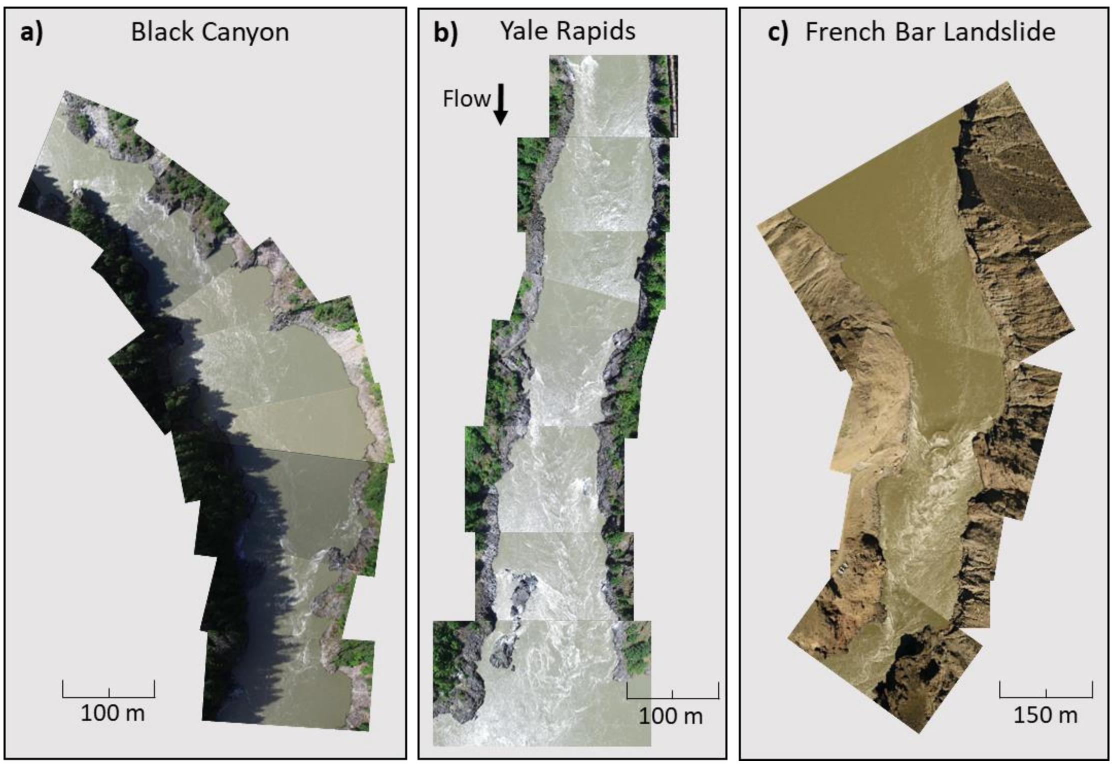

Figure 3.4. Examples of surface hydraulics for: a) Plunging Flow, b) Rapid and c) Overfall.

upwelling (Figure 3.4a). The appearance of white-water through the constriction is due largely to bank roughness. Yale Rapids presents an example of a typically rapid, with lots of 'white-water' – resulting from the turbulence experienced as flow passes over the bedrock steps – through the middle of the channel, but can extend all the way towards the banks in narrower sections (Figure 3.4b). The landslide in French Bar Canyon is the site of a new overfall where a concentrated section of white-water can be seen at the location of the overfall steps (Figure 3.4c). Directly upstream of the constriction the water surface is smooth, fast moving and forms a V-shape leading into the overfall steps. Overfalls are uncommon, but other examples include the Bridge River Rapid and Hell's Gate where there is a substantial elevation change in the water surface at low flows over a short downstream distance.

3.3. Comparison of river centerline velocity to salmon swimming capabilities

When only looking at centerline velocities, it would appear that a large portion of the Fraser Canyon, even at low flow, would not be passable to the salmon species of interest without them being forced to swim anaerobically (i.e. prolonged or burst swim type) for a substantial portion of their migration (Figure 3.5). Encounter velocities have been marked as requiring prolonged if they exceed the maximum passable encounter velocities for sustained swimming, as requiring burst if they exceed prolonged thresholds, and as above burst if they exceed burst thresholds. Maximum bursting

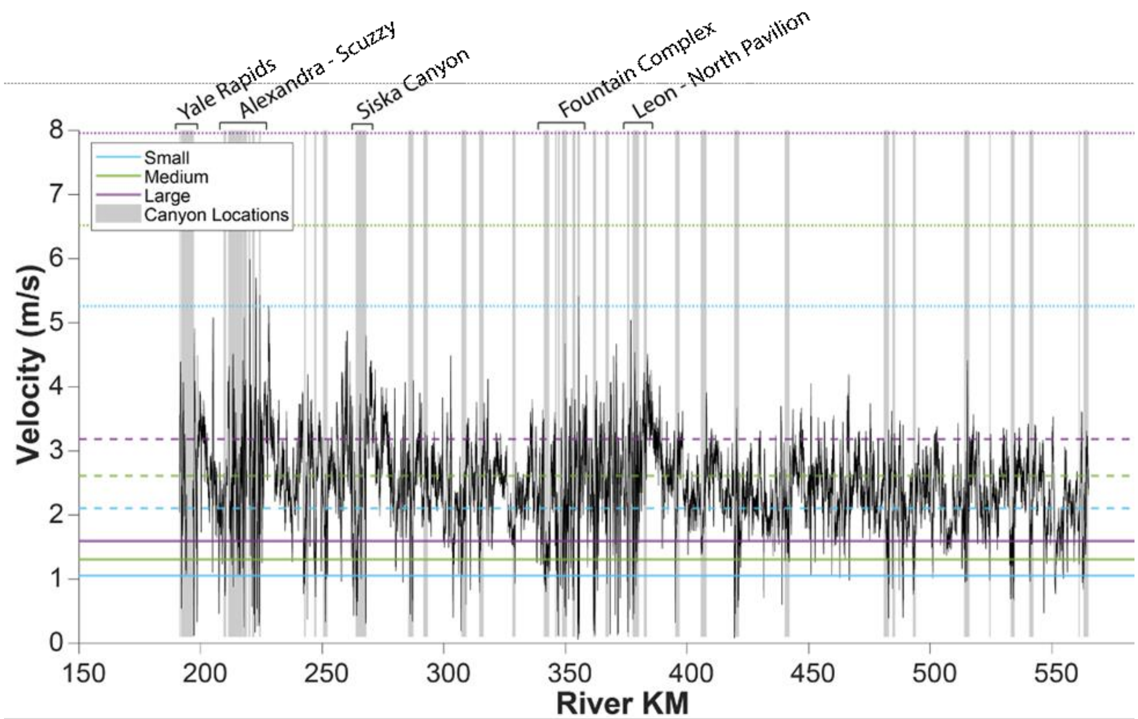

Figure 3.5. Along-stream velocity profile (solid black line) through the Fraser Canyon indicating where thresholds for sustained (solid line), prolonged (dashed line), and burst (dotted line) swim speeds for small, medium, and large salmon are likely to be exceeded. Regions with frequent canyons and higher velocity have been marked.

abilities have been defined as the maximum instantaneous swim speed that a fish is able to achieve (Table 2.1), and is not measured over a channel distance. Based on the burst speed thresholds that I have assigned to each size class of salmon, all high velocity zones appear passable for the large and medium fish, but not small fish. However, since fish can only swim at burst speeds for short periods of time, it is unlikely that they would be able to sustain anywhere near these maximum speeds for the required time that this along-stream velocity plot would suggest.

My centerline velocity results would suggest that locations requiring anaerobic swimming occur throughout the Fraser Canyon (Figure 3.6) and can be observed within all morphologies (Figure 3.5). For larger fish, 326 km of the 375 km Fraser Canyon requires some form of anaerobic swimming, with 48 km requiring burst speeds and 0.12 km requiring speeds above burst. The swim categories are based on the assumption that fish will traverse 50 m long channel sections at a time before stopping to rest. None of the sections exceed maximum bursting ability (7.96 m/s) and could be passed if rest areas are within these high centerline velocity sections, thus breaking them into smaller sections of burst/rest movement. For medium sized salmon, locations requiring anaerobic swimming covered a total of 332 km. Of this distance, 145 km requires medium sized salmon to swim at burst speeds and 4.3 km would require speeds above burst. None of the locations exceed maximum bursting ability (6.52 m/s). For smaller fish, 333 km of the Fraser Canyon requiring anaerobic swimming, 145 km requiring burst speeds and 110 km requiring speeds above burst. In a number of locations maximum bursting ability for smaller fish (5.26 m/s) is exceeded. This highlights the importance of fish size when looking at the frequency and location of potential velocity barriers (Figure 3.6).

The abundance of locations flagged as requiring anaerobic swim is likely an overestimate of how frequently this is required as I am focused on the centerline velocity. Since it is unlikely that salmon will choose to swim through the center of the channel, looking at centerline velocity is only able to give us an idea of which sections are likely the greatest barriers. To explore what the potential barriers look like on a one-to-one basis, I need to examine the spatial distribution of velocity through morphologies apt to produce barriers.

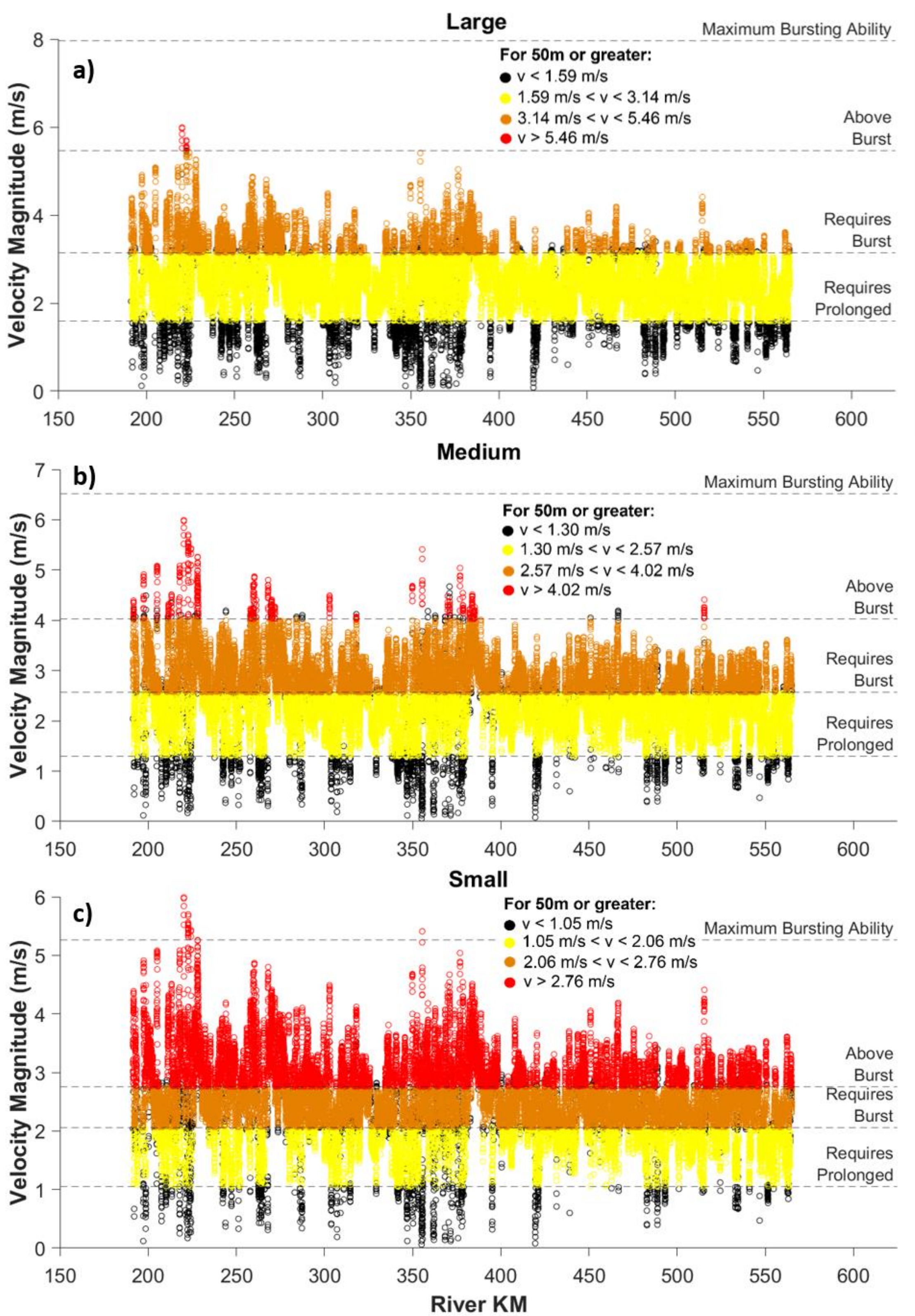

Figure 3.6. **Sections of the Fraser Canyon where centerline velocities suggest that swim speeds that use anaerobic respiration are required for a) large, b) medium, and c) small salmon.**

Chapter 4.

Velocity structure through morphologies creating high velocity zones

4.1. LSPIV validation

In order to validate the LSPIV method for my observations, I used the top bin of ADCP measurements which gives the velocity at ~1 m below the surface. For locations where the 2009 ADCP track follows the centerline of the channel (Figure 4.1a-b) the correlation between ADCP and LSPIV measurements is strong. As the ADCP track deviates from the centerline, the correlation decreases (Figure 4.1c). Through Devil's Tooth as the ADCP line switches from one bank to the other, missing the thalweg, the velocities separate and no correlation is observed between the ADCP and LSPIV measurements (Figure 4.1d).This is not surprising as velocities along the bank are more dynamic, with turbulent eddies and upwelling features more common. The LSPIV accounts for these as it is a time-averaged measurement whereas the ADCP measurements are instantaneous and more apt to reflect dynamic flow structures. The deviation between LSPIV and ADCP even where correlation is high is not surprising. The measurements are taken twelve years apart and there are documented changes in bed surface cover that may affect surface velocities (Hurson et al., 2022). The relation between ADCP and LSPIV velocities is substantial and strong enough to justify the use of LSPIV to accurately represent surface velocities.

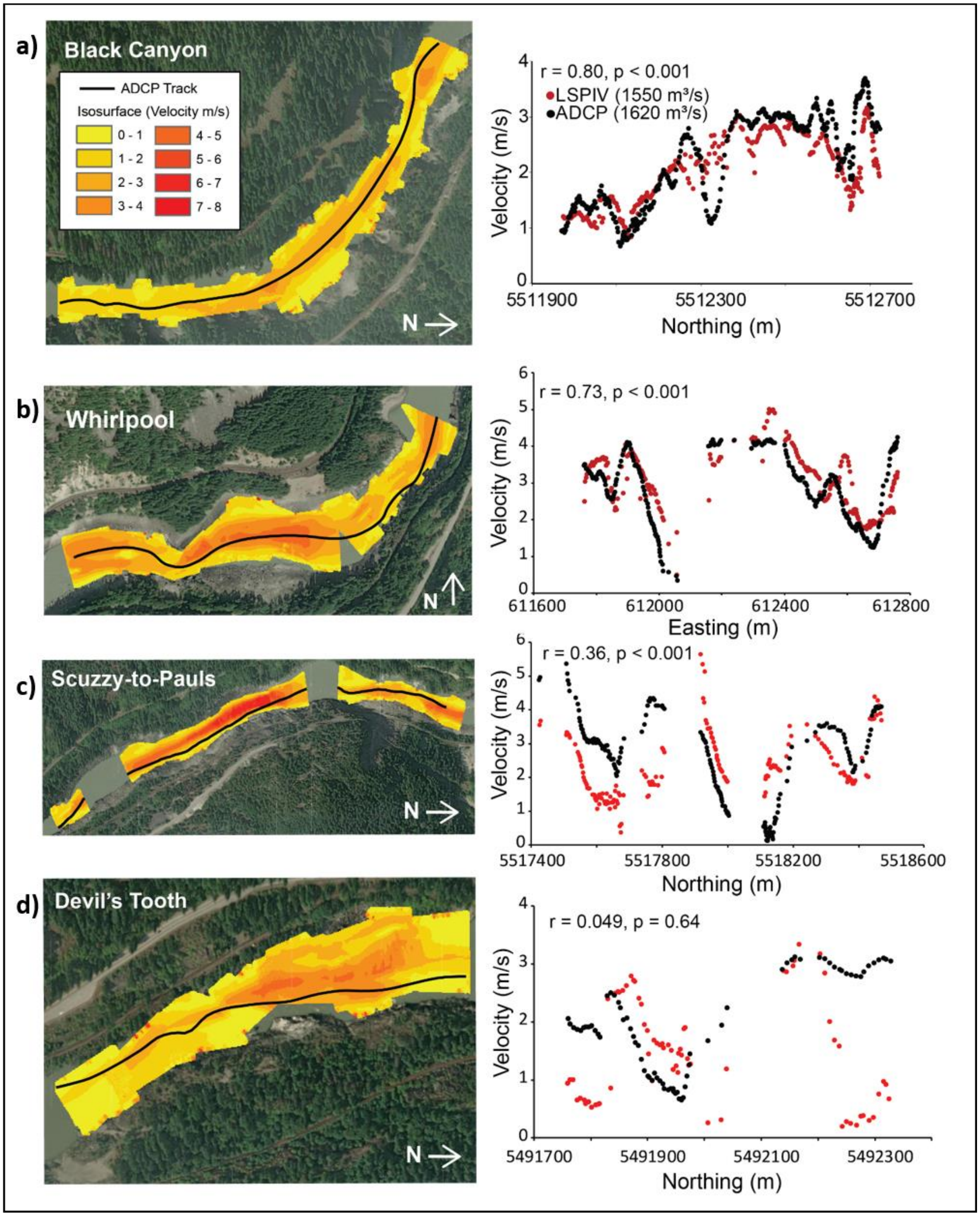

Figure 4.1. Comparison of LSPIV and ADCP derived surface velocities for four key locations.

4.2. Velocity patterns at plunging flows, rapids, and overfalls

Comparing high flow measurements, I see that Yale Rapids and the French Bar Canyon landslide have sections of higher surface velocity than does Black Canyon (Figure 4.2). At all three sites a high velocity core through the center of the channel is observed, with lower velocities out towards the banks. Black canyon follows this pattern but with patches of higher velocity observed through the center (Figure 4.2a). Yale Rapids (Figure 4.2b) has a consistent pattern of high velocity through the center of the whole site, and the French Bar Canyon landslide (Figure 4.2c) has two sections where velocity is highest, the more upstream and larger section being the location of the overfall. In Black Canyon, the higher velocities (Figure 4.2a) occur at the locations where surface turbulent features are observed (Figure 3.4a). The wider section between the more constricted higher velocity sections of Black Canyon has lower velocity throughout and could potentially act as a rest location for salmon. In Yale Rapids, the observed high velocity centerline (Figure 4.2b) aligns well with the turbulent, or white-water, features observed in the Figure 3.4b imagery. The same thing is observed for French Bar Canyon, with the highest velocity (Figure 4.2c) observed through and between the two constrictions where I observe the surface white-water features (Figure 3.4c).

At higher discharges, higher velocities were observed for all three flow types (Figure 4.3). Between high and moderate flow, Black Canyon and Yale Rapids have discharge changes of ~ 4750 m^3/s. The change between high and moderate, and moderate and low flow are relatively similar, at ~ 2350 m^3/s and ~ 2400 m^3/s respectively. Data for the French bar landslide was extracted from pre-existing imagery and thus had a slightly different discharge change of ~ 4230 m^3/s between high and low flow. Between high and moderate flow there was a change of ~ 1480 m^3/s and between moderate and low flow there was a change of ~2750 m^3/s.

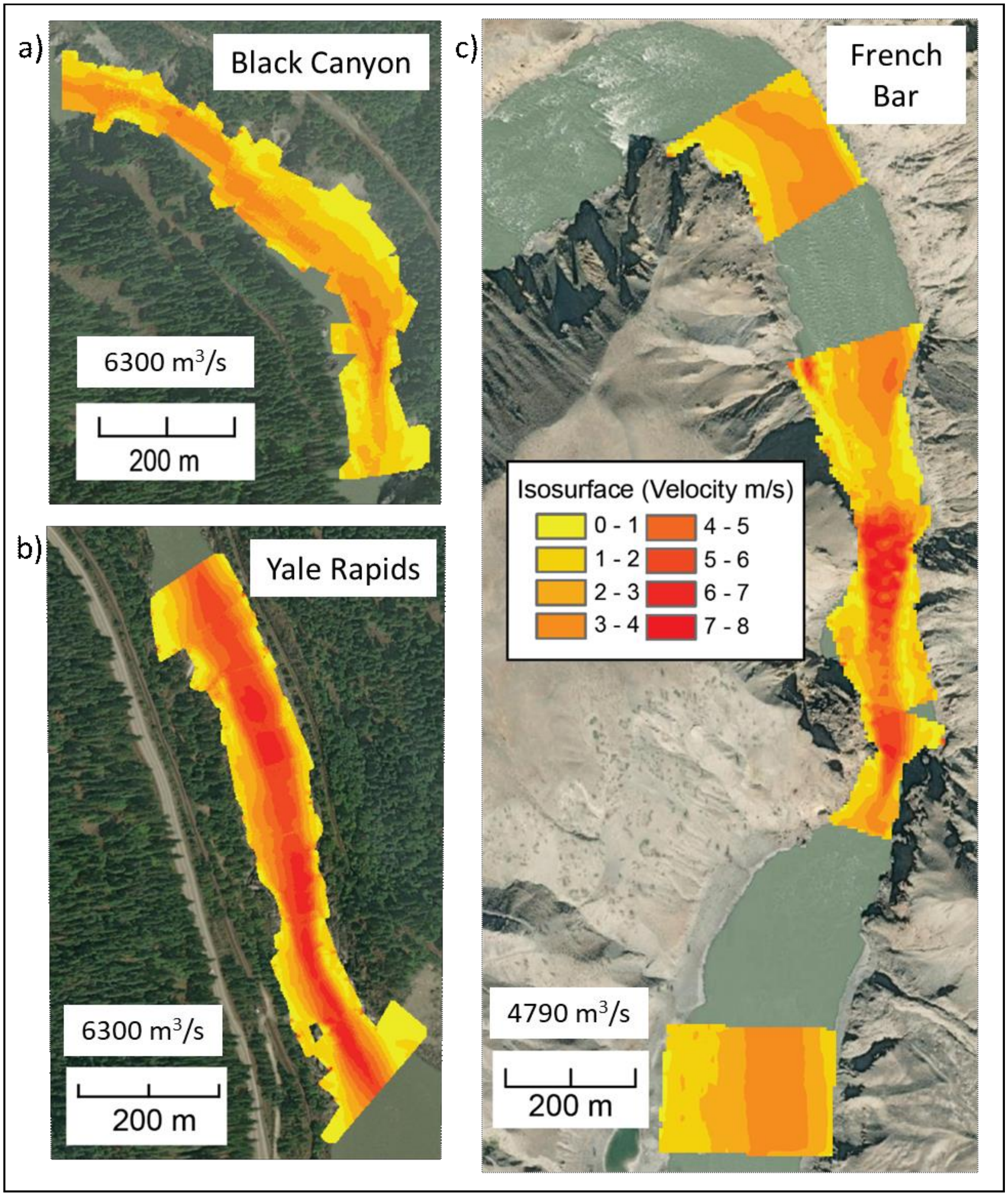

Figure 4.2. High flow measurements for a) Black Canyon, b) Yale Rapids and c) French Bar Canyon landslide.

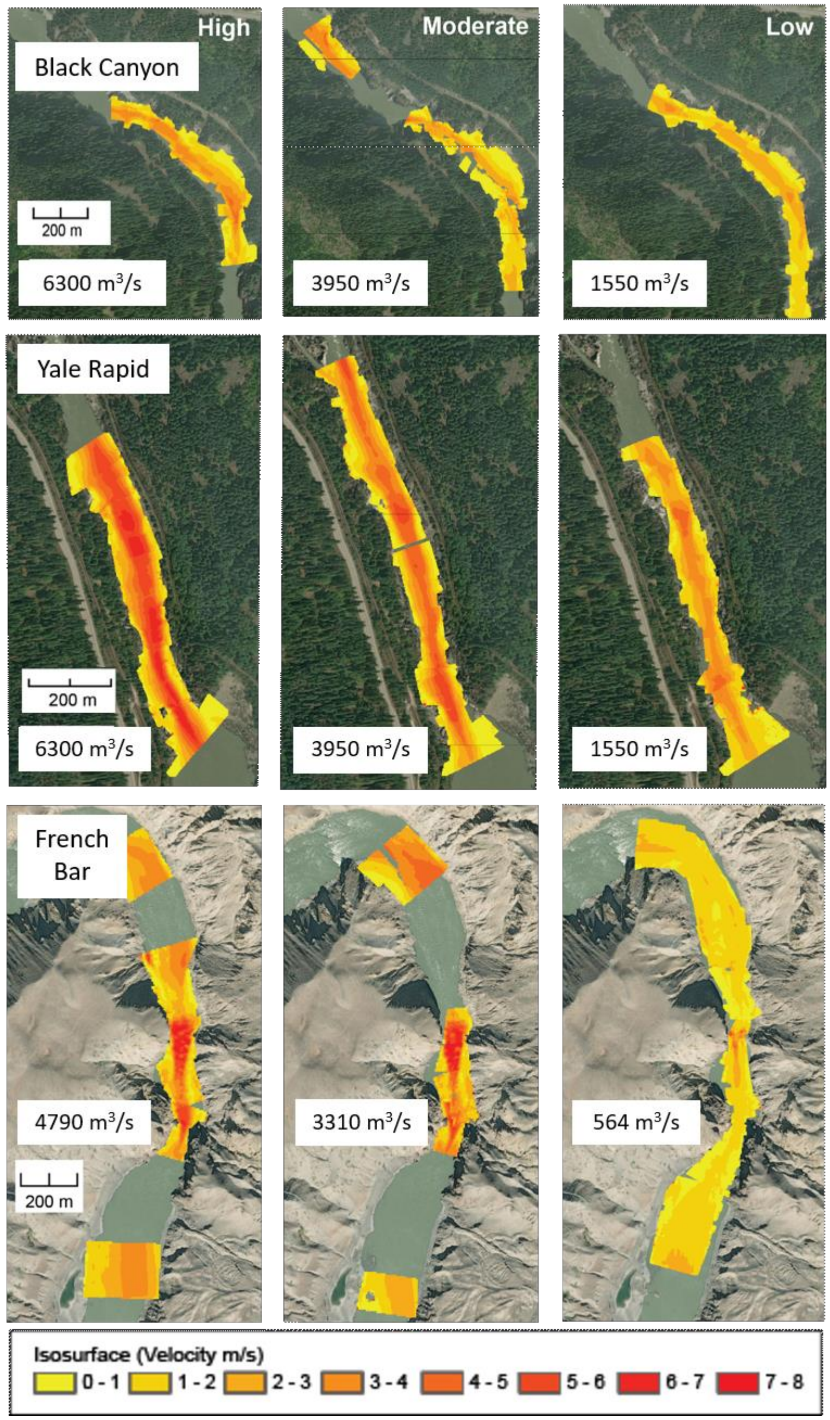

Figure 4.3. Examples of how surface velocity changes with discharge for different types of high velocity zones.

For Black Canyon, between the highest and lowest flow there was an average surface velocity decrease of about 0.58 m/s, with 79% of this change observed between high and moderate flows. For Yale Rapids, between the highest and lowest flow measurements there was an average surface velocity decrease of about 1.72 m/s with 64% of the change in velocity observed between the high and moderate flow measurements. Both sites experienced the greatest overall change in surface velocity between high and moderate flows, over only 49% of the discharge change. At French Bar, the difference in surface velocity between the highest and lowest flows there was an average decrease of about 2.02 m/s. 73% of this change was observed between moderate and low flows, which covers about 65% of the overall discharge change. This highlights that encounter velocities are stage dependent, which is important when barrier frequency based on fish migration times.

At all three discharges, the pattern of where high velocity was found along the channel was relatively similar. Black Canyon continues to have the highest velocities through the center of the channel, with some deviation towards the river-left bank for low flow. Yale Rapids still has the center of the channel as the highest velocity, with low flow being a bit patchier and less consistent in velocity magnitude. French Bar Canyon's highest velocity is observed at and between the two constrictions, with the upper constriction being the highest velocity section in all three flow types. At low flow, the entire French Bar landslide site is below 3 m/s.

Calculating the bank velocity at the location of each individual potential barrier is not possible with the data available, but I am able to infer how bank velocity will compare to centerline velocity based on the morphology type of the barrier (Figure 4.4). CPWs have relatively low variability between bank and centerline velocities, and between higher and lower flows (Figure 4.4a-c). This flatter distribution is not surprising, as I expect to see surface velocities that are lower than the depth-averaged centerline velocities as I know that the high velocity in morphologies similar to those of Black Canyon, will plunge towards the bed. From observations of Black Canyon it is known that CPW sequences create vertical upwelling along the river banks (Venditti et al., 2014), potentially making near bank swimming more challenging. At all three tested flow levels, rapids have higher centerline velocities than bank velocities. For all three flows, near bank velocities are between 1 m/s and 3 m/s (Figure 4.4d-f). This suggests that even at high flows, major rapids with similar width and morphology as Yale Rapids, should be passable for salmon swimming near the banks. Overfalls are typically laterally constricted, creating a lesser gradient between the centerline velocity and the bank velocity (Figure 4.4g-i). When looking at only the cross-sections taken from over the

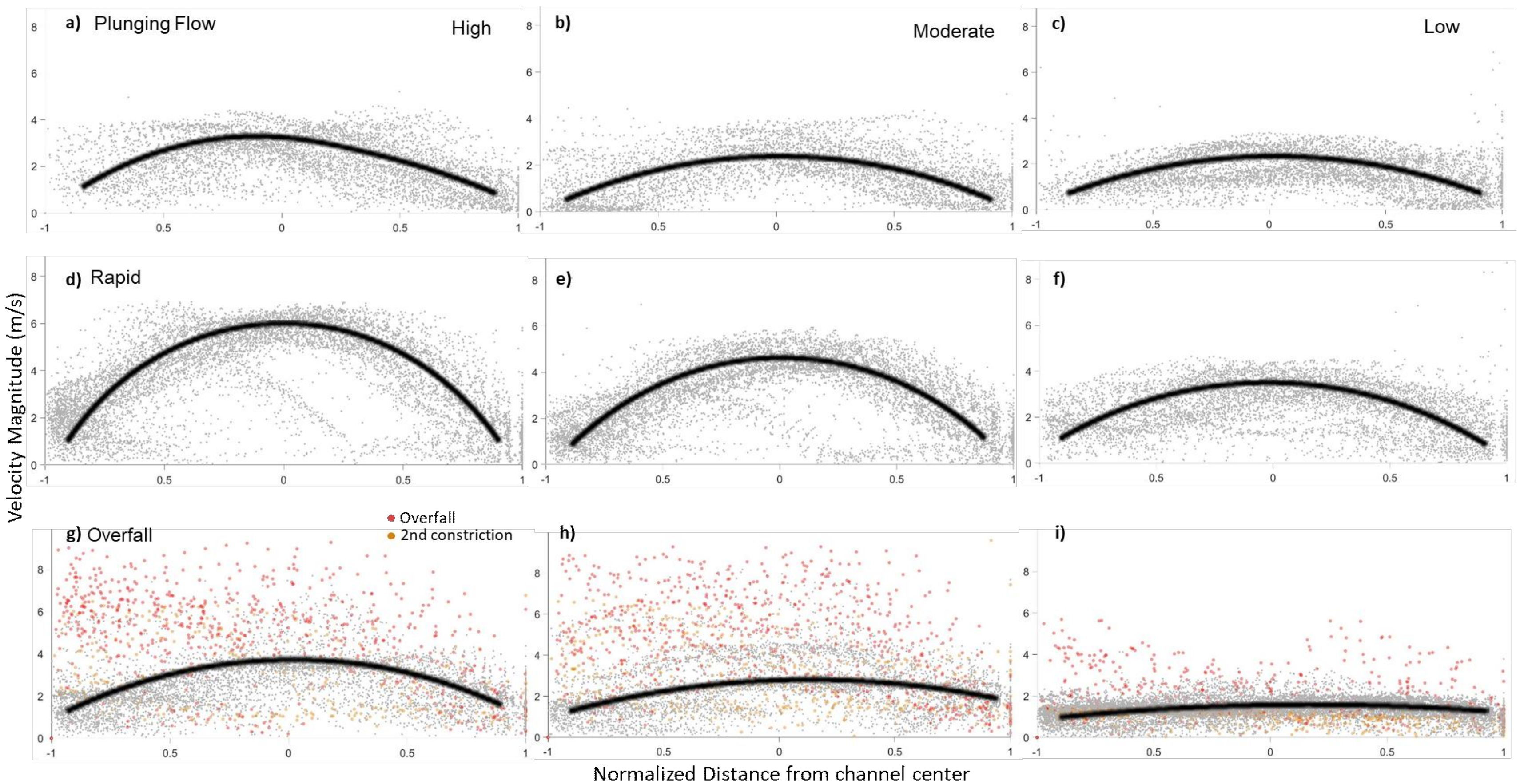

Figure 4.4. **Distributions of cross-stream surface velocity normalized by channel width (-1 is the river right bank and 1 is the river left bank) for a CPW sequence at a) high, b) moderate, and c) low flow; a rapid at d) high, e) moderate, and f) low flow; and an overfall at g) high, h) moderate, and i) low flow.**

overfall location and ignoring the rest of the site, at high flows velocities are high almost all the way across the channel, making overfalls more challenging for salmon to navigate as there are no low velocity sections to ‘hide’ or rest (Figure 4.4g-h). Since French Bar includes information from the overfall, the second – downstream – constriction as well as the upstream and downstream sections, it has the greatest degree of variability when it comes to bank and centerline velocities when compared with the other sites. This variability is most apparent for high and moderate flows, as low flow has relatively low velocities throughout the entire channel width. At high and moderate flows, the profiles with higher velocity are those directly at the overfall location, whereas the lower ones are those above and below the actual overfall steps. Black Canyon has relatively lower surface flow velocities and a low velocity gradient. Yale Rapids has higher flow velocities and a steeper velocity gradient. French Bar has the highest velocities, but the lowest gradient.

4.3. Comparison of spatial surface velocity to salmon swimming capabilities

Surface velocity observations demonstrate that, even at high flows, sections of the channel appear to be passable – do not require swim speeds above burst – for medium sized adult salmon (Figure 4.5). For different barrier types, the amount of the channel that would likely require anaerobic swim types varies. Through the center of the channel at Black Canyon, prolonged and burst speeds are required. Along the banks there are some sections that would suggest the need for anaerobic respiration, but there are also sections where water velocities would only require sustained swimming. As discharge decreases, the areas requiring prolonged and burst speed also decrease. Based on surface velocity measurements, no sections exceed the maximum bursting ability of medium adult salmon. Comparatively, in Yale Rapids more of the channel would suggest the need for swim speeds that require anaerobic respiration. At high and moderate discharges much of the center of the channel requires burst speeds, with some small sections at high flow exceeding bursting abilities for medium adult salmon. At all three discharges, there are sections along the banks that allow for sustained swimming. These slower velocity areas increase as discharge decreases. Looking at French Bar, through the most constricted section, anaerobic swim speeds are required to pass at all discharges. At high and moderate discharges there are also sections at the

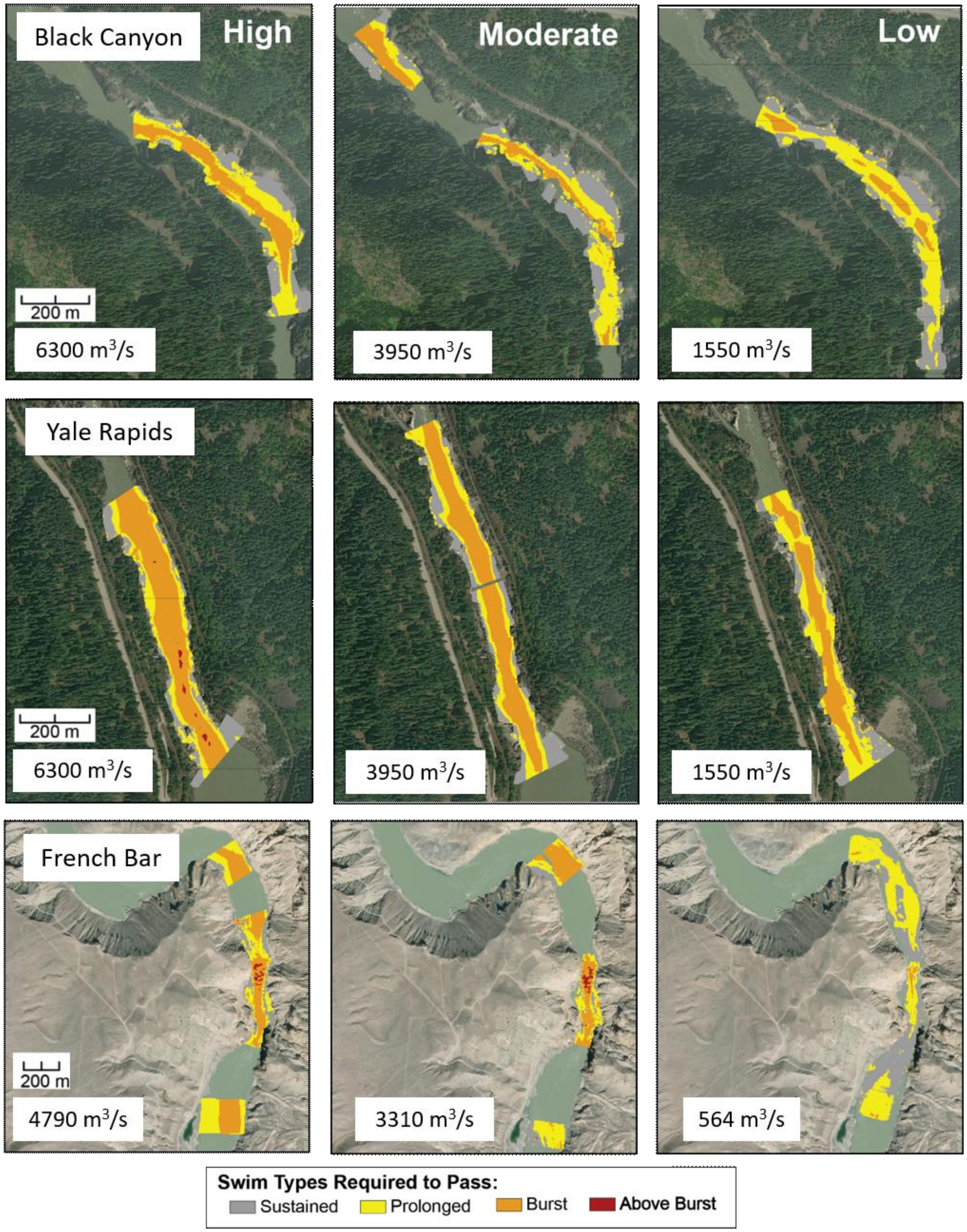

Figure 4.5. Examples of how surface velocity compares to swimming capabilities of medium sized salmon (body-length 65.2cm) for different types of high velocity zones.

landslide site where water velocities exceed bursting abilities. At high and moderate discharges, there are very few sections that would suggest sustained swimming is possible. This changes as discharge continues to decrease, with much more of the channel having velocities below anaerobic thresholds.

Looking at species separately – using mean body-length values from Kraskura (2022) – there are still sections at each site, and across all discharges, that allow fish to swim at speeds that do not require anaerobic respiration (Figure 4.6, see Appendix for individual species figures). Timing of when each salmon species of interest are found within the river will vary and determine if it matters whether the channel is passable for them or not. During the late spring and early summer months, when flow is typically the highest, Chinook and Sockeye return to the Fraser River on their way to spawning grounds. Chinook are the largest salmon, with average lengths greater than those used for medium salmon in my analysis (Figure 4.5), suggesting that they should be able to pass through these sites at the higher flows without extreme difficulty. As a result of their size, there are sections of the channel that appear to be passable to Chinook without requiring anaerobic respiration (Figure 4.6). Sockeye are smaller than Chinook and may be forced to swim anaerobically slightly more frequently than Chinook. During the late summer and early fall, when flows begin receding and become more moderate, all five salmon species of interest can be found within the Fraser. At these moderate flows, all three study sites have sections along the banks that are passable to all species. Pink, which are the smallest and roughly around the size of the small salmon estimates that I have used, travel through the Fraser in the fall when flows should be between the moderate and low levels. The passable sections expand as flow continues to decrease, making it so any species traveling in the late fall and winter – such as Coho – are able to get through these sections.

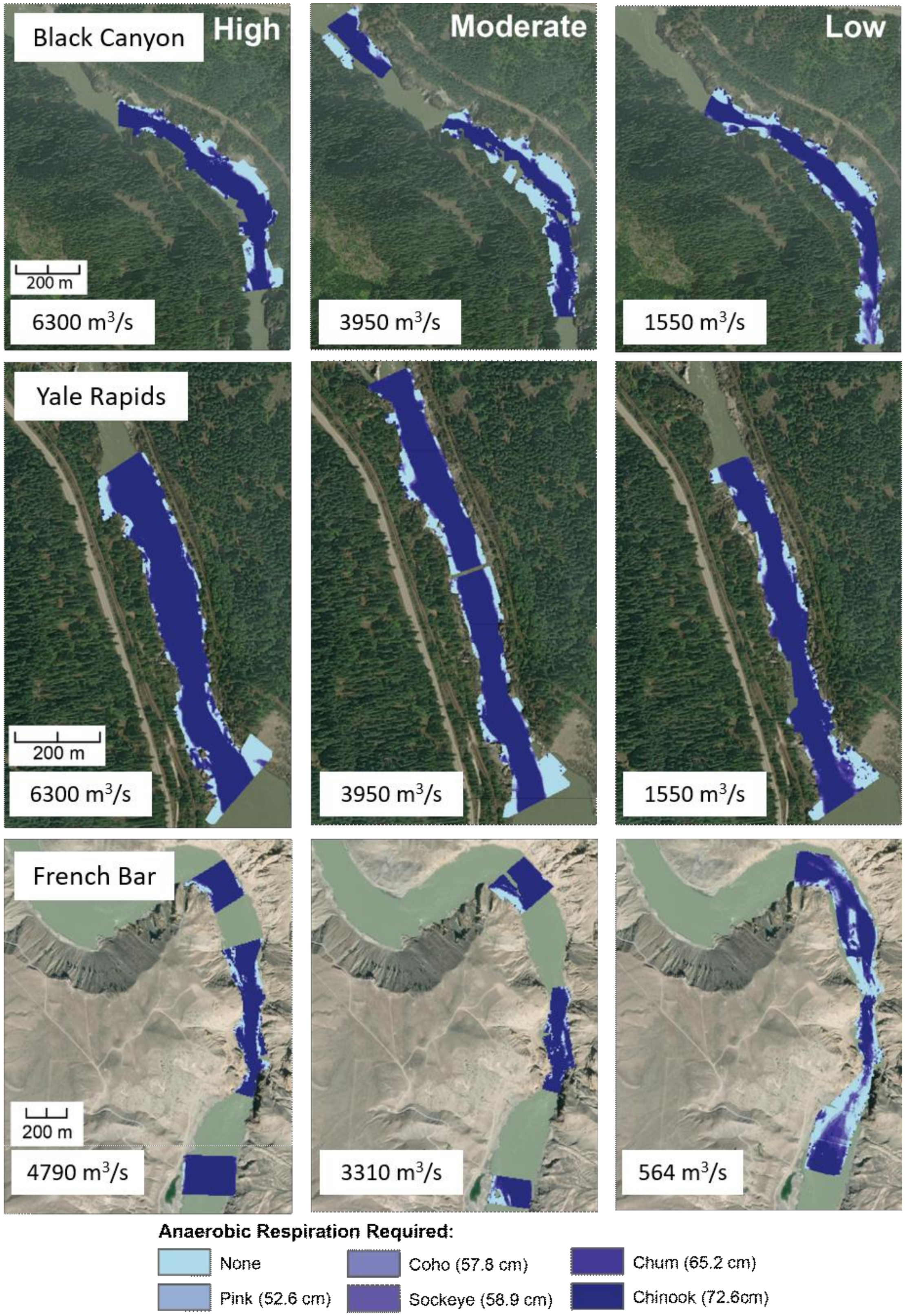

Figure 4.6. **Examples of how surface velocity compares to the anaerobic thresholds for the 5 salmon species of interest, using mean body-size, for different types of high velocity zones.**

Chapter 5.

Discussion

My results highlight the importance of fish size and flow level when considering the passability of a potential barrier. River morphology has created a number of locations in the Fraser River that may act as barriers to adult salmon migration, slowing or blocking upstream movement depending on fish size, and by extension species. Further, I have noted how varying channel morphologies influence centerline and bank velocities differently. At locations that are constricted and have fast flow, such as the landslide site in French Bar, cross-stream velocity gradients are lower and bank velocities above 8 m/s are observed. This suggests that the greatest barriers will occur at sites with similar morphology to French Bar Canyon. In morphologies similar to either Black Canyon or Yale Rapids, although lower bank velocities are observed, there are still bank velocities present which surpass aerobic swimming abilities of the five salmon species of interest.

5.1. Abundance of morphologies that may form hydraulic barriers

My results suggest that there are 22 locations that have the potential to act as hydraulic barriers to adult salmon migration. Exploring the locations and frequency of the morphologies most likely create hydraulic barriers – major rapids, plunging flows, and overfalls – I find there to be a greater distribution of locations (Figure 5.1). Locations of major rapids have been noted based on imagery of the river at a variety of flows. Major rapids have been marked at locations that have bedrock steps that protrude far enough into the flow to create rapids even at higher flows. There are 12 major rapids marked, with all of these occurring in the southern half of the Fraser Canyon. The easiest way to identify locations of plunging flows from the data is by noting the locations of the major pools in CPW sequences. Sections of the Fraser Canyon that had widths < 100 m (constricted) and depths >15 m (pool) were marked as possible CPW sequences.

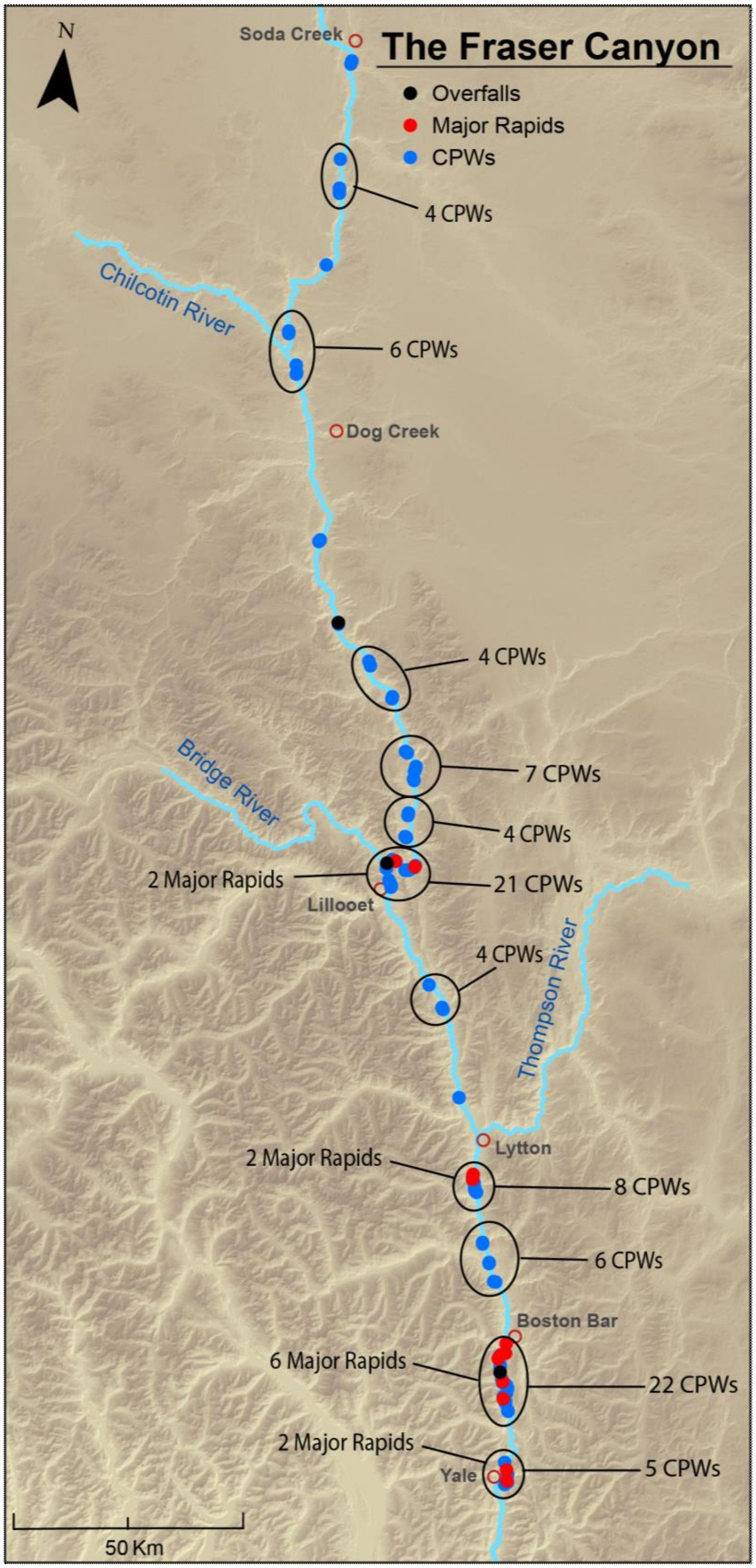

Figure 5.1. Overfalls, major rapids, and constriction-pool-widenings through the Fraser Canyon.

This was further refined to only look at sections where this criteria was met for at least 20 m along-stream (i.e., there were at least 2 subsequent measurements that met this criteria) and occurred within 100 m of a canyon. This left us with 99 marked CPWs throughout the Fraser Canyon. Overfalls have been marked based on observations made in the field as the instruments are unable to collect data over these sections (because of flow aeration as well as danger to equipment and operators). The 3 major overfalls through the Fraser Canyon are French Bar landslide, Bride River Rapids, and Hell's Gate. The locations of major rapids, CPWs and overfalls in the central and southern portions of the Fraser Canyon aligns with the locations of high velocity and suspected high velocity. In the norther portion (north of French Bar) there are CPWs present but no high velocity or suspected high velocity sections.

One of the limitations of my study is that I only have one complete along-stream velocity profile of the Fraser Canyon. Since I am using a low flow measurement, it is likely that the size frequency of the channel segments with higher velocities resulting in the need for fish to frequently rest will be discharge dependent, and vary for species based on when they are spawning. Continued monitoring and data collection at multiple flows throughout the entire canyon as well as at a variety of smaller focus sites would be beneficial to extend the results past low flow – and obtain high flow data for more than just a select few sites. Further data collection would also allow for the creation of a model to show how barriers, found throughout the entire river, change with flow.

5.2. Potential pathways for barrier navigation

How salmon navigate hydraulic barriers will be dependant on the channel morphology. For plunging flows, medium sized salmon are likely able to travel along the banks using a combination of sustained and prolonged swim speeds. As seen in Black Canyon, at locations with plunging flows there are typically wider sections at the downstream end that would likely allow adult salmon to rest before having to traverse the more narrow upstream constriction. As discharge decreases, the portion of the channel that requires burst swimming also decreases, this extends lower bank velocities further into the channel and expands the possible pathways. For rapids, salmon will likely swim closer to the banks, avoiding the high velocity core that is observed through the center of the channel at all discharges. Looking specifically at Yale Rapids, at all observed discharge levels there are sections along both banks that would allow for salmon to swim upstream, using sustained or prolonged swim speeds, without having to cross to the opposite bank. At the downstream end there is also a wide section that salmon likely rest in before attempting to pass the rapid. Much of the site allows salmon to swim along the banks without swimming anaerobically, but there are small sections where salmon will likely be required to use burst speeds even along the banks. For overfalls, salmon are forced to swim against greater velocities and traverse a vertical barrier as well. At high and moderate flows, the overfall location at the French Bar landslide site requires burst swimming – across the entire width of the channel – to pass. There is a section of the channel between the two constrictions that widens and, even at the higher flow stage, has velocities low enough that fish would likely be able to rest here before attempting to pass the upstream constriction – where the overfall is located. This wider section also consists of a back eddy so flow along the bank are actually moving in the upstream direction, making it even easier for fish to travel in this section. The size of the rest area increases and the velocity within the section decreases with decreasing discharge. All barrier types are likely to force salmon to swim at burst speeds at some point while attempting to pass. The distance covered using burst swimming required will likely vary though, with plunging flows requiring minimal burst swimming, rapids requiring slightly more, and overfalls requiring the most.

5.3. Cumulative impacts and management implications

In the Fraser River, during years where discharge is unusually high – and thus river encounter velocities are also higher – or when peak discharges occur earlier or later than expected, energy demands to travel the same distance to the spawning grounds are likely higher (Rand et al., 2006). Thus, energy expenditure is highly dependent on the frequency of morphologies and flow structures that are likely to create hydraulic barriers. Upstream migration during spawning for Pacific salmon is energetically expensive and is done by fish using only their reserved energy as feeding ceases before they re-enter fresh water. My approach to velocity barriers ignores the cumulative distance upstream that each barrier occurs at, not taking into account recovery times associated with fatigue. Some of the most challenging barriers occur after salmon have overcome many other barriers. For example, Bridge River Rapid is 347 km upstream of the ocean and beyond the Scuzzy to Alexandra Canyon complex where velocities average 2.62 m/s, with maximum values of 5.99 m/s (the actual maximum is likely higher as measurements are missing from Hell's Gate due to high aeration of flow) for ~ 15 km. French Bar exists another 72.5 km upstream (river kilometer 419.5) of the Bridge River Rapid and the rest of the Fountain Canyon complex where velocities average 2.17 m/s, with maximum values of 5.41 m/s for ~9 km. This means that barriers of the same velocity magnitude are potentially more problematic the further upstream they are as the fish have depleted energy supplies. Consequently, I may be underestimating the degree or prevalence of upstream barriers. Another compounding factor is attempt rate. It is common for fish to take multiple attempts to pass a barrier, with the first attempt often being undertaken at swim speeds that are not optimum to pass, thus resulting in failure to pass (Castro-Santos, 2005). It has been shown that attempt rate as well as swimming capabilities determine an individual's ability to traverse velocity barriers (Castro-Santos, 2004). With the timing and the magnitude of the freshet differing year to year, further work exploring the discharges that make certain locations impassable to various species of spawning salmon would be a valuable next step in the analysis of hydraulic barriers and examination of potential mitigation options such as installation of fish passage structures.

My methods provide only one way of looking at hydraulic barriers to migration. To confirm these locations as velocity barriers, the results should be compared with radio tag data from salmon tagged at different sizes. Radio tag data approaches the same problem but from an opposite angle, looking initially at the fish to see how long they are spending in a single location. The addition of activity sensor tags (eg. Fuchs & Caudill, 2019) would also allow for an estimate of energy expenditure across each location. Using these two methods to look at morphology and fish energy expenditure, I would be able to increase the confidence in the locations of the velocity barriers substantially. Together, the resulting frequency and distributions of the different types of barriers will have implications for salmon management as it will shed light on locations that salmon are likely struggling the most to pass and thus the most vulnerable to predation. At key locations where it is likely that fish are required to rest, guidelines for salmon harvesting could be implemented.

Chapter 6.

Conclusion

I have presented depth-averaged velocity measurements through the entire Fraser Canyon as well as a focus on surface velocities for Black Canyon, Yale Rapids, and French Bar Canyon to highlight locations, morphologies, and discharges that are likely to act as hydraulic barriers to adult salmon migration. My observations lead to the following conclusions:

1. There are twenty-two locations, concentrated between French Bar Canyon to Fountain Canyon, and Siska Canyon to Yale Rapids, that have been marked as potential hydraulic barriers.
2. Three morphologies have been identified that create flow structures associated with hydraulic barriers: constriction-pool-widenings, bedrock steps, and overfall steps. The frequency of these morphologies suggests that there are more than the twenty-two identified locations that could impede upstream fish movement.
3. Locations with high velocities and lower gradients between centerline and bank velocities will act as the greatest barriers to salmon migrations. These flow conditions are typically observed through overfalls, with rapids and plunging flows typically exhibiting lower bank velocities. Cross stream velocity trends do not appear to be discharge dependant.
4. For all barrier types, at high and moderate flows, there are sections that require fish to swim using anaerobic speeds.

My work suggests that hydraulic barriers are present in all morphologies found through the Fraser Canyon, but are likely to be most problematic within the narrower bedrock-bound reaches. With anthropogenic factors, such as climate change and ocean warming, already threatening salmon species, it is imperative that efforts are focused on minimizing any other obstacles to migration. Management efforts should be focused on the sections of the river that have canyon complexes, as these are also the river sections with the highest frequency of hydraulic barriers.

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Appendix.

Species specific comparison of surface velocity and swimming capabilities

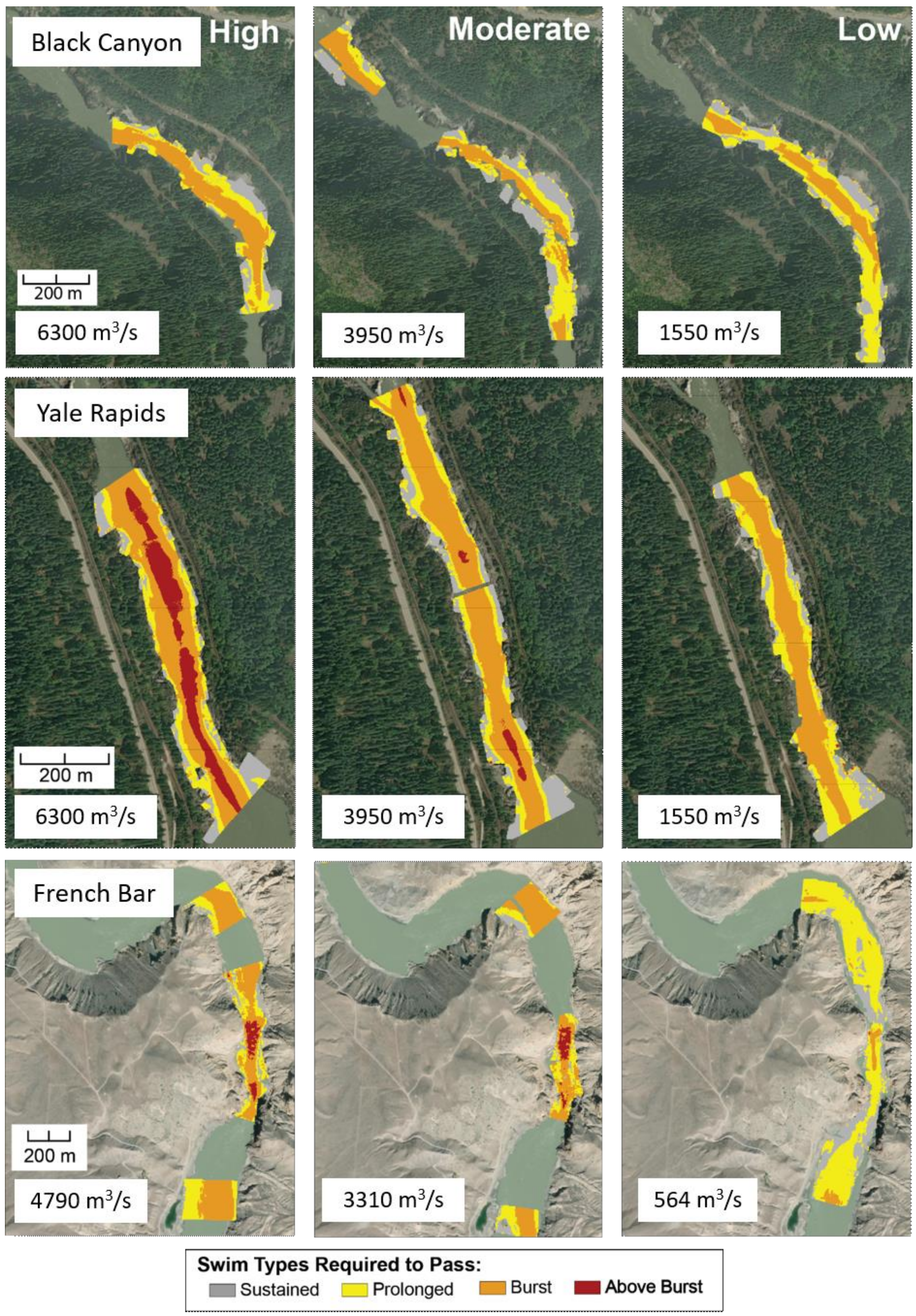

Figure A1. **Examples of how surface velocity compares to swimming capabilities of a medium size Pink salmon (body-length 52.6 cm) for different types of high velocity zones.**

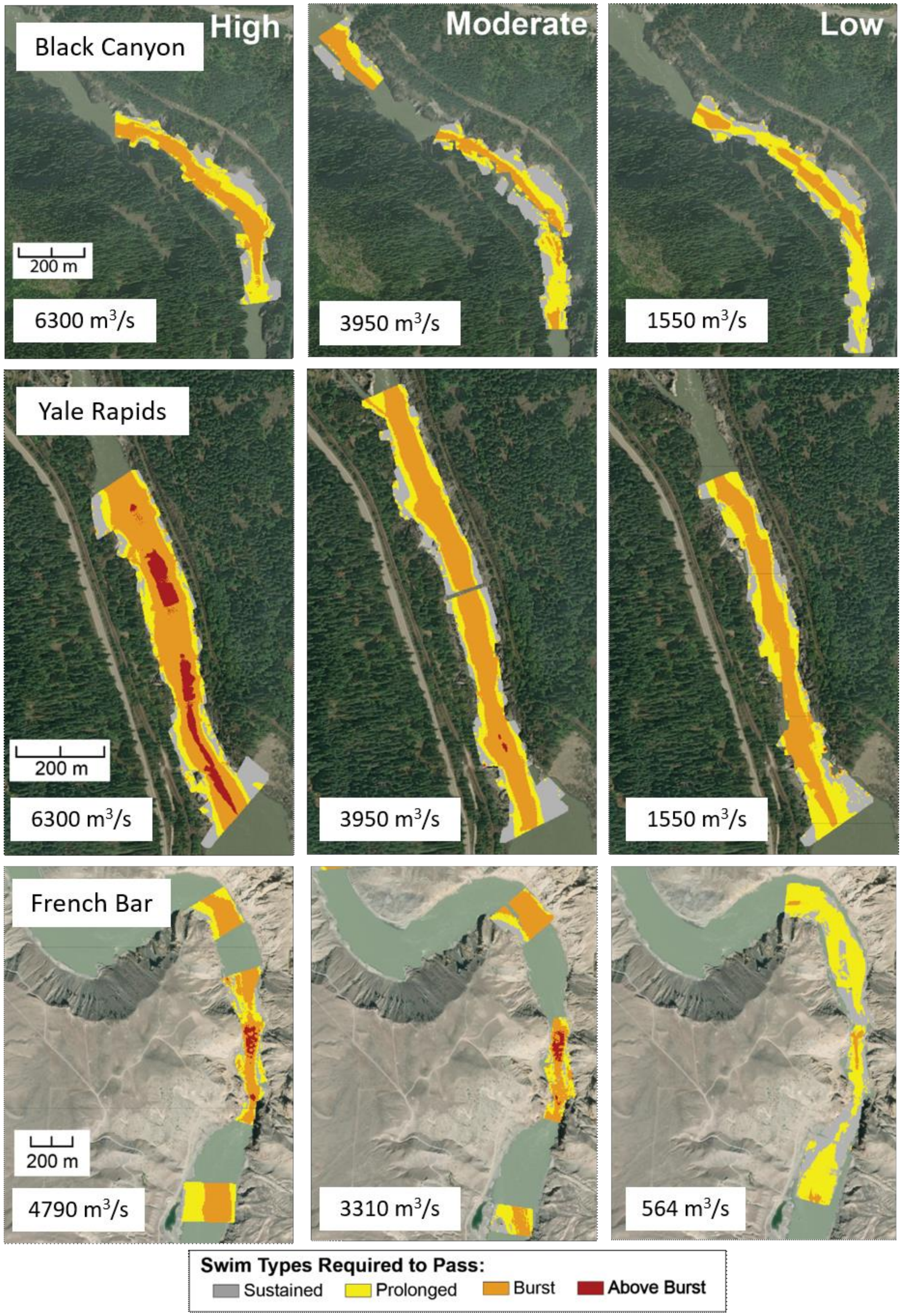

Figure A2. **Examples of how surface velocity compares to swimming capabilities of a medium size Coho salmon (body-length 57.8 cm) for different types of high velocity zones.**

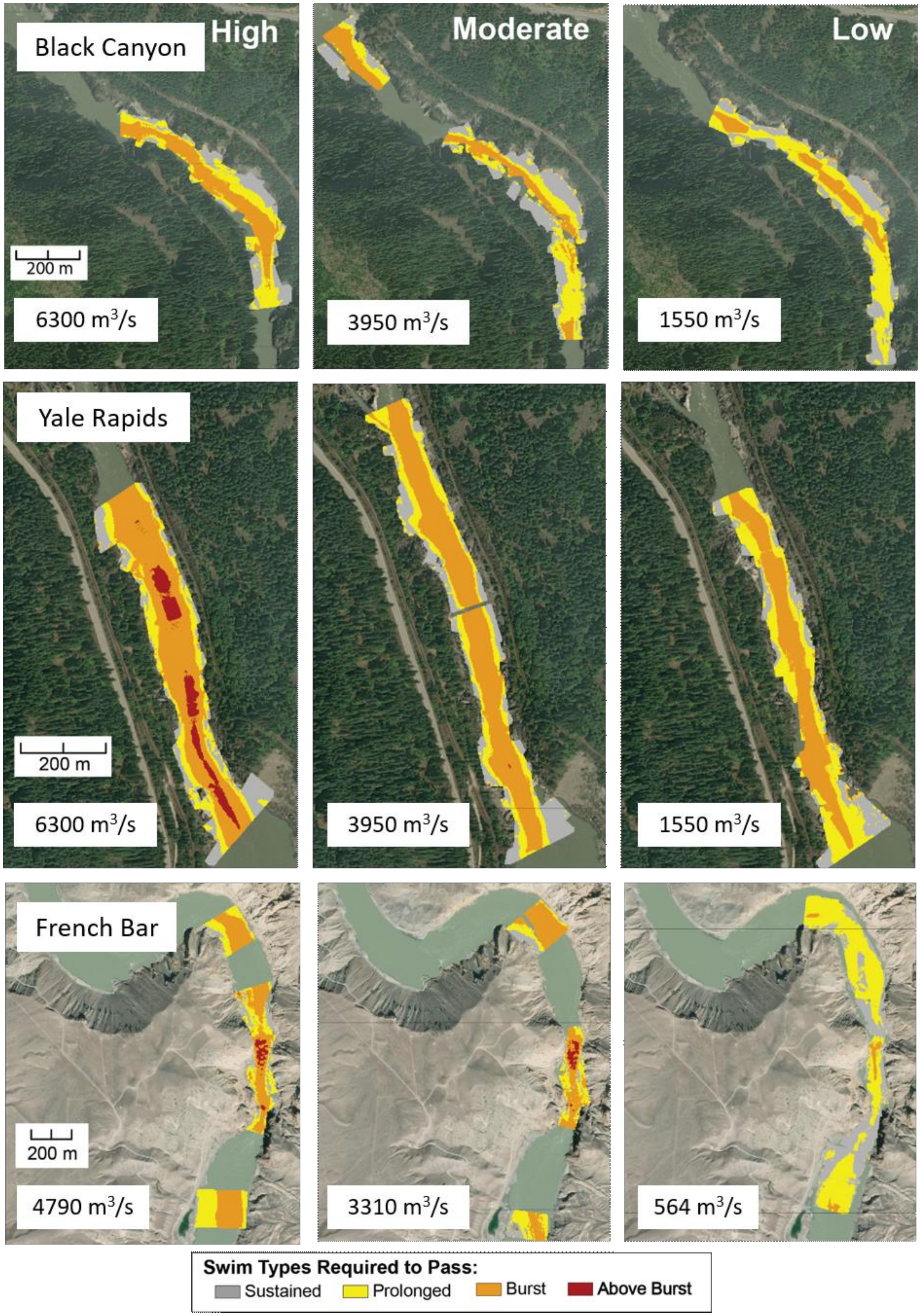

Figure A3. **Examples of how surface velocity compares to swimming capabilities of a medium size Sockeye salmon (body-length 58.9 cm) for different types of high velocity zones.**

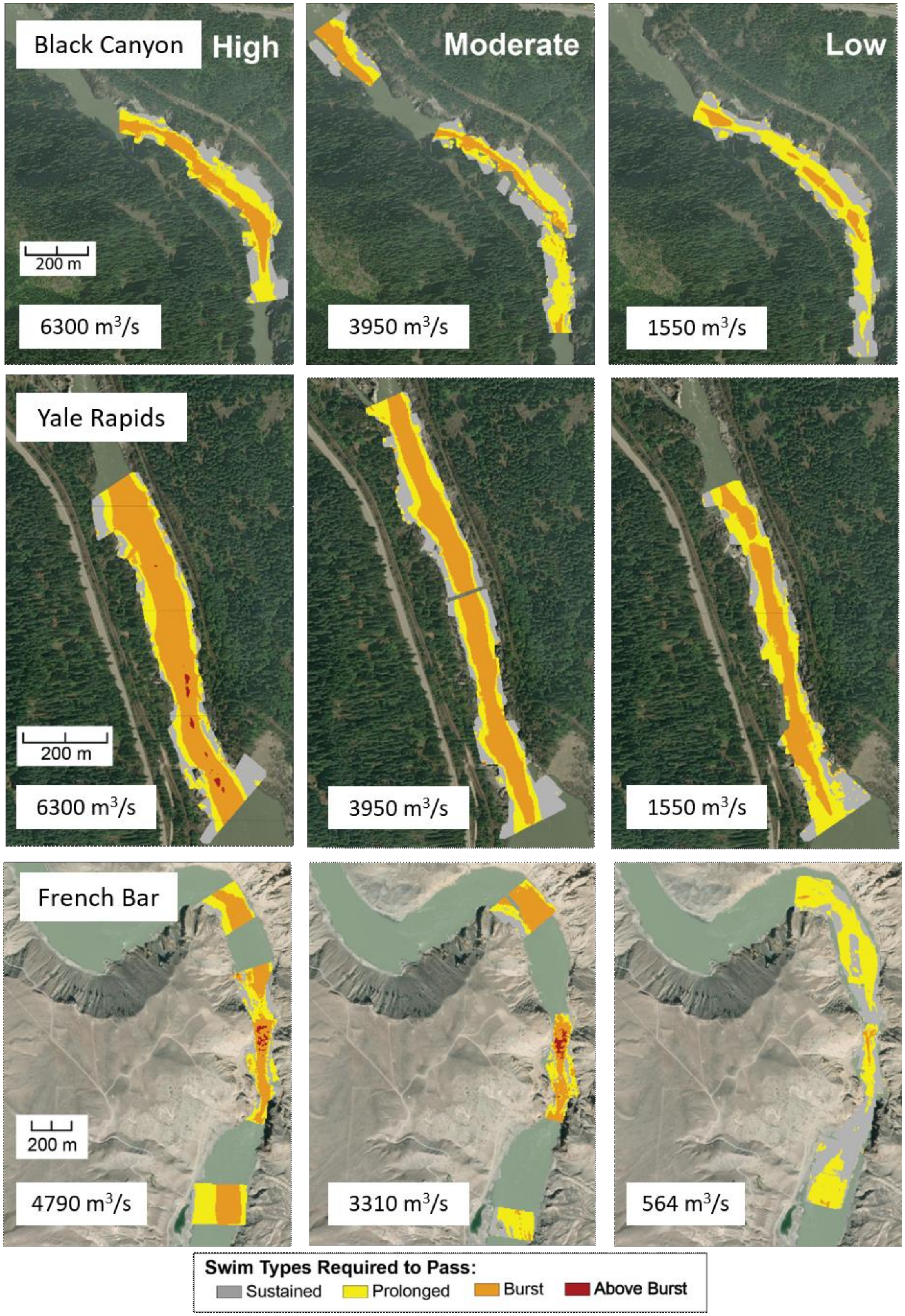

Figure A4. **Examples of how surface velocity compares to swimming capabilities of a medium size Chum salmon (body-length 65.2 cm) for different types of high velocity zones.**

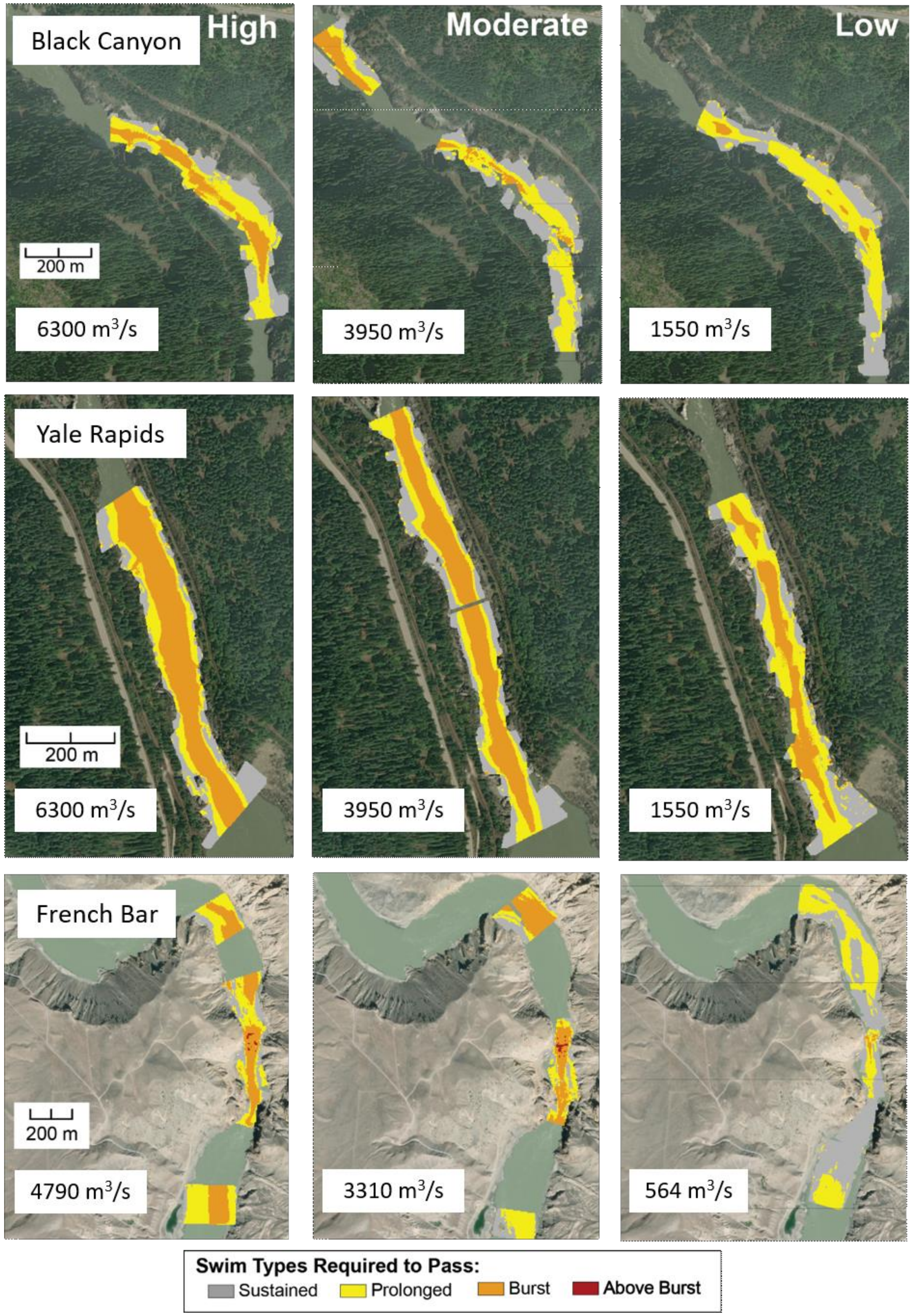

Figure A5. **Examples of how surface velocity compares to swimming capabilities of a medium size Chinook salmon (body-length 72.6 cm) for different types of high velocity zones.**