Restoration of Salmonid Spawning Habitat in the Upper Serpentine River

by

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Executive Summary

Urbanization has caused drastic changes to the hydrology and geomorphology of streams and rivers. Increased streamflow leads to stronger erosive forces and the degradation of spawning habitat for salmonids. The Serpentine River is a low-elevation, rain-dominant river located in the City of Surrey, British Columbia. Urbanization of the upper watershed has led to flow changes resulting in erosion of spawning gravels and increased fine sediment from bank erosion. The current project evaluated past spawning gravel supplementation efforts in the Upper Serpentine River and proposed a restoration plan to increase spawning habitat more effectively.

Previous restoration did not address the river's increased sediment carrying capacity and increased siltation. Grain size analysis of the study sites found up to 57% fine sediment in the subsurface particles, attributing to siltation rates of 1.2-1.6 kg/m^2/day. The tractive forces calculated were able to mobilize particles from 29-164 mm, which mostly exceeded the median grain size preferred by most spawning salmonids. This was verified with a tracer rock study, in which particles in the preferred size range mobilized after a modest storm event. The data suggested that instream structures were required to reduce tractive forces and increase gravel retention at the restoration sites.

Newbury weirs, or constructed riffles, were recommended to reduce tractive force by decreasing upstream slope, promote gravel retention, and create intergravel flows important for incubation. Newbury weirs consist of large diameter rocks spanning across the entire stream, causing accumulation of gravel upstream and pool formation downstream. Substrate scoured at the pool will be deposited at the tail end of the pool, creating spawning habitat in accelerating and downwelling waters. Bank stabilization using dense live staking with a protective rock toe key was prescribed to reduce further bank erosion and siltation. In addition, long-term watershed-level priorities were recommended, including passage through the Serpentine sea dam, monitoring for urban contaminants, and installation of green infrastructure.

The proposed treatments are a relatively inexpensive way to reduce repeat addition of spawning gravel and increase spawning habitat quality in the Serpentine River. Monitoring data from restoration works should be used to inform future stream restoration projects and contribute to the continual improvement of restoration techniques. The effects of restoration on not only sediment form (i.e. gravel depth and size) but also processes (i.e. sediment scour and fill) should be investigated in the future to verify theoretical models.

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I would like to express my appreciation for my field assistants, Kate, Caitlin, Nicole, Jane, Darian, Christine, and Tim, as this project would not have been possible without their help and company. Thank you also to my friends and family for their patience and support, and for putting up with my piles of pink rocks.

Last but not least, I want to thank the Coast Salish peoples for the opportunity to learn on their ancestral territory.

Table of Contents

Approval ii
Executive Summary iii
Acknowledgements iv
Table of Contents v
List of Tables viii
List of Figures ix
List of Acronyms xi

1 Introduction 1
1.1 Salmonids in British Columbia 1
1.1 Effects of Urbanization on Streams 1
1.1.1 Hydrology 1
1.1.2 Geomorphology 2
1.1.3 Barriers to Passage 2
1.1.4 Contaminants 3
1.2 Project Overview 3
1.3 Stakeholders 4

2 Background 5
2.1 Study Area 5
2.2 Physical Conditions 6
2.2.1 Climate and Weather 6
2.2.2 Surficial Geology and Land Forms 7
2.2.3 Soils 7
2.2.4 Hydrology 7
2.3 Biological Conditions 8
2.3.1 Fish 8
2.3.2 Macroinvertebrates 11
2.3.3 Wildlife 11
2.3.4 Vegetation 12
2.4 First Nations Use 12
2.5 Land Use and Stressors 13
2.5.1 Agriculture 13
2.5.2 Dyke Construction 13
2.5.3 Urban Encroachment 15
2.5.4 Climate change 16

3 Salmonid Spawning Habitat Requirements 18
3.1 Dissolved Oxygen 19
3.2 Temperature 19
3.3 Depth and Velocity 19

3.4 Grain Size ... 20

4 Past Spawning Habitat Restoration ... 22
4.1 Design Considerations ... 22

5 Current Conditions and Site Assessment ... 25
5.1 Site Locations ... 25
5.2 Methods ... 25
5.2.1 Water Quality ... 25
5.2.2 Wetted Depth and Velocity ... 26
5.2.3 Grain Size Analysis ... 26
5.2.4 Hydraulic Analysis ... 27
5.2.5 Tracer Rock Verification ... 28
5.2.6 Siltation ... 30
5.2.7 Barriers to Passage ... 30
5.3 Results ... 30
5.3.1 Water Quality, Depth, and Velocity ... 30
5.3.2 Grain Size Analysis ... 33
5.3.3 Hydraulic Analysis ... 36
5.3.4 Tracer Rock Verification ... 37
5.3.5 Siltation ... 39
5.3.6 Barriers to Passage and Areas of Spawning Gravel ... 39
5.4 Discussion ... 40
5.4.1 Water Quality, Depth, and Velocity ... 40
5.4.2 Grain Size Analysis ... 40
5.4.3 Hydraulic Analysis ... 42
5.4.4 Tracer Rock Verification ... 42
5.4.5 Siltation ... 43
5.4.6 Barriers to Passage and Existing Spawning Gravel ... 43
5.5 Conclusion ... 44

6 Proposed Restoration Treatments ... 46
6.1 Desired Future Conditions ... 46
6.1.1 Restored Conditions and Processes ... 46
6.2 Goals and Objectives ... 48
6.3 Site Prioritization ... 49
6.4 Instream Restoration Treatments ... 51
6.4.1 Newbury Weirs ... 51
6.4.2 Gravel Addition ... 53
6.4.3 Streambank Stabilization ... 54
6.5 Site-Specific Plans ... 55
6.5.1 Site 1 ... 56
6.5.2 Site 2 ... 57

6.5.3 Site 3 ... 58
6.5.4 Site 4 ... 59
6.5.5 Site 5 ... 60
6.5.6 Site 7 ... 61
6.6 Biostandards for Estimating Restoration Benefits ... 62
6.7 Watershed-scale Recommendations ... 63
6.7.1 Stormwater Management ... 63
6.7.2 Mitigation of Downstream Stressors ... 63
7 Implementation ... 65
7.1 Planning ... 65
7.1.1 Engagement with stakeholders ... 65
7.1.2 Regulations and Permits ... 65
7.1.3 Finalizing Weir Designs ... 66
7.1.4 Construction Budget ... 66
7.2 Implementing Restoration Treatments ... 68
7.2.1 Bank Stabilization ... 68
7.2.2 Weir Construction and Gravel Addition ... 68
7.2.3 Work Schedule ... 70
8 Monitoring ... 71
8.1 Metrics of Success ... 71
8.2 Baseline Monitoring ... 72
8.3 Physical Monitoring ... 73
8.3.1 Gravel Depth and Sediment Budget ... 73
8.3.2 Gravel Size ... 75
8.3.3 Geomorphic Changes ... 75
8.3.4 Other Parameters ... 75
8.4 Biological Monitoring ... 75
8.4.1 Spawning Activity and Redds ... 75
8.4.2 Fry Surveys ... 76
8.4.3 Vegetation ... 76
8.5 Structural Integrity ... 76
8.6 Photomonitoring ... 76
8.7 Maintenance ... 76
9 Conclusion ... 77
References ... 79
Appendix A ... 88
Appendix B ... 89
Appendix C ... 90
Appendix D ... 93
Appendix E ... 94

List of Tables

Table 1. Spawning requirements for five salmonid species present in the Serpentine River. Dissolved oxygen values are based on swimming experiments in laboratory studies. Temperature, depth, and velocity values are based on measurements at redds. Grain size values are recommendations for artificial spawning channels. 18

Table 2. Summary of past spawning habitat restoration projects. 23

Table 3. Mean particle sizes and number of particles deployed at the study sites. 28

Table 4. Water quality parameters measured at study sites during the spring and fall of 2017..32

Table 5. Fall assessment of spawning habitat requirements at study sites. Depth and velocity are expressed ranges within the three transects sampled. D_{50} is based on surface Wolman pebble counts....32

Table 6. Channel geometry and bed shear stress of study sites. Bankfull width and cross-sectional bankfull depth are expressed as means calculated from three transects ± SD. 36

Table 7. Mean mass of fine sediment (<4 mm) accumulated per accumulator between January 18, 2018 and January 30, 2018, calculated accumulation/m^2/day, and mean percent fines after the 12-day study period in sites 1, 3, and 7. Values are means ± SD. 39

Table 8. Desired restored conditions and processes in the Upper Serpentine River and possible outcomes of the current restoration plan. 47

Table 9. Site prioritization based on site limitations and recommended treatments. 49

Table 10. Description of the three restoration phases to be carried out in the Upper Serpentine River. Phases 1 and 2 involve instream restoration treatments, while phase 3 focuses on watershed-level stormwater management....50

Table 11. Estimated fish production calculated from a 261 m^2 increase in spawning habitat proposed by the current restoration plan. 62

Table 12. Estimated construction costs based on preliminary site plans. Contingency value of 20% is based on a Class C Estimate recommendations according to the Guide to Cost Predictability in Construction (JFG/ICPT 2012). 67

Table 13. Estimated number of personnel and work days to carry out construction activities. ...68

Table 14. Gantt chart summarizing sequence and timing of restoration tasks. 70

Table 15. Metrics of success of restoration treatments for year 1, year 3, and year 5 post-restoration. 72

List of Figures

Figure 1. Location of the Serpentine River within the City of Surrey and the surrounding municipalities (modified from Google Earth 2017). Yellow box outlines the project study area. Inset: location of the Serpentine River in the province of British Columbia. 5

Figure 2. Mean monthly precipitation and monthly average temperatures for the period of 1981 to 2010. Precipitation data was obtained from the Surrey Kwantlen Park weather station and temperature data was obtained from the Surrey Newton weather station (Government of Canada 2017). 6

Figure 3. Top: rainfall data collected from the Surrey Kwantlen Park weather station for the year of 2017. Bottom: hydrograph of the Serpentine River at the 104 Avenue gauge station for the year of 2017 (data obtained from FlowWorks 2018). 8

Figure 4. Top: Serpentine River coho escapement from 1953 to 1992 (DFO 1999). Bottom: Coho, chinook, and chum counted at the fish fence located in the Upper Serpentine River from 2002 to 2017. 10

Figure 5. Historical photographs of the Surrey Dyking District crews dredging the Serpentine River using a dragline (Left: Surrey Archives n.d., right: Gordon Bishop n.d.). 14

Figure 6. Skaters take advantage of the ice formed after flooding in the Serpentine floodplain in 1962 (Surrey Archives n.d.). 14

Figure 7. Aerial photographs of the Upper Serpentine watershed from 1949 (top) and 2016 (bottom). Images obtained from City of Surrey Online Mapping System (COSMOS). 15

Figure 8. Evidence of streambank erosion in site 1 (left) and site 7 (right; Yuan 2017). 16

Figure 9. Locations of seven study sites in the Upper Serpentine River (modified from Google Earth). 25

Figure 10. Downstream view of site 6 showing orientation of tracer particles placed instream (Yuan 2017). 29

Figure 11. Grain size distribution curves of study sites based on surface Wolman pebble counts. Percent finer was calculated by particles. Vertical black dotted lines represent the recommended range of 13 – 102 mm for spawning gravel (Bell 1986). 33

Figure 12. Subsurface grain size distribution of study sites. Individual lines within the graphs represent each subsurface sample collected. Percent finer was calculated by weight. Vertical black dotted lines represent the recommended range of 13 – 102 mm for spawning gravel (Bell 1986). 35

Figure 13. Bankfull erodible grain sizes calculated using average cross-sectional shear stress along three transects per site. Each shaded bar represents a different transect. The black dotted line represents the recommended D_{50} for placed spawning gravel. 37

Figure 14. The fractions of tracer particles under full, partial, and no mobility after the study period of October 23, 2017 to February 4, 2018. Numbers within the bars indicate the number of mobilizing events where the calculated bed shear stress exceeded the critical erodible shear stress of the mean particle size. Tracer analysis could not be completed in site 6 due to a log jam downstream of the site causing sediment accumulation and burial of tracer particles. 38

Figure 15. Design characteristics of a Newbury weir (video, Newbury Hydraulics 1996). 52

Figure 16. Cross-sectional view of bank stabilization treatment using willow stakes and a rock toe key. 54

Figure 17. Top: location of site 1 (orange) within the context of surrounding roadways. Bottom: schematic of prescribed restoration treatments in site 1. The rock toe key and live staking will be carried out in phase 1, and the Newbury weirs will be installed in phase 2. 56

Figure 18. Top: location of site 2 (orange) within the context of surrounding roadways. Bottom: schematic of prescribed restoration treatments in site 2. 57

Figure 19. Top: location of site 3 (orange) within the context of surrounding roadways. Bottom: schematic of prescribed restoration treatments in site 3. 58

Figure 20. Top: location of site 4 (orange) within the context of surrounding roadways. Bottom: schematic of prescribed restoration treatments in site 4. 59

Figure 21. Top: location of site 5 (orange) within the context of surrounding roadways. Bottom: schematic of prescribed restoration treatments in site 5. 60

Figure 22. Top: location of site 7 (orange) within the context of surrounding roadways. Bottom: schematic of prescribed restoration treatments in site 7. 61

Figure 23. Scour and fill measured by a scour chain and sliding bead monitor. (a): Before peak flow. (b): Maximum scour during peak flow. Exposed beads slide to the end of the cable. Redd and eggs have been excavated and washed downstream. (c): Sediment deposition after peak flow. (d): measurements of scour and fill recorded by a scour chain (Nawa and Frissell 1993). 74

List of Acronyms

DO	Dissolved oxygen
ISC	Impervious surface cover
NTU	Nephelometric turbidity units

1 Introduction

1.1 Salmonids in British Columbia

Pacific salmon (*Oncorhynchus* spp.) are iconic species in British Columbia and are central to the province's culture, economy, and ecology. Pacific salmon are a traditional food source of cultural importance for Indigenous Peoples, and convey significant economic value to commercial and recreational fisheries. Pacific salmon bring marine-derived nutrients into terrestrial systems each year during their upstream spawning migration, fertilizing much of British Columbia's forest ecosystems (Cederholm et al. 2000). They are a seasonal resource for numerous aquatic and terrestrial predators. In the marine environment, chinook salmon (*O. tshawytscha)* are a primary summer food source for the critically endangered southern resident killer whales (*Orcinus orca*; Hanson et al. 2010). The ability of Pacific salmon to transport nutrients beyond ecosystem boundaries and support large food webs has led to their recognition as keystone species (Willson and Halupka 1995, Cederholm et al. 2000). In urban areas, salmonids increase social value and provide opportunities for public engagement and education.

The production of Pacific salmon has historically fluctuated, often coinciding with shifts in oceanic environment and climate of the north Pacific (Beamish and Bouillon 1993, Beamish et al. 1999, Beamish et al. 2000). During the 1990s, salmon catches declined rapidly, the most noticeable being coho salmon (*O. kisutch)* and chinook salmon (Noakes et al. 2000). While it is difficult to pinpoint the exact cause of the rapid decline, likely causes include climate change, overfishing, aquaculture, and the loss of freshwater habitat (Noakes et al. 2000). Pacific salmon have been extirpated from 40% of their historical range in the Pacific Northwest (Wilderness Society 1993). In large cities, urbanization is a major threat to freshwater habitat. Conservation and effective management of Pacific salmon is vital in protecting their ecological, social, cultural, and economic values.

1.1 Effects of Urbanization on Streams

1.1.1 Hydrology

Urbanization negatively affects the riverine habitat of salmonids. Low vegetation cover and high impervious surface cover (ISC) reduce evapotranspiration and infiltration of precipitation, leading to an increase in surface runoff (Dunne and Leopold 1978). In a catchment with 10-20% ISC, surface runoff increases twofold from forested watersheds; a catchment with 35-50% ISC experiences a threefold increase in runoff; 75-100% ISC increases runoff by over fivefold (Arnold and Gibbons 1996). The resulting change in stream hydrology is characterized by higher peak discharge, faster flood onset, lower basal flows, and a sharper decline in discharge after precipitation (Espey et al. 1965, Hirsch et al. 1990).

1.1.2 Geomorphology

Streams generally undergo two major phases of geomorphological change in response to urbanization (Paul and Meyer 2001). During development and construction, hillslope erosion supplies a pulse of sediment that results in channel aggradation and subsequent overbank deposition due to the decreased channel capacity (Wolman 1967). After the construction phase, sediment supply is reduced and the channel enters an erosional phase. High ISC increases stream flow and the stream channel begins to deepen and widen to accommodate the higher discharge (Hammer 1972, Booth 1990). Tractive forces exerted upon the streambed increases, leading to mobilization of bed substrate and bank erosion. During this phase, channel and bank erosion becomes the major sediment source (Wolman 1967, Trimble 1997).

The changes in hydrology and geomorphology in urbanized streams alter the hydraulic conditions and sediment dynamics of streams, affecting the quality of salmonid spawning gravel. Increased discharge raises tractive force, leading to erosion of spawning gravel (Leopold 1973, Morisawa and LaFlure 1979). Furthermore, increased sediment yield from upstream land uses and bank erosion leads to siltation within interstitial spaces of gravel, reducing porosity and oxygen delivery to incubating eggs and alevin (Wolman 1967, Leopold 1968, Chevalier et al. 1984, Trimble 1997).

1.1.3 Barriers to Passage

Culverts are used extensively in urban areas to facilitate roadways and other means of transportation. Many culverts are barriers to fish passage due to issues with velocity, water depth, perching, and obstructions (Whyte et al. 1997). In the estuary, sea dams are often installed to prevent salt-water intrusion into agricultural fields. In the Serpentine River, tidal gates on the sea dam are pressure-mediated and can remain closed for long periods of time, delaying upstream and downstream migration of salmonids (Cox and McFarlane 1978).

1.1.4 Contaminants

Urban runoff introduces a wide range of chemicals into streams depending on the type of urban land use. In general, urban streams exhibit increased concentrations in most parameters, particularly biochemical oxygen demand, conductivity, suspended solids, ammonium, hydrocarbons, and metals (Porcella and Sorenson 1980, Lenat and Crawford 1994, Latimer and Quinn 1998, USGS 1999). These chemicals enter stream ecological communities through direct exposure in the water column and ingestion of contaminants associated with sediments and organic matter (Paul and Meyer 2001).

1.2 Project Overview

The Serpentine River is a low elevation rain-dominant river supporting five salmonid species. Urban encroachment of the upper reaches has resulted in hydrologic changes and the associated degradation of spawning habitat (Dillon 2012). While it is important to recognize that the long-term solution to address the root stressor lies in better stormwater management and installation of green infrastructure, instream restoration works in the interim is necessary to provide adequate spawning gravel for existing salmonid populations.

In a pilot project in 2012, Dillon Consulting conducted gravel reach assessments of the mainstem and major tributaries of the Upper Serpentine River, and classified the reaches based on substrate condition (Dillon 2012). This preliminary assessment concluded that the Upper Serpentine River was lacking in spawning habitat and identified seven sites that would be ideal candidates for gravel addition. From 2013 to 2016, City of Surrey added gravel in bulk at five of the seven sites. Except for visual assessments of the streambed, little to no monitoring has been conducted. The few visual assessments indicated that the placed gravels have mostly mobilized downstream, and several of the sites have required supplementary gravel (Urban Systems 2015; Liana Ayach, City of Surrey, pers. comm., 2017).

While previous restoration work provided supplementary spawning gravel, hydraulic conditions that affect gravel movement were not considered. An analysis of tractive forces and erodible grain size of the sites show that the placed gravels would become unstable and mobilize during high flow events (Dillon 2012). While bedload transport is a natural process in river systems, accelerated and frequent transport can nullify benefits of restoration by washing away eggs during the incubation period. In order for these sites to hold supplemental gravel, restoration must address the hydraulic conditions.

The current project was a partnership with the City of Surrey to initiate the next phase of restoration efforts, which included an evaluation of past restoration efforts and a restoration plan to effectively increase salmonid spawning habitat in the Upper Serpentine River. Current site conditions, including substrate and hydraulics, were re-assessed. The data provided basis for instream structures and watershed-scale restoration recommendations to reduce shear stress, promote gravel retention, and increase the quality of spawning habitat. The goal of the restoration plan was to create suitable conditions for spawning, and ultimately, increase salmonid production in the Serpentine River.

The Pacific Northwest is predicted to experience wetter winters in the future while continued development will further increase ISC (Mote and Salathe 2010, Urban Systems 2015). Therefore, there is an urgent need to increase resilience to projected future conditions and prevent the continued loss of spawning habitat in urban streams. With the exception of a few examples, spawning habitat restoration in urban streams is not well documented in literature (Booth 2005, Levell and Chang 2008). Understanding of the effectiveness and challenges associated with gravel supplementation will lead to improvements in restoration methods for future projects.

1.3 Stakeholders

The project was supervised by Dr. Ken Ashley of the BCIT Rivers Institute and sponsored by Liana Ayach of the City of Surrey. Other stakeholders included the Serpentine Enhancement Society, Metro Vancouver, the Fisheries and Oceans Canada, and the residents of Surrey.

2 Background

2.1 Study Area

The Serpentine River is a rain-dominant river and a major tributary of Boundary Bay, located southeast of the Strait of Georgia (Figure 1). Most of the watershed is located within the City of Surrey, with a catchment area of 154.2 km^2 and a total length of 27 km excluding its major tributaries, Latimer Creek, Mahood (Bear) Creek and Hyland Creek (DFO 1999). The lowland floodplain of the river is tidally influenced and controlled by sea dams to protect infrastructure and facilitate farming (City of Surrey 2017). Water from the Serpentine River is used for irrigation, livestock watering, and drinking water. In the lowlands, the marshy Serpentine Wildlife Area is an important wintering area for waterfowl, raptors, and shorebirds, and is part of the Fraser River Delta Ramsar Wetland of International Significance. This assessment of restoration options will focus on sections of the river north of 88th Avenue, where the pilot project initiated by the City of Surrey has identified seven sites that could benefit from restoration work (Dillon 2012).

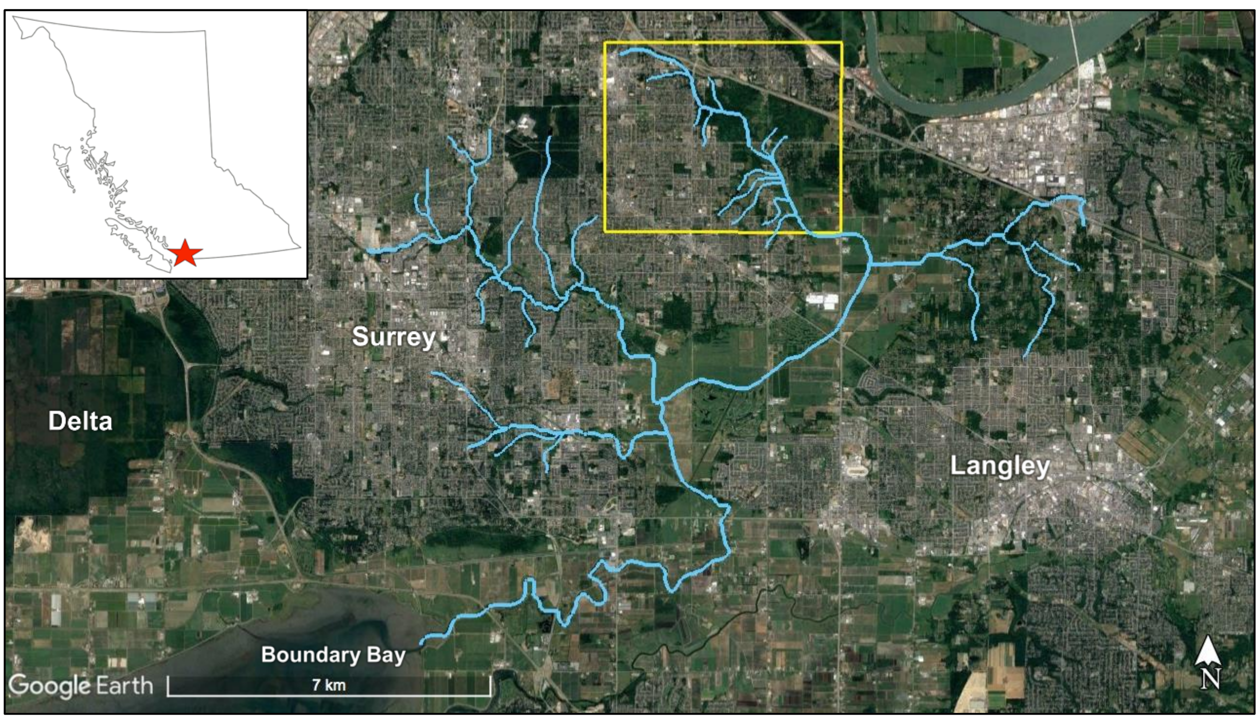


Figure 1. Location of the Serpentine River within the City of Surrey and the surrounding municipalities (modified from Google Earth 2017). Yellow box outlines the project study area. Inset: location of the Serpentine River in the province of British Columbia.

2.2 Physical Conditions

2.2.1 Climate and Weather

The Serpentine River is located within the Coastal Western Hemlock (CWH) Biogeoclimatic Zone (Meidinger and Pojar 1991), and experiences mild, wet winters and warm summers (Kendrew and Kerr 1955). Oceanic conditions of the Pacific are responsible for the mild winters, and the Coastal and Cascade Mountains to the east make the area prone to precipitation. Summers are warm but extreme heat is prevented by sea breezes (Kendrew and Kerr 1955).

The Upper Serpentine watershed receives on average 1,522 mm of rainfall per year and 41 mm of snow. The wettest month is November, and the driest are July and August. October to January are wet months, receiving on average greater than 150 mm of precipitation (Figure 2). Greatest daily precipitation reached as high as 139.7 mm in January of 1968, exemplifying the intensity of extreme storm events (Government of Canada 2017). Snowfall is minimal and generally occurs on average 8.3 days out of the year. August is the warmest month of the year (daily average 18.2°C), while December is the coldest (daily average 3.4°C). Mean daily minimum temperatures for December and January near freezing (0.6°C and 0.9°C respectively; Government of Canada 2017)

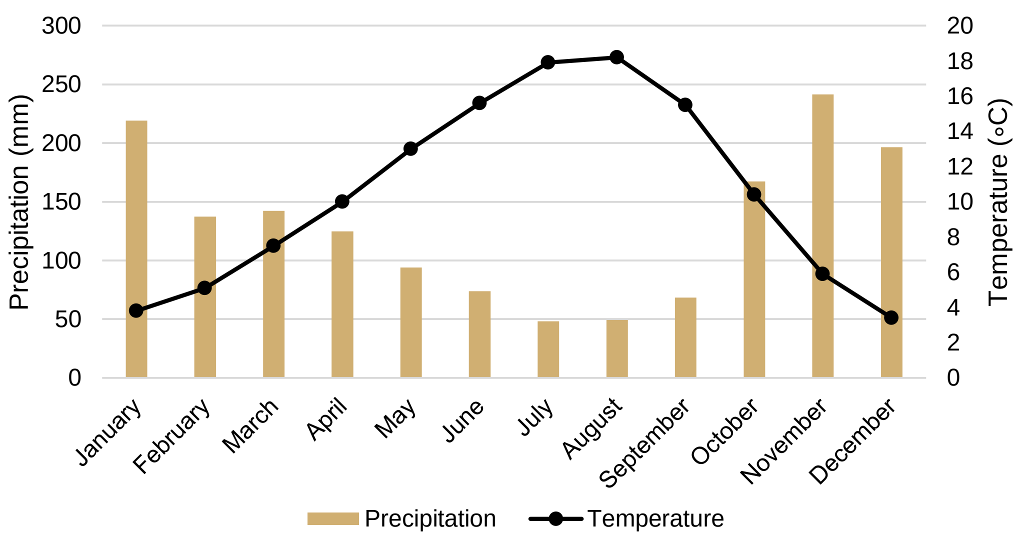


Figure 2. Mean monthly precipitation and monthly average temperatures for the period of 1981 to 2010. Precipitation data was obtained from the Surrey Kwantlen Park weather station and temperature data was obtained from the Surrey Newton weather station (Government of Canada 2017).

2.2.2 Surficial Geology and Land Forms

The Serpentine-Nicomekl basin is a flat-bottomed valley, and is part of the Fraser Lowland (Holland 1976). The area has a complex Pleistocene and recent history involving marine and non-marine, glacial and non-glacial deposition. During past glaciations, the area was covered with around 2,300 m of ice, which depressed the land (Holland 1976). The floodplain of the lower reaches is a result of the retreat of a Cordilleran glaciation around 11,000-14,000 years ago. The headwaters are located on a 100-m high moraine that borders the northern side of the valley (Cox and McFarlane 1978). A large portion of the lower floodplain has an elevation of 1-2 m (geodetic datum) which is lower than the spring and winter high tide levels (Cox and McFarlane 1978). Both rivers drain into Mud Bay, the eastern extension of Boundary Bay (Cox and McFarlane 1978). Main alterations to the topography in both rivers include roads in the urbanized upper watershed and extensive dyking in the agricultural lowlands. Detailed history of dyking in the Serpentine River is described in section 2.5.2.

2.2.3 Soils

The upland soils of the Lower Fraser Valley consist of moderately fine-textured material of glacio-marine origin. The lowland soils are of marine, floodplain, or deltaic origin with a large constituent of organic material (AECOM 2010). The predominant soils of the study area are generally finely grained and consist of shallow tills, topsoil or clay/silt caps overlaying dense, silty sand soils (Urban Systems 2015).

2.2.4 Hydrology

The Serpentine is a rain-dominant system and receives most of its water during the wet fall and winter months (Figure 3). While this ensures adequate flow at the time of upstream migration by anadromous salmon, streams during this period also experience the highest tractive forces. Low flows coincide with the driest months of the year, July and August (Government of Canada 2017).

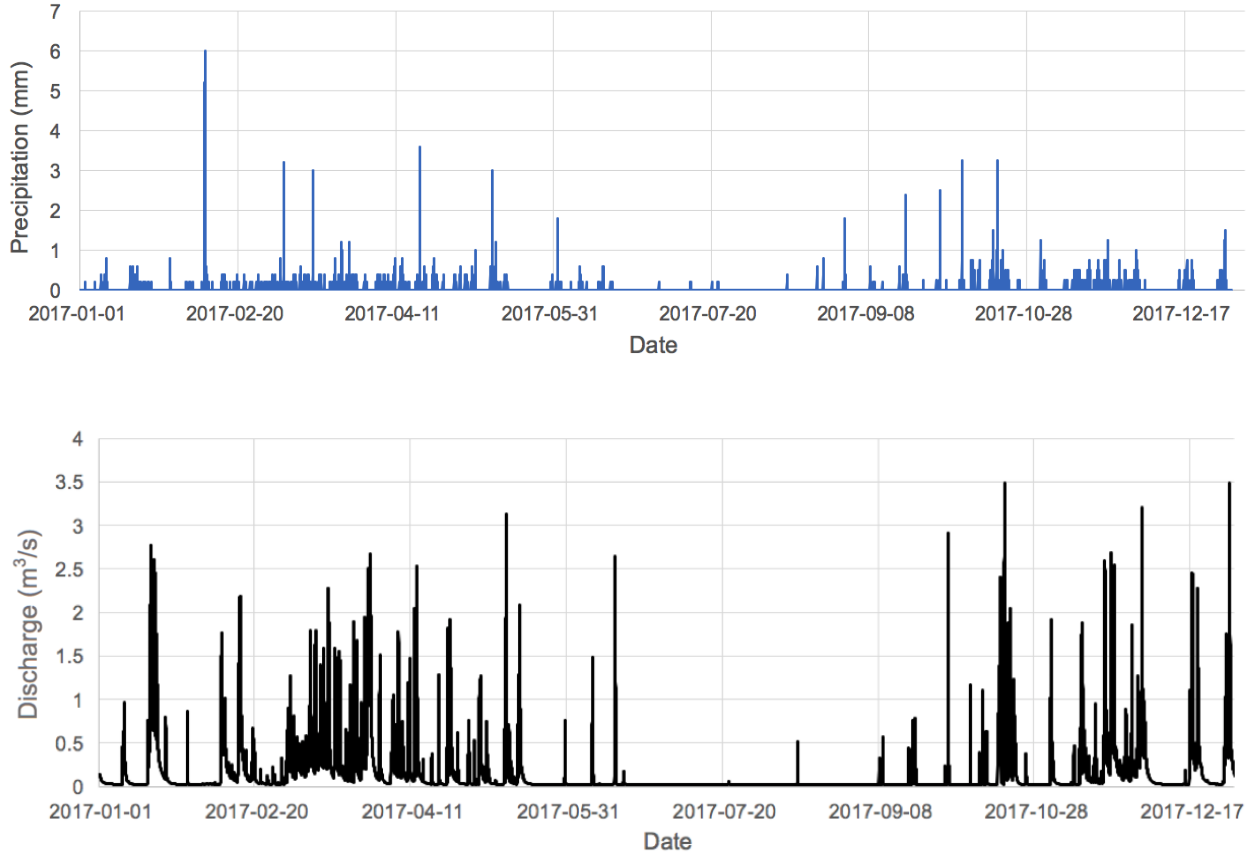


Figure 3. Top: rainfall data collected from the Surrey Kwantlen Park weather station for the year of 2017. Bottom: hydrograph of the Serpentine River at the 104 Avenue gauge station for the year of 2017 (data obtained from FlowWorks 2018).

The river originates at 75 m elevation but the majority is below 15 m (Town 1986). Within the Serpentine-Nicomekl valley, thick, unconsolidated deposits of silty clay, silty sand, sandy silts, and sand lenses provide leaky conditions and manifest as discharge zones of a major groundwater flow system (Halstead 1978). The Serpentine and Nicomekl may have historically been connected by meandering channels prior to agricultural development. Presently, the two rivers are joined by a series of drainage ditches (Cox and McFarlane 1978).

2.3 Biological Conditions

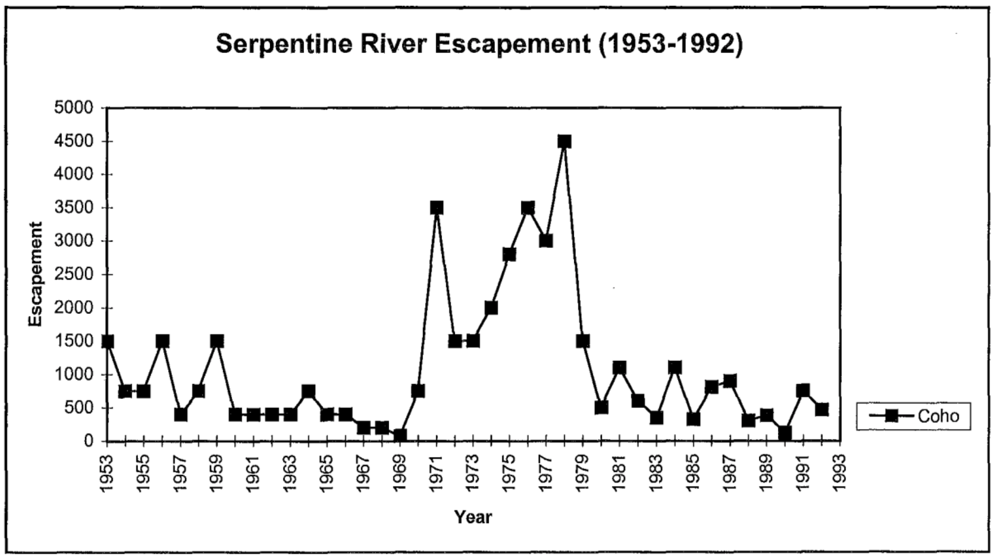
2.3.1 Fish

It has been reported that the Serpentine and Nicomekl Rivers once supported around 6,500 steelhead (*O. mykiss*), 3,500 cutthroat trout (*O. clarkii*), and 15,000 coho (Town 1984). Coho numbers declined to about 500 by the 1990's (Figure 4, top; DFO 1999). The decline of salmon was likely partly attributed to negative effects of urbanization on upstream spawning habitat and agriculture on downstream rearing habitat (Town 1986). In 1988, the Tynehead Hatchery (now Serpentine Enhancement Society) was formed with a goal to rehabilitate the salmon run in the Upper Serpentine River. Today, the Serpentine supports coho, chinook, chum (*O. keta*), steelhead and cutthroat (Lesley England, Serpentine Enhancement Society, pers. comm., 2017). Chinook and chum were not historically present in large numbers, although some have been reported (Backman and Simonson 1985). The current populations of chinook and chum may have been stocked and propagated by the Serpentine Enhancement Society.

From 2013 to 2017, the five-year averages of fish fence counts conducted at the Serpentine Enhancement Society were 1,207 coho, 318 chinook, and 381 chum (Figure 4, bottom). Counts only occurred when volunteers were available to operate the fence. During the remainder of the time the fence gates were left open to allow fish passage. Therefore, these numbers represent only a portion of the returns and may not reflect the true population due to limitations arising from volunteer-based fence counting (Lesley England, pers. comm., 2017). The fish counts also do not capture individuals spawning in the other three major tributaries of the Serpentine River. Despite this, some notable trends were observed in the reported numbers. The proportions of wild and hatchery coho were generally equal, but there were two years (2009 and 2016) when hatchery returns outnumbered wild returns by 2-fold and 2.7-fold respectively (Lesley England, pers. comm., 2017). Furthermore, chinook males consistently outnumbered females by ratios ranging from 1.7-13.5. The predominance of males can be attributed to a large proportion of males returning as jacks (Lesley England, pers. comm., 2017). Jacks are individuals that sexually mature and return to freshwater after only spending a year at sea, before females of the same cohort. They are usually smaller than other returning males, and are considered undesirable to commercial fisherman and hatcheries. Although hatcheries historically have selected against this trait, the incidence of jacking is still higher in hatcheries than wild stocks (Bocking and Nass 1992). Hatcheries provide optimal growing conditions and ample nutrition during the early life stages which may contribute to precocious sexual maturation. Heath et al. (1994) found that while there is a genetic component to jacking, genetic-environmental interactions were found in which acceleration of early development rates increased incidences of jacking. The higher incidence of jacking in hatcheries suggest that environmental factors still play an important role in the accelerated sexual maturation of salmonids.

Given the fact that fish fence counts only represent a portion of the adult escapement of the Serpentine River, it may appear as though salmon populations are relatively stable. However, high escapement in recent years is likely due to inflation of fry production from hatcheries. Therefore, the escapement numbers does not necessarily reflect the reproductive success of the wild population.

Other fish species that reside in the Serpentine River include three-spine stickleback (*Gasterosteus aculeatus*), prickly sculpin (*Cottus asper*), redside shiner (*Richardsonius balteatus*), and western brook lamprey (*Richardsonius balteatus*; DFO 1999, GVRD 2004).



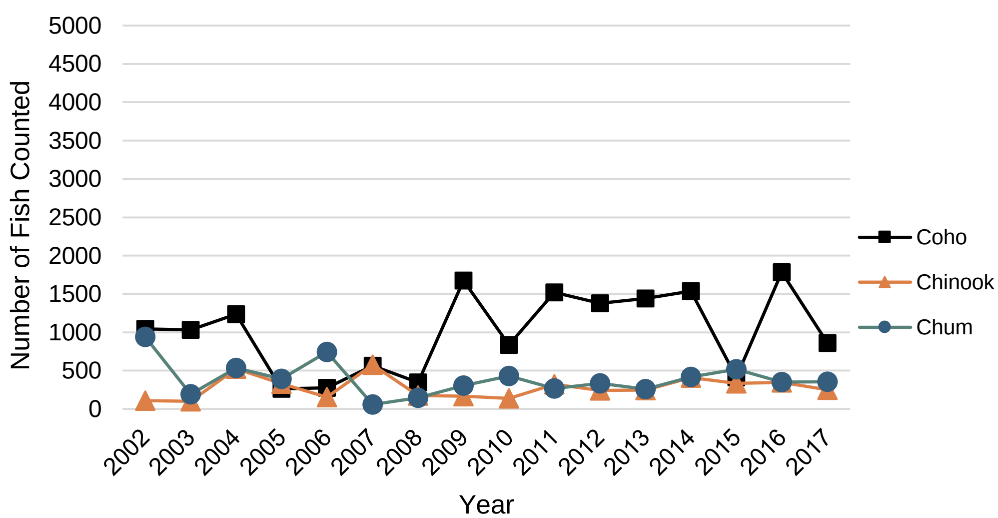


Figure 4. Top: Serpentine River coho escapement from 1953 to 1992 (DFO 1999). Bottom: Coho, chinook, and chum counted at the fish fence located in the Upper Serpentine River from 2002 to 2017.

2.3.2 Macroinvertebrates

Surveys of benthic macroinvertebrates in 1984 found that more than 50% of total taxa consisted of moderately tolerant taxa in high gradient and low gradient sites in the Upper Serpentine River, indicating reduced water quality. Meanwhile, the mid-gradient sites had a lower proportion of tolerant taxa and were the most productive (Backman and Simonson 1985). Chemical spills and fish kills have been reported in the Upper Serpentine, and high gradient sites would have been affected the most due to their close proximity to the contaminant source (Backman and Simonson 1985). Low gradient sites are located within agricultural land, and experience organic loading, degradation of banks, and loss of stream cover, all of which alter macroinvertebrate communities (Backman and Simonson 1985). Of particular concern was one tributary, now known as Townline Creek, that had notably low macroinvertebrate production with over 75% consisting of moderately tolerant taxa. Interestingly, Townline Creek was historically a fish producing stream where salmonids existed in abundance up until 1978. Since then, water quality has decreased and salmonid production has stopped. The reason for these changes was never determined (Backman and Simonson 1985).

A more recent study assessed the Serpentine River using the benthic index of biological integrity (B-IBI, Page et al. 2008). Mean B-IBI values for four sampling years between 1999 and 2005 ranged from a low of 12.5 in 1999 to a high of 20.5 in 2003. These scores place the Serpentine in the “poor” category in terms of stream condition. B-IBI scores in this study showed correlation with watershed-scale factors associated with human disturbance and urbanization, such as total impervious surface cover, riparian forest cover, water temperature, and specific conductivity. The low B-IBI score for the Serpentine River accurately indicated that the watershed had been extensively altered by urbanization and human disturbance (Page et al. 2008).

Based on the two studies, the Upper Serpentine is not severely polluted but has water quality issues indicative of land use in the watershed.

2.3.3 Wildlife

The Serpentine-Nicomekl watershed is part of the Fraser River Estuary and Delta system, an important overwintering spot for migratory birds along the Pacific Flyway (Cox 1975). The area is frequented by over 150 bird species, 66 passerine, and numerous raptors (Cox 1975). Most commonly observed animals in the nearby riparian forest and open fields include raccoons (*Procyon lotor*), eastern cottontail rabbits (*Sylvilagus floridanus*), Douglas squirrels (*Tamiasciurus* *douglasii*), eastern grey squirrels (*Sciurus carolinensis*), voles (family Cricetidae), red-legged frogs (*Rana aurora*), and garter snakes (*Thamnophis* spp.). Rarer sightings include American bittern (*Botaurus lentiginosus*), green heron (*Butorides virescens*), bald eagle (*Haliaeetus leucocephalus*), rough-legged hawk (*Buteo lagopus*), Townsend's vole (*Microtus townsendii*), and snowshoe hare (*Lepus americanus*; GVRD 2004).

2.3.4 Vegetation

The presence of large cedar stumps with springboard cuts in riparian zones throughout the upper watershed suggests that the Serpentine was logged as far back as the late 1930's, when the chainsaw began to replace the manual crosscut saw. Currently, the riparian zone near residential areas consists of early succession species such as alders (*Alnus* spp.), maples (*Acer* spp.), cottonwoods (*Populus* spp.), and cedars (*Thuja* spp.). In Tynehead Regional Park, a more mature forest community with greater conifer presence exists along the riparian zone. The park was created in 1975 and had been left relatively undisturbed since its establishment (GVRD 2004). Salmonberry (*Rubus spectabilis*) is abundant in the understory and along streambanks. Several invasive species, including English ivy (*Hedera helix*), Japanese knotweed (*Fallopia japonica*), and yellow archangel (*Lamiastrum galeobdolon*) can be found in the riparian and nearby forest. Glyphosate treatment has been used to treat Japanese knotweed and yellow archangel throughout the upper reaches (pers. obs. 2017).

2.4 First Nations Use

Archaeological evidence dates human activity in the lower Fraser River back to 9,000 years ago (GVRD 2004). The area was utilized by many Coast Salish nations, the largest being the Musqueam, Kwantlen, Chilliwack, and Stó:lō. The Stó:lō consisted of numerous bands, including Katzie, Coquitlam, Whonnock, Nicomen, Pailarlt, and Tait. The Serpentine River was part of a network of rivers, lakes, and mountain ridges that made up an extensive communications, travel, and economic route system. Along with the Nicomekl and Salmon Rivers, the Serpentine River connected Boundary Bay to the Fraser River. In the Stó:lō Atlas, the lower reaches of the Serpentine were identified as part of a tribal watershed for Kwantlen and Snokomish peoples. At first contact with Europeans, it was estimated that 30,000 people were living within Stó:lō territory (GVRD 2004).

2.5 Land Use and Stressors

2.5.1 Agriculture

Agricultural land use predominates the lower portions of the Serpentine watershed. Much of the attention in the Serpentine has been paid to fresh water for irrigation, flood control, and drainage (Town 1986). In 1913, a sea dam was constructed in the lower reaches of the Serpentine River to prevent salt water intrusion into agricultural fields and provide freshwater for irrigation. Seven pressure gates open passively when pressure from the upstream side is greater than the opposing pressure at the downstream side (ie. at low tide or during rain events). When pressure from the downstream side is greater than the upstream side, the gates close. There is a strong correlation between monthly precipitation and the number of hours the gates stay open that month (Town 1986). The sea dam is a barrier to upstream migration, particularly during late summer and early fall when levels of tidal water remains greater than the river level for long periods (Backman and Simonson 1985). In 1974, the dam was rehabilitated due to excessive leakage (Town 1986).

There are concerns for water quality in the lower portions of the river due to nutrient loading from agricultural land use. In 1984, two recorded fish kills of around 500 adult coho in the Lower Serpentine coincided with low pH (6.2) and dissolved oxygen concentration (~6.5 mg/L; Backman and Simonson 1985). Furthermore, water quality problems are exacerbated by the complete clearing of riparian vegetation in the agricultural lowlands. The loss of riparian cover, water withdrawal, and increased drought conditions in recent years raise concerns for water temperature rises in the lower portions of the river. Lastly, extensive dyking for flood control and channelization has cut off access of the main channel to the floodplain in the lower reaches.

2.5.2 Dyke Construction

As early as the late 1800’s, farmers began installing dykes and canals in the Serpentine and Nicomekl lowlands for agricultural purposes. Much of this area is close to sea level and was historically an intertidal zone. In 1910, the Surrey Dyking District was formed under the Drainage, Ditch, and Dike Act. Its mandate was to construct dykes and sea dams on the Serpentine and Nicomekl Rivers. Dyking began in the 1920’s, but in the 1950’s, the acquisition of a dragline mechanized the process and dredging became a regular project (Figure 5). Dredging removed silt which was used to build up the dykes. However, despite efforts by the Surrey Dyking District, significant flooding caused by high tides continued to occur in the lowlands (Figure 6). In 1997, the City introduced the Lowland Flood Control Strategic Plan, whereby flooding was significantly reduced through strategic installation of dykes, pump stations, and conveyance improvements within the agricultural lowlands (City of Surrey 2017).

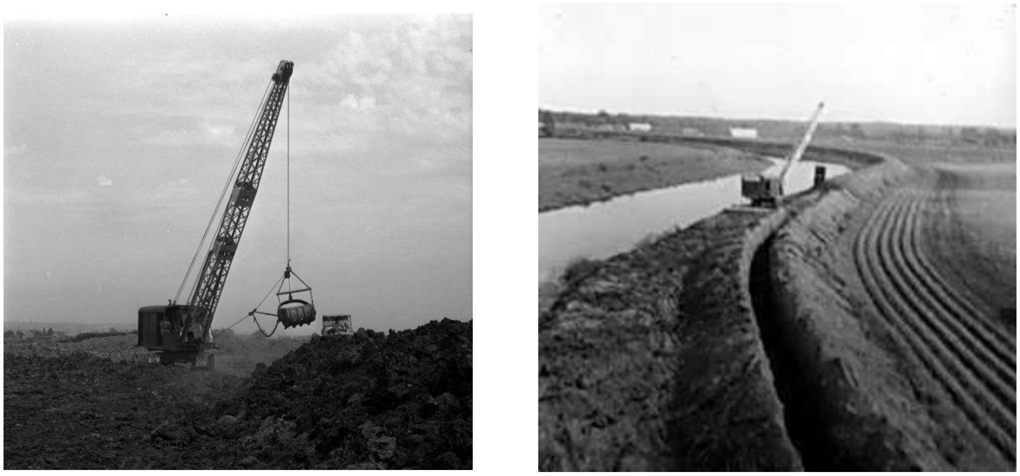


Figure 5. Historical photographs of the Surrey Dyking District crews dredging the Serpentine River using a dragline (Left: Surrey Archives n.d., right: Gordon Bishop n.d.).

Figure 6. Skaters take advantage of the ice formed after flooding in the Serpentine floodplain in 1962 (Surrey Archives n.d.).

2.5.3 Urban Encroachment

Figure 7. Aerial photographs of the Upper Serpentine watershed from 1949 (top) and 2016 (bottom). Images obtained from City of Surrey Online Mapping System (COSMOS).

Urban encroachment has drastically altered the landscape of the Upper Serpentine over the last half of the century (Figure 7). Today, densely packed residential areas have replaced sparse residences of the past. The remaining green spaces include the 261-ha Tynehead Regional Park and some farm land as the river moves downstream toward the agricultural lowlands. The Upper Serpentine watershed has an average ISC of 29.8%, with most of the impervious surface cover concentrating in the developed uplands, which has an ISC of 44.2% (Urban Systems 2015). Increases in impervious surface cover, particularly in the developed upland areas of the watershed, have caused changes in hydrology and sediment dynamics (Dillon 2012). Increased discharge during precipitation events erodes spawning gravel and causes channel incision. Bank erosion provides a constant source of fine sediment that degrades downstream spawning habitat (Figure 8).

Figure 8. Evidence of streambank erosion in site 1 (left) and site 7 (right; Yuan 2017).

In addition to the degradation of spawning habitat, the Upper Serpentine has experienced other negative effects from urbanization including stream channelization, installation of impassable culverts, removal of stream bank vegetation, and input of contaminants from residential, commercial, and industrial sources.

2.5.4 Climate change

The Pacific Northwest is predicted to experience wetter winters and drier summers in the future (Mote and Salathe 2010). Wetter winters will increase flood frequency and intensity which pose a clear challenge to gravel restoration projects. Many channelized urban streams cannot access their floodplain, and gravel retention will be increasingly difficult as flows and tractive forces increase. Restoration must address urban runoff from a watershed perspective, and gravel addition must be combined with instream structures that sufficiently reduce tractive forces to retain gravel under future hydrologic conditions. Furthermore, drier summers can be detrimental to the lower portions of the river where there is little riparian shade cover. Fish kills occur when water temperature rises above the upper lethal limit for salmonids, around 25°C (Bell 1986). Access to cold water and riparian vegetation establishment should be a priority to reduce the effects of climate warming in the lower reaches.

3 Salmonid Spawning Habitat Requirements

Adult salmonids returning to freshwater endure physically demanding and sometimes lengthy upstream migrations to their natal streams. The freshwater environment should provide suitable discharges, temperatures, and water quality to enable adults to reach spawning grounds with sufficient energy reserves for reproduction. Spawning habitat should also provide the proper environment for egg incubation. Salmonids have evolved in streams with natural fluctuations in water temperature, discharge, and water quality (Bjornn and Reiser 1991). They exhibit natural flexibility in their maturation, migration, and spawn timing to deal with delays caused by unsuitable flows, temperatures, or turbidities. Flexibility in timing is unique to each population, which is why transplanted populations generally underperform compared to native populations. Despite the behavioural plasticity in salmonids, human activity can alter streams so extensively that the changes overwhelm the coping mechanisms (Bjornn and Reiser 1991). There are five key parameters that are considered key requirements for spawning habitat and they will be discussed in this chapter: dissolved oxygen, temperature, depth, velocity, and grain size. The table below summarizes these requirements.

Table 1. Spawning requirements for five salmonid species present in the Serpentine River. Dissolved oxygen values are based on swimming experiments in laboratory studies. Temperature, depth, and velocity values are based on measurements at redds. Grain size values are recommendations for artificial spawning channels.

Species	Dissolved oxygen (mg/L)	Temperature (˚C)	Depth (m)	Velocity (m/s)	Grain Size (mm)
Coho	6.5-7[a]	4.4-9.4[b]	0.18[c]	0.30-0.91[c]	13-102[b]
Chinook	6.5-7[a]	5.6-13.9[b]	0.24[c]	0.30-0.91[c]	13-102[b]
Chum	6.5-7[a]	7.2-12.8[b]	0.18[c]	0.46-1.01[e]	13-102[b]
Steelhead	6.5-7[a]	3.9-9.4[b]	0.24[e]	0.40-0.91[e]	6-102[d]
Cutthroat	6.5-7[a]	6.1-7.2[b]	0.06[d]	0.11-0.72[d]	6-102[d]

[a]Davis et al. 1963
[b]Bell 1986
[c]Thompson 1972
[d]Hunter 1973
[e]Smith 1973

3.1 Dissolved Oxygen

Dissolved oxygen (DO) concentration affects the swimming performance of migrating salmonids. Maximum sustained swimming speeds of coho salmon declined sharply when DO dropped to 6.5-7.0 mg/L (Davis et al. 1963). Adult migration ceased completely below 4.5 mg/L and only resumed when DO recovered above 5.0 mg/L (Hallock et al. 1970). The minimum requirements for spawning should be well above 5.0 mg/L, with optimal conditions above 7.0 mg/L.

3.2 Temperature

Temperature affects the metabolism and aerobic scope of migrating salmonids, which determines their physical performance during their upstream migrations (Eliason et al. 2011). Each population exhibits slightly different thermal optima, having evolved to spawn at times that maximizes the survival of offspring (Bell 1986, Bjornn and Reiser 1991). Despite different thermal optima, most salmonids have a thermal tolerance range (i.e. lower lethal to upper lethal limit) of around 0-25°C (Bell 1986). Salmonids have been observed to delay spawning when temperatures in natal streams are too hot or too cold (Bjornn and Reiser 1991). In general, anadromous salmon exhibit a wide range of spawning temperatures and have migrated between 1 and 20°C, though favourable ranges are much narrower (Table 1; Bell 1986, Bjornn and Reiser 1991).

During incubation, temperature affects the rate of development and the capacity of dissolved oxygen in water. The warmer the temperature, the faster the development and the shorter the time to emergence (Heming 1982). Accelerated or slowed development can adversely affect fry if conditions at time of emergence, such as food availability, are unfavourable.

3.3 Depth and Velocity

Based on measurements of water depth at redds, salmonids generally spawn in water that was deep enough for full submersion, but many spawn in deeper water (Bjornn and Reiser 1991). It is not known whether the fish preferentially selected the sites based on depth or other hydraulic characteristics. Species-specific preferences are provided in Table 1.

Streamflow can be barriers to salmon passage as salmon have certain cruising, sustained, and darting speeds. As streamflow increases, more gravel is inundated and becomes suitable for spawning. However, as streamflow continues to increase, velocities become too high for spawning, and the area suitable for spawning decreases (Hooper 1973). Salmonids have been observed to spawn in a wide range of water velocities, but most spawned between 0.2 to 1.0 m/s (Bjornn and Reiser 1991).

3.4 Grain Size

Bed substrate material must be small enough to be moved during redd excavation (Kondolf 2000a). Although not all particles need to be moved, most of the framework particles (larger particles that make up the structure of the substrate) should be movable. This requirement sets the upper limit of the suitable gravel size range for salmonids. Kondolf (2000a) suggested that assessing whether framework particles are too large can be done by comparing the D_{50} and D_{85} (particle sizes at which 50% and 85% of the sample, respectively, are finer) to values reported from the field. In general, salmonids can move gravels with a median diameter (D_{50}) of about 10% of their body length (Kondolf and Wolman 1993). While chinook salmon have been observed to spawn in particles with a median size of 78 mm, most salmonids usually spawned in median sizes well below 50 mm (Kondolf and Wolman 1993).

During incubation, spawning gravel should be relatively free of fine sediment to enable sufficient flow of water through the gravel. This water exchange is important for the delivery of dissolved oxygen to the redds and removal of metabolic waste produced by the embryos (Chevalier et al. 1984, Groot and Margolis 1991). Coarser fine sediment can also affect fry emergence by blocking upward migration of fry (Bjornn 1969, Phillips et al. 1975, Harshbarger and Porter 1982). Studies have demonstrated the negative effects of fine sediment on embryo survival, where steady declines in survival were observed after substrate exceeded 10-30% fines (defined as <6.35 mm in these studies; Tappel and Bjornn 1983, Irving and Bjornn 1984). In laboratory studies using <1 mm as the criterion for fine sediment, 50% emergence corresponded with around 14% fines (Kondolf 2000a). This was close to the standard drawn from field observations, where salmonids were observed to spawn in substrate with up to 12% fine sediment (McNeil and Ahnell 1964, Cederholm and Salo 1979). When setting precise thresholds for the lower limits of spawning gravel size, it is important to consider the different criteria of fine sediment used in studies and the variability of reported results.

When assessing spawning gravel quality, percent fines should be adjusted downward to account for the cleaning effect of redd building (Kondolf 2000a). Comparisons of fine sediment content between redds and comparable unspawned gravels showed that redds contained a lower proportion of fine sediment compared to unspawned gravels (Chambers et al. 1954, Kondolf et al. 1993). Despite this cleaning effect, adverse effects can still be caused by fine sediment accumulation over the incubation period. Lastly, seemingly good quality gravels may not be used for spawning if hydraulic conditions for inter-gravel flow are absent. Dye studies have shown that irregularities in the stream profile, such as redds and riffle-pool sequences, promote inter-gravel flow and create stable incubation environments by promoting steady exchange of water past embryos (Cooper 1965, Vaux 1968).

4 Past Spawning Habitat Restoration

Gravel augmentation has been widely used to restore salmonid spawning habitat (Rosenau and Angelo 2000, Roni et al. 2002). Treatments generally include bulk addition of gravel, instream structures, or a combination of both. Many studies indicate positive results, including increased spawner recruitment, increased fry production, and improved physical characteristics associated with early life-stage survival (Table 2). A review of stream restoration projects in Oregon revealed that instream structures were largely effective in recruiting spawning gravels, creating pool and riffle habitats, and increasing fish production (House 1989). However, many stream restoration projects are not monitored sufficiently and do not provide information on the longevity of instream structures and the long-term biophysical response to restoration (Bash and Ryan 2002, Roni et al. 2002). In some cases, gravel placement failed due to a lack of attention paid to the geomorphic processes of the site (Kondolf et al. 1996).

Literature on spawning habitat restoration are mostly related to stressors from hydroelectric development and logging. There is little documentation of spawning habitat restoration in urban settings. Urban streams present unique challenges to restoration, including low water quality and rapid changes in flow following precipitation. These challenges are exemplified by projects described in Booth (2005) in Table 2.

4.1 Design Considerations

Substrate sizes used for spawning gravel restoration projects typically represent suitable sizes for target species, but can depend on the logistics of gravel sourcing. Gravel ranging from 20-100 mm was used in Robertson Creek, British Columbia for spawning channels for pink (*O. gorbuscha*), coho, and chinook salmon (Lucas 1960). Spawning mixture used in the Merced River in California were 13-102 mm (Kondolf et al. 1996), following recommendations of Bell (1986). In the Mokelumme River, 2.5 to 15 cm gravel was taken from a nearby floodplain quarry and used for gravel augmentation (Merz et al. 2006).

Table 2. Summary of past spawning habitat restoration projects.

Source	Location	Stressor	Species	Methods	Results
Palm et al. 2007	River Kalix, Sweden	Stream channelization for timber floating	Brown trout (*Salmo trutta*)	Boulder and gravel, and Boulder only	Increased age 0+ density, and increased egg to fry survival in the boulder and gravel treatment.
Merz and Setka 2004	Mokelumne River, California	Dam	Chinook	Gravel placed in berm and gravel bar configurations	Increased intergravel permeability, dissolved oxygen, and water velocity. Reduced channel depths. Use by Chinook for all 3 spawning seasons emcompassed by study.
Kondolf et al. 1996	Merced River, California	Dam	Chinook	Excavation of riverbed followed by backfilling with suitably-sized spawning gravel	Spawning gravel scoured at a flow with a return period of 1.5 years.
House 1996	Lobster Creek, Oregon	Logging, log jam clearing	Coho, chinook, steelhead, cutthroat	Full-spanning rock gabions and boulder structures	Increased coho spawners by 2.5-fold, increased spawning habitat by 115%, 50% spawners used newly recruited gravels, increased coho and cutthroat juveniles, gabions began to disintegrate after 10 years, boulders remained stable
Booth 2005	Madsen Creek, Seattle	Urbanization	Salmon	LWD, spawning gravel addition, riparian planting	Large rainstorm delivered large quantities of sand and silt throughout the project site, site remains sandy and ill-suited for spawning 8 years later
Booth 2005	Longfellow Creek, Seattle	Urbanization	Coho	LWD, Spawning gravel addition, channel reconstruction, riparian planting, barrier removal	Large pre-spawn mortality of coho salmon post-restoration, spawning gravels largely unused

Roni et al. (2002) reviewed stream restoration techniques and concluded that for low elevation streams (<3%), weir and deflector structures were generally successful in increasing spawning habitat. An evaluation of 812 full-spanning structures installed in the Salem District in Oregon found that 86% were fully functional, suggesting that these structures are suitable restoration treatments across a wide range of stream conditions (House et al. 1989).

Many unsuccessful river restoration projects aimed to mimic habitat form without considering the fluvial and geomorphic processes at the watershed and reach scale (Kondolf 1998, Kondolf 2000b). Gravel imported into the Merced River in California was scoured at modest flows because the sediment transport capacity under the flow regime at the time was not considered (Table 2; Kondolf et al. 1996). Kondolf (2000b) recommended that before gravel is imported into a stream, anticipated bed mobility should be calculated under post-project flow conditions. Ongoing changes in channel form and function should also be accounted for in the project planning process. In urban systems, understanding future development and climate change effects on stream hydrology will be crucial to the development of effective restoration prescriptions. Lastly, project objectives should address biologically limiting factors of the target species and include long-term monitoring to evaluate project success (Kondolf 1998, Kondolf 2000b).

The following chapter is an evaluation of current conditions of the seven study sites in the Upper Serpentine River. The goals of the site assessments were to 1) determine whether the substrate is suitable for spawning, 2) predict gravel mobility at the study sites, and 3) measure fine sediment delivery rates. Based on the results, a restoration plan was developed with particular consideration to local fluvial geomorphic processes to effectively increase spawning habitat in the Upper Serpentine River.

5 Current Conditions and Site Assessment

5.1 Site Locations

Locations of the study sites are shown in Figure 9. Sites 1 to 3 are located in Guildford Brook, whose catchment includes Guildford Town Centre and nearby residential areas. Site 4 is located in Townline Creek and drains nearby residential areas. Site 5 is located in the mainstem Serpentine within Tynehead Regional Park. Sites 6 and 7 are located in East Creek and receives runoff from nearby residential and agricultural lands.

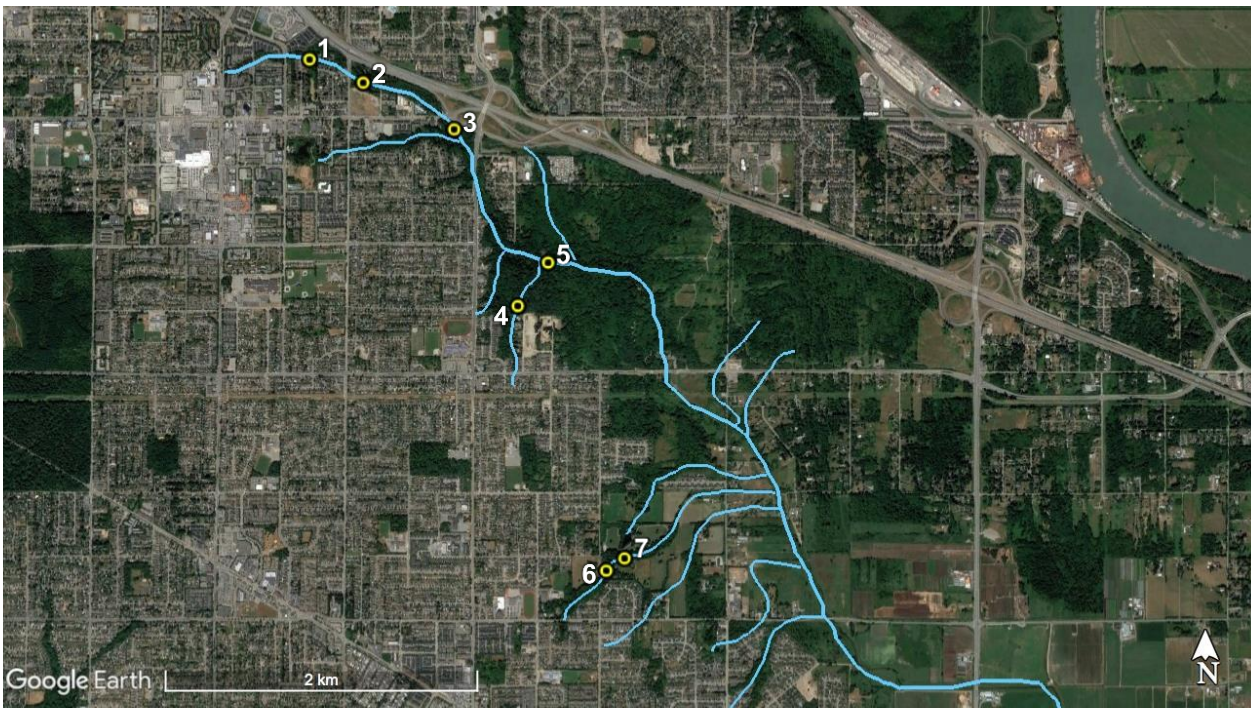


Figure 9. Locations of seven study sites in the Upper Serpentine River (modified from Google Earth).

5.2 Methods

5.2.1 Water Quality

Temperature, dissolved oxygen, salinity, conductivity, and pH measurements were taken using a YSI Professional Plus Multiparameter Meter during the spring and fall of 2017. Turbidity measurements were also taken during these periods using a LaMotte 2020we Portable Turbidity Meter. Three repeat samples were taken at the same location in the middle of the stream at the upstream end of each site.

5.2.2 Wetted Depth and Velocity

Wetted depth and velocity were measured along three transects at 1/4, 1/2, and 3/4 of the site length. Each transect was sampled at 1/4, 1/2, and 3/4 of the transect width to obtain depth and velocity values for the transect. Velocity was measured at 60% of the depth below the surface using a Hach FH950.0 Flow Meter.

5.2.3 Grain Size Analysis

Surface particles are generally coarser than subsurface particles due to the selective transport of fine sediment during lower flows (Kondolf 2000a). While surface grain size analysis does not provide an accurate estimate for fine sediment content and gravel permeability of redds, surface sampling does provide a good estimate for the framework particle sizes (Kondolf 2000a). Surface grain size sampling was conducted across each site using a modified Wolman pebble count method in a zig-zag pattern. One hundred particles were sampled, measured along the b-axis (the longest intermediate axis perpendicular to the longest axis) and analyzed for grain size distribution.

According to Kondolf (2000a), pebble counts in a zig-zag pattern leads to the undesired mixing of different stream features (i.e. riffles and pools). However, it is difficult to sample a minimum of a hundred particles in one transect in narrow streams without repeat sampling of the same location. The zig-zag sampling method was developed to overcome this issue in small, narrow streams. Furthermore, degraded streams lack clearly-defined riffle-pool sequences and exhibits a more homogeneous substrate. Given the site limitations and the nature of the substrate in disturbed streams, zig-zag sampling was conducted as a best alternative method.

Subsurface sediment sampling was conducted to assess the smaller grain size matrix and gravel permeability. Subsurface sampling was conducted along transects using a random systematic sampling design. Transects were spaced at double the bankfull width of each site, with the location of the first transect being randomly selected. Within each transect, a subsurface sample was collected at each 1.5-m interval. The location of first sample within a transect was also randomly selected. A shovel was used to dig and fill a 10-cm diameter by 11-cm tall aluminum can with gravel, which constituted a sample. Samples were dried, sieved into size classes, and weighed for grain size distribution analysis.

5.2.4 Hydraulic Analysis

Understanding gravel mobility requires estimation of the shear stress exerted on the streambed by the moving water and the grain size such forces can mobilize (critical erodible grain size). Cross-sectional average bed shear stress at bankfull was calculated using (Leopold et al. 1964):

$$\tau_b = \rho_f gRS \qquad (1),$$

where τ_b is the bed shear stress (N/m^2), ρ_f is the density of water (1,000 kg/m^3), g is gravity (9.8 m/s^2), R is the hydraulic radius (m), which is approximated by the water depth in shallow, wide channels, and S is the energy slope, which is approximated by the water surface slope. Because bed shear stress (τ_b) is a function of hydraulic radius and water surface slope, channel surveys were conducted to measure slope and bankfull depth along three transects at each study site.

Critical erodible grain size was calculated using the Shields equation (Vanoni 1975, Richards 1982):

$$\tau_{ci} = \tau_{*ci} (\rho_s - \rho_f) g d_i \qquad (2),$$

where τ_{ci} is the critical shear stress required to move particle size d_i, τ_{*ci} is a dimensionless shear stress also known as the Shields parameter, and ρ_s is the density of sediment, which is assumed to be 2,650 kg/m^3 (Hickin 1995). The dimensionless shear stress, τ_{*ci}, is a function of the properties of the sediment. Generally, the Shields parameter for gravel is constant at 0.06 (Hickin 1995). However, for gravel-bed rivers in British Columbia, the Shields parameter is dependent on the extent of packing: 0.06 for normal, >0.06 for underloose, and <0.06 for overloose (Hickin 1995). For the current study, a value of 0.06 was be used as the placed gravels should exhibit normal packing. Using the calculated bed shear stress, τ_b, as the critical shear stress, τ_{ci}, the Shields equation was solved to obtain erodible grain size at bankfull flow. The erodible particle sizes were compared to the D_{50} of the spawning gravel which will be imported for supplementation. According to the equal mobility theory (Parker and Klingeman 1982), each grain size in a well-mixed gravel bed exhibits the same critical shear stress as that of the D_{50}. In other words, all bed material moves together at the same shear stress determined by the D_{50}.

5.2.5 Tracer Rock Verification

In studying sediment transport rates and patterns, there are still substantial inconsistencies between data collected in the field and results obtained from theoretical models (Hassan and Ergenzinger 2003). These inconsistencies arise largely from limitations of field work and the complex interactions of variables that influence sediment movement. The use of tracer rocks has enabled researchers to better understand sediment transport characteristics in the field. Tracer rocks are marked particles introduced to streams for the purpose of being tracked following flow events. Data collected from tracer rocks in the current project was used to verify bed shear stress calculations and provide information on the potential mobility of placed gravels under varying flow conditions at each site. Since placed gravels are intended to stay at the seven selected sites, tracer rocks were only monitored for their disappearance from the sites and not located downstream. Monitoring how tracer rocks mobilize and disappear at each site will provide a preview of how placed gravels might deplete if they are simply placed in bulk without instream structures.

During the fall of 2017, 288 painted particles were introduced into the seven study sites. Three size classes ranging from pebble to large cobble were deployed at each site in rows (Table 3). Row 1 was made up of particles around 30 mm diameter, which is similar to the desired gravel size for spawning. The other two rows were comprised of particles of the site-specific calculated erodible grain size and as well as a larger size class.

Table 3. Mean particle sizes and number of particles deployed at the study sites.

Site	Row 1 (mm)	No. of Particles	Row 2 (mm)	No. of Particles	Row 3 (mm)	No. of Particles
1	29	30	n/a*	n/a*	102	10
2	28	30	n/a*	n/a*	103	10
3	30	30	102	10	139	5
4	30	30	99	10	139	5
5	35	27	117	10	155	5
6	35	21	108	10	144	5
7	35	30	139	7	148	3

*estimated critical erodible grain size was within the same size class as the first size class used

Particles of the same size class were placed across the entire bankfull width of each site (Figure 10). Three rows of tracer rocks were installed at each site, with the exception of sites 1 and 2 where only two rows were installed because the critical erodible grain sizes at these sites were similar to that of spawning gravels. Rows were spaced at least 2 m apart and particles were spaced at least one particle diameter apart to eliminate interaction between particles. Wherever possible, particles were placed in riffles because they represent the highest energy feature of the reach. To avoid artificially inflating particle mobility compared to the rest of the streambed, particles were set into the substrate by lightly stepping on them.

Figure 10. Downstream view of site 6 showing orientation of tracer particles placed instream (Yuan 2017).

Monitoring occurred after every major flow event between October 23, 2017 and February 4, 2018. A visual survey of the tracer rocks was conducted and mobilized particles were noted. Staff gauges were installed at each site and checked periodically to relate instream water level to the water level measured at a permanent gauge in the Serpentine River at 104 Avenue. This enabled back-calculation of water level at each site during major flow events, which was used to determine the number of mobilizing events for each tracer size class.

5.2.6 Siltation

To investigate the rates of fine sediment accumulation in the study sites, sediment baskets were installed following Reynolds (2017) in three of the seven sites that exhibited the highest proportion of fine sediment (sites 1, 3, and 7). Seventeen 1.6-mm holes were drilled in the bottom of 4”x4”x4” containers to enable drainage. Containers were then filled to the brim with clean ¾ inch crushed gravel to create interstitial spaces. Five containers were installed flush to the streambed in a pentagon configuration across the width of the channel. The baskets were installed on January 18, 2018 and collected on January 30, 2018. The contents of the baskets were dried at 430°F for 20 minutes before fine sediment was separated using a 4-mm sieve and weighed.

5.2.7 Barriers to Passage

There are numerous culverts along the Upper Serpentine River. Culverts along the migration route to study sites were visually assessed for any potential barriers to passage. Areas downstream of study sites were also visually assessed for any spawning gravel that may have deposited as a result of previous restoration efforts.

5.3 Results

5.3.1 Water Quality, Depth, and Velocity

DO concentrations measured in the Upper Serpentine River were well above the minimum requirement for salmonids, around 6.5-7 mg/L (section 3.1, Table 4). DO levels ranged from a low of 9.4 mg/L to a high of 11.2 mg/L in the spring. In the fall, DO ranged from a low of 8.2 mg/L to a high of 10.4 mg/L. DO levels were generally higher during spring, potentially due to lower water temperatures.

Water temperatures were within the recommended range for spawning for most species present in the Upper Serpentine, with the exception of coho and steelhead, whose preferred spawning temperature is below 10°C (section 3.2, Table 4). However, fall temperature readings were taken in October, and a large proportion of anadromous salmon do not return to the

Serpentine River until mid-November, when temperatures are cooler. Furthermore, the temperatures recorded are well below the upper lethal limits for salmonids, around 25°C.

Conductivity, salinity, and pH were within expected ranges of a rain-fed system. Instream turbidity levels were low and generally stayed below 2 NTU. Higher turbidity levels of 5.1 and 7.4 NTU were measured at sites 6 and 7, respectively, during a rain event. This was within the allowable increase of 8 NTUs above background levels set by the Canadian Water Quality Guidelines for the Protection of Aquatic Life (CCME 2002).

Depth and velocity were low during times of sampling and coincided with low basal flows between periods of precipitation (Table 5). Low water depth can be a barrier to upstream migration. Additionally, salmonids generally do not spawn in slow moving water due to the lack of gravel aeration. Fortunately, fish migration occurs later on in the fall when precipitation and flow are consistently higher. Furthermore, salmonids have adapted to periodic low flows by holding in ponds during dry periods and continuing upstream when flows become sufficient (Bjornn and Reiser 1991). Spawners were observed at sites 3, 5, and upstream of site 7, suggesting those sites were accessible either during higher flows or by maneuvering through deeper portions of the channel.

Table 4. Water quality parameters measured at study sites during the spring and fall of 2017.

Site	Season	DO (mg/L)	Temperature (°C)	Conductivity (uS/cm)	Salinity (ppt)	pH	Turbidity (NTU)
1	Spring	9.4	8.9	252.5	0.18	7.4	1.3
	Fall	8.2	12.4	86.6	0.05	6.9	0.5
2	Spring	9.7	10.8	271.0	0.18	7.4	1.0
	Fall	9.9	11.9	103.0	0.06	6.7	0.6
3	Spring	11.2	8.5	263.2	n/a	7.5	1.8
	Fall	10.4	10.7	126.4	0.08	7.0	0.6
4	Spring	9.7	9.1	207.1	0.14	7.6	0.8
	Fall	9.7	10.9	230.3	0.15	7.1	0.1
5	Summer*	8.8	15.6	201.7	0.12	7.8	0.1
	Fall	10.0	10.7	183.4	0.12	7.5	0.1
6	Spring	10.9	10.1	179.7	0.12	7.7	0.7
	Fall	8.6	11.2	62.4	0.04	6.9	5.1**
7	Spring	10.4	9.8	208.5	n/a	7.7	1.5
	Fall	9.3	11.3	59.7	0.03	6.8	7.4**

*Changed site location during the summer of 2017

**Data collected during high flows after rain event

Table 5. Fall assessment of spawning habitat requirements at study sites. Depth and velocity are expressed ranges within the three transects sampled. D_{50} is based on surface Wolman pebble counts.

Site	DO (mg/L)	Temperature (°C)	Depth (m)	Velocity (m/s)	D_{50} (mm)
1	8.2	12.4	0.03 - 0.10	0.05 - 0.40	19
2	9.9	11.9	0.09 – 0.14	0.03 – 0.09	32
3	10.4	10.7	0.05 – 0.12	0.02 – 0.14	39
4	9.7	10.9	0.03 – 0.04	0.06 – 0.16	30.5
5	10.0	10.7	0.09 – 0.14	0.14 – 0.32	52
6	8.6	11.2	0.03 – 0.05	0.17 – 0.20	22
7	9.3	11.3	0.05 – 0.10	0.03 – 0.26	20.5

5.3.2 Grain Size Analysis

Surface grain size

Grain size distribution curves for surface Wolman pebble counts showed that most of the sediment at the study sites fell within the recommended range for salmonid spawning gravel (Figure 11). Particles that fell outside the recommended range were mostly smaller in size. Sites 2, 3, and 4 exhibit the most appropriate grain sizes at the surface for spawning, with 80% of the substrate falling within the recommended range. Site 5 had a substantial amount of large particles, with 20% of the substrate above the recommended upper limit of 102 mm. D_{50} values ranged from a low of 19 mm in site 1 to a high of 52 mm in site 5.

From visual observations of the streambed surface, many sites exhibited mixing of fine and large particles. Pockets of gravel rarely existed in continuous patches, but were often nestled between clusters of cobbles and boulders.

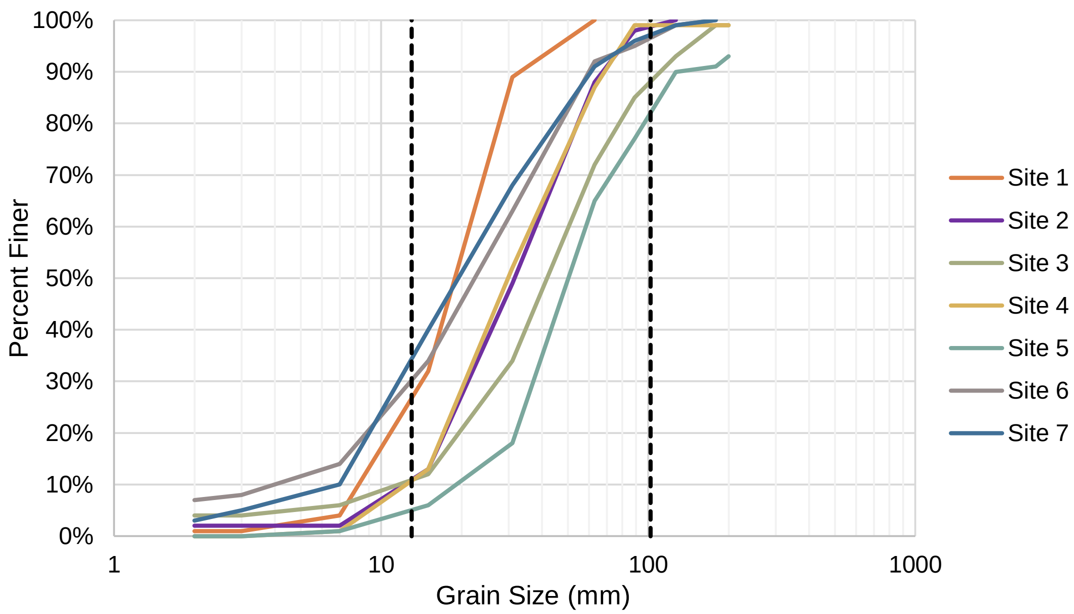
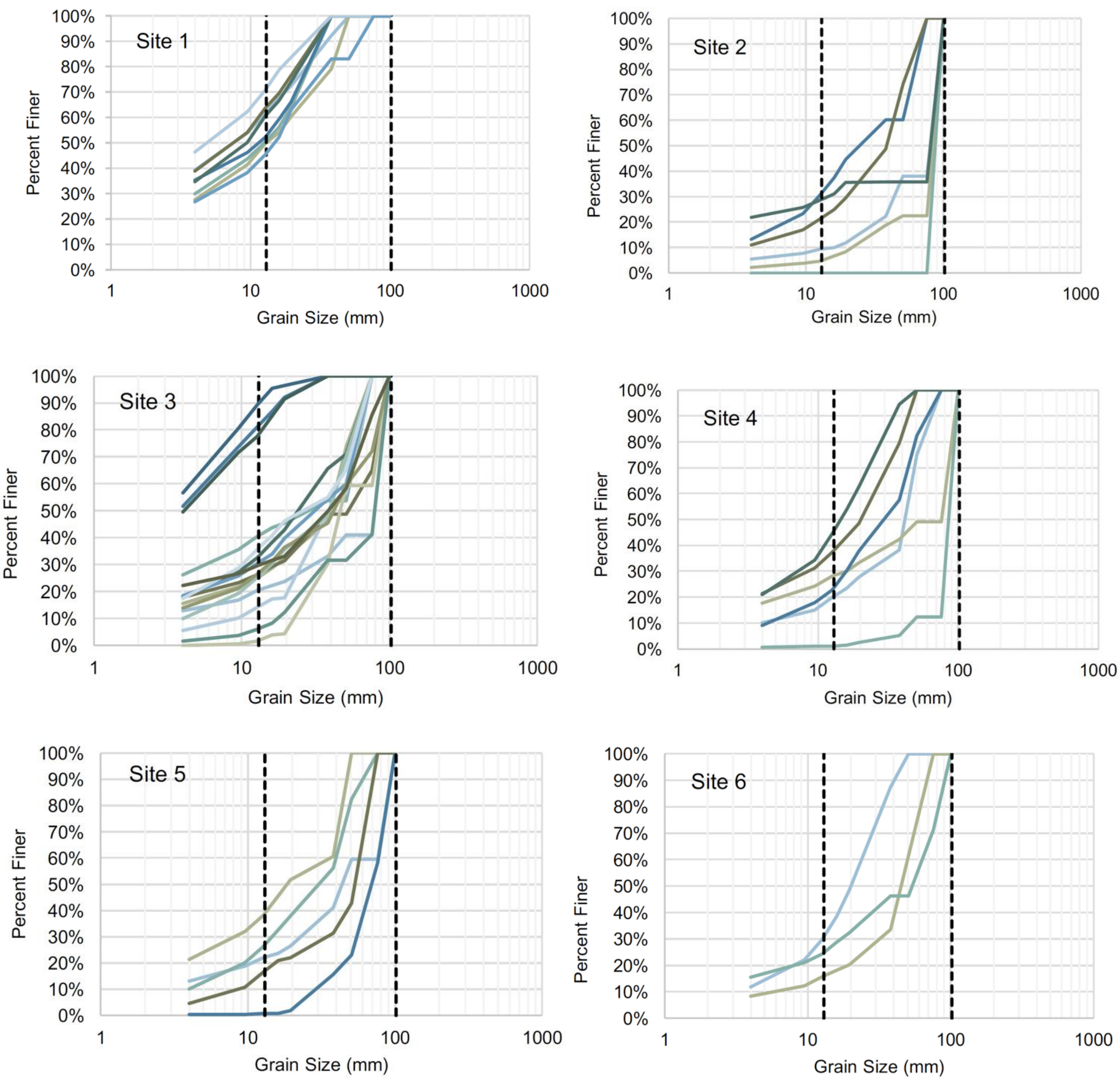


Figure 11. Grain size distribution curves of study sites based on surface Wolman pebble counts. Percent finer was calculated by particles. Vertical black dotted lines represent the recommended range of 13 – 102 mm for spawning gravel (Bell 1986).

Subsurface grain size

Subsurface grain size distribution curves of study sites exhibited varying degrees of within-site heterogeneity (Figure 12). Site 1 had a markedly narrower band of distribution curves compared to the other sites. This was consistent with field observations that noted a more homogeneous substrate of small pebbles that were embedded in fine sediment. In comparison, other sites exhibited different substrate patches, including some riffle-pool features. Sites 1 also had a much higher percent of fines (28 to 46%) compared to other sites. In general, samples from most sites contained up to 20% by weight in fines. The exceptions were sites 1 and 3, where fine sediment constituted up to 46% and 57% of the sample, respectively. Samples that were too large (i.e. greater than the sampling container) or too small (i.e. 100% sand) were not included in the distribution curves, but are noted in Appendix A.

It is important to note that surface grain size was analyzed on a per particle basis and subsurface grain size was analyzed on a per weight basis. Per weight particle analysis gives larger particles greater influence on the distribution curve and causes the curves to be drastically right-shifted. Therefore, the two analyses cannot be compared directly. Despite this limitation, it is evident that the subsurface contained a greater proportion of fine sediment that is protected from erosive forces by larger surface particles.



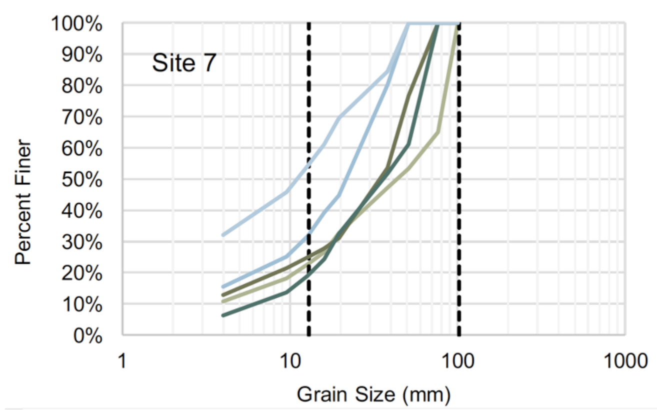


Figure 12. Subsurface grain size distribution of study sites. Individual lines within the graphs represent each subsurface sample collected. Percent finer was calculated by weight. Vertical black dotted lines represent the recommended range of 13 – 102 mm for spawning gravel (Bell 1986).

5.3.3 Hydraulic Analysis

Channel geometry of the study sites are summarized in Table 6. Site gradient ranged from 0.8% in site 1 to 3.0% in site 6. With the exception of site 6, where bankfull width was less than 3 m, most sites exhibited mean bankfull widths between 5-8 m. Mean cross-sectional bankfull depths ranged from 0.22-0.75 m. Calculated mean bed shear stress ranged from a low of 34 N/m^2 in site 1 to a high of 134 N/m^2 in site 7. The high shear stress in site 7 can be attributed to the combination of high bankfull depth as well as high gradient. Erodible grain sizes ranged from 29 mm to 164 mm (Figure 13). With the exception of site 1, erodible grain size exceeded D_{50} of suitably sized spawning gravel (35 mm).

Table 6. Channel geometry and bed shear stress of study sites. Bankfull width and cross-sectional bankfull depth are expressed as means calculated from three transects ± SD.

Site	Slope (%)	Mean Bankfull Width (m)	Mean Cross-sectional Bankfull Depth (m)	Mean Bed Shear Stress (N/m^2)
1	0.8	6.17 ± 0.26	0.46 ± 0.08	34 ± 6
2	1.3	5.19 ± 0.34	0.42 ± 0.16	45 ± 11
3	2.1	7.13 ± 0.84	0.53 ± 0.22	121 ± 33
4	2.0	5.87 ± 1.07	0.48 ± 0.07	96 ± 8
5	1.3	7.95 ± 1.23	0.75 ± 0.01	94 ± 1
6	3.0	2.79 ± 0.78	0.22 ± 0.08	56 ± 13
7	2.3	5.01 ± 0.93	0.60 ± 0.03	134 ± 6

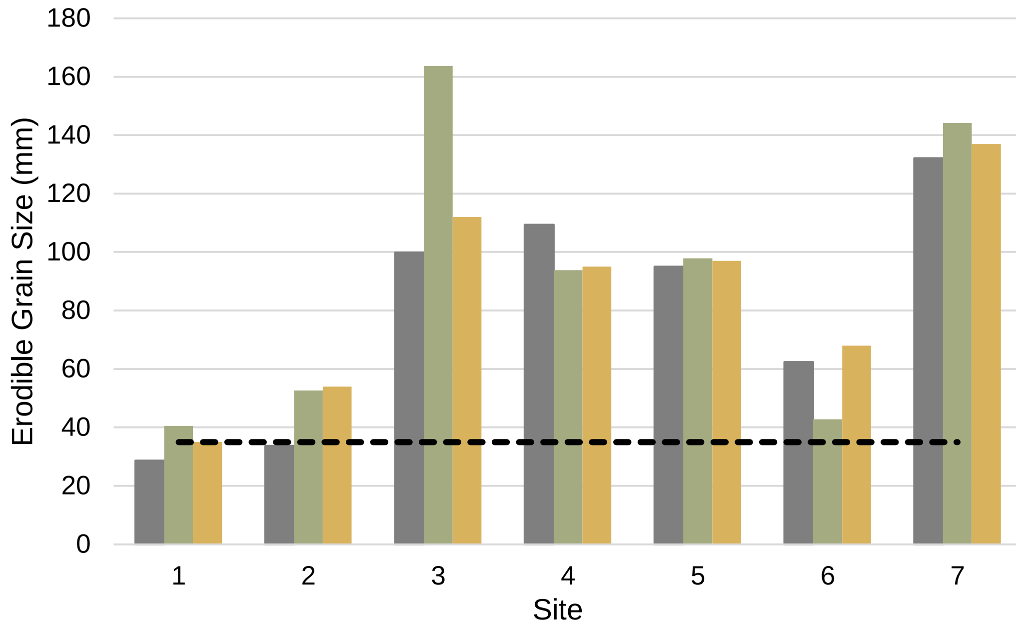


Figure 13. Bankfull erodible grain sizes calculated using average cross-sectional shear stress along three transects per site. Each shaded bar represents a different transect. The black dotted line represents the recommended D_{50} for placed spawning gravel.

5.3.4 Tracer Rock Verification

With the exception of site 1, at least 70% of the particles in the pebble size class were mobilized in each study site (Figure 14). Most immobile particles in this size class were located along the sides of the channel, where shear stress is lower compared to the channel thalweg. Particle movement was generally predictable, as higher proportions of larger particles remained immobile compared to smaller particles. However, there were still inconsistencies when considering the number of mobilizing events that occurred over the study period (Figure 14). Many of the larger sized particles showed partial or full movement despite sub-critical water levels. In site 1, the 102-mm size class exhibited similar proportions of movement compared to the 29-mm size class. In site 4, disappearance of particles of the 139-mm size class was likely due to burial rather than mobilization as particles were observed to be partially buried during a site visit.

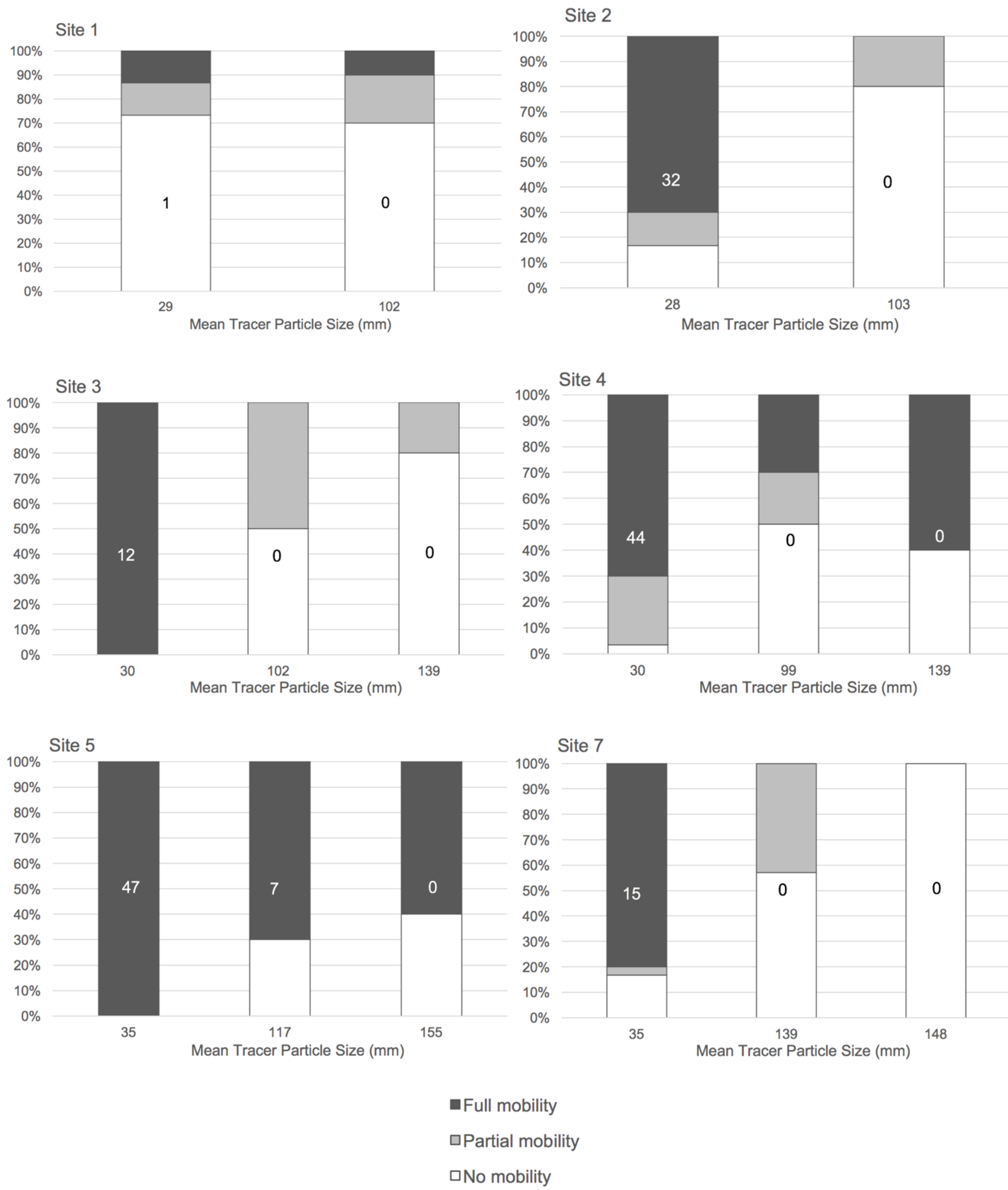


Figure 14. The fractions of tracer particles under full, partial, and no mobility after the study period of October 23, 2017 to February 4, 2018. Numbers within the bars indicate the number of mobilizing events where the calculated bed shear stress exceeded the critical erodible shear stress of the mean particle size. Tracer analysis could not be completed in site 6 due to a log jam downstream of the site causing sediment accumulation and burial of tracer particles.

5.3.5 Siltation

Of the 15 sediment accumulators deployed, 12 were recovered. Three accumulators from site 3 could not be located. Mean mass of fine sediment accumulated over a 12-day period for sites 1, 3, and 7 were 225 g, 306 g, and 272 g, respectively (Table 7). Values ranged from 176-345 g in site 1, 263-507 g in site 3, and 150-500 in site 7. When accumulation rates were extrapolated to a per m^2 basis, daily accumulated rates ranged from 1.2-1.6 kg/m^2/day. It is important to note that extrapolation assumed that rates of sedimentation are homogeneous across the entire reach, which was shown to be untrue by the wide range of accumulated mass. Fine sediment accumulated over the study period constituted an average of 15-20% of the weight of the sample.

Table 7. Mean mass of fine sediment (<4 mm) accumulated per accumulator between January 18, 2018 and January 30, 2018, calculated accumulation/m^2/day, and mean percent fines after the 12-day study period in sites 1, 3, and 7. Values are means ± SD.

Site	Mass of fine sediment/accumulator (g)	Accumulation/m^2/day (kg)	Percent fines after study period (12 days)
1	225 ± 24	1.2 ± 0.3	15 ± 3%
3	306 ± 66	1.6 ± 0.4	20 ± 3%
7	272 ± 106	1.5 ± 0.6	18 ± 7%

5.3.6 Barriers to Passage and Areas of Spawning Gravel

A culvert that crosses 104 Avenue at the upstream end of site 3 was determined to be a barrier to passage using the *Field Assessment for Determining Fish Passage Status of Closed Bottom Structures* (MOE 2011). A final score of 31 exceeded the threshold of 20 for barriers (Appendix B). Poorly designed culvert features include a large entrance height restriction, sheet flow within the culvert, high gradient, and a high channel to culvert width ratio. Adult spawners were observed in site 3 but not in the upstream sites 1 and 2. Historically, spawning has been observed above site 3 (Backman and Simonson 1985), but access may have been cut off by alterations to the culvert.

Areas downstream of site 3 and 7 appear to be depositional zones with appropriately sized spawning gravels. Deposited materials could have been a result of gravel addition efforts in previous years in site 3, but gravel addition was never implemented in site 7. Reaches around the

Serpentine Enhancement Society on 96 Avenue are in an area of active spawning. During August of 2017, instream rock weirs were installed near the hatchery, which increased spawning gravel in the area (Lesley England, pers. comm., 2018).

5.4 Discussion

5.4.1 Water Quality, Depth, and Velocity

Water quality parameters measured in the Upper Serpentine were within recommended ranges for spawning. However, the current study did not test for heavy metals and other contaminants commonly found in urban streams. While urban contaminant analysis was outside the scope of the current project, it should not be entirely ignored due to the adverse effects of these contaminants on aquatic life. Given that episodic fish kills have occurred in the past, testing for heavy metals is strongly suggested to ensure water quality standards for aquatic life are met.

Depth and velocity measurements were conducted too early in the season to properly assess suitability for spawning. Low depth and velocity measurements in some of the upstream sites and tributaries may reflect the lower basal flows caused by hydrologic changes in urban watersheds.

5.4.2 Grain Size Analysis

The range of D_{50} values (19-52 mm) were within the reported D_{50}'s synthesized by Kondolf and Wolman (0.1-69 mm; 1993) for the five species present in the Upper Serpentine River. However, the D_{50} statistic does not provide sufficient information on the spread of particle sizes, including the upper and lower range (ie. framework particles and fine sediment) which are key determinants of spawning gravel quality (Kondolf 2000a). Surface grain size distribution curves showed that surface particles were generally smaller than the upper recommended limit of 102 mm for spawning gravel at most sites. The exception was in site 5, where around 20% of the particles were larger than 102 mm, suggesting that this site may be one of the most energetic sites, contrary to indications from the hydraulic analysis. This is further supported by the tracer rock analysis, where site 5 saw the largest proportion of mobilized particles in all size classes. Possible explanations for the discrepancy between hydraulic analysis and observations are provided in the discussion of the hydraulic analysis and tracer rock analysis.

Visual observations determined that the substrate was well-mixed and lacked continuous patches of spawning gravel. Increased mixing could be a result of the quick decrease in flow in urban streams after storms subside, causing substrate to settle out without much sorting. Some indication of riffles and pools exist, but they did not follow the spacing found in natural gravel-bed rivers (~6 bankfull widths; Leopold et al. 1964, Newbury et al. 1997). These observations suggest that the sites could benefit from restoration to re-establish riffle-pool sequencing, which promotes natural sorting of spawning gravels at the tail-end of pools (Alan Jonsson, Fisheries and Oceans Canada, pers. comm., 2018).

Subsurface grain size analysis indicated that a substantial fraction of the substrate consisted of fine sediment. Prevalence of fines would have been even greater had some fines not been lost during shovelling. A high fraction of fine sediment can be expected in urban systems where bank erosion and fine sediment input from the roads commonly cause siltation problems in gravel beds. Field and laboratory studies indicated that salmonids generally spawn in substrate with 10-12% fine sediment (<1mm; McNeil and Ahnell 1964, Cederholm and Salo 1979), which was similar to the threshold of 12-14% for incubation effects (Kondolf 2000a). The current study used <4 mm as the threshold for fine sediment, which ranged from 0 to 57% in samples. This differed from the value normally used for fine sediment analysis, which is <1 mm. Due to this, results from this project cannot be directly compared to the above values obtained from literature. However, there were studies that measured the effects of larger fine sediments (3-10 mm) on the emergence of fry, but they showed considerable variability (Kondolf 2000a). In these studies, the proportion of fine sediment that resulted in 50% emergence of salmonids was around 29.5% (Koski 1966, Koski 1975, Phillips et al. 1975, Koski 1981). Therefore, it could be concluded conservatively that sediment with >30% fine sediment using the <4 mm criteria may adversely affect incubation. Fortunately, redd construction kicks up fine sediment which is then transported downstream. Pairwise comparisons of redds and potential spawning gravels showed that percentage of fines (<4 mm) in redds were about 58% that of pre-construction (Chambers et al. 1954, Kondolf et al. 1993). Even with consideration of the cleaning effect of redd construction, efforts should still be made to reduce fine sediment input from bank erosion and roads. Bank erosion leads to further channel incision and sediments from roads can carry harmful contaminants. Therefore, bank stabilization techniques and sediment control in the watershed can serve multiple functions.

5.4.3 Hydraulic Analysis

Shear stress calculations showed that most sites were not conducive to gravel retention and possessed enough energy to erode any spawning gravel that is added in bulk. Therefore, gravel augmentation may be more successful if instream structures are installed to reduce tractive forces and promote deposition. Shear stress was calculated based on bankfull flows, which has an average return period of 1.5 years (Dunne and Leopold 1978). While instream structures must be sized to withstand larger flood events, floods that overtop bankfull may not add significant shear stress if water can access the floodplain. However, in channels that are along steep ravines, it is recommended to size structures to withstand at least a 10-year flood, depending on feasibility and cost.

Although the calculated erodible grain sizes at the study sites were higher than the D_{50} of imported spawning gravel, many sites exhibited D_{50} well below the erodible grain size. In fact, many of the sites exhibit surface D_{50}'s similar to that of imported spawning gravel. This observation could be attributed to scour-and-fill processes and compaction. High shear stress initially scours the streambed of smaller particles and leaves behind larger particles. As the storm subsides, fine sediment from bank erosion and upstream gravels carried in the water column settles out, reducing D_{50}. Furthermore, fine sediment intrusion compacts gravels and creates a hardened surface that is protected from the flow of the river. Compaction inflates the Shields parameter, which increases the shear stress required to move a particle. It is also possible that the bankfull depths, which were used to calculate shear stress, were overestimated in some sites that exhibited channel incision. This would have resulted in the overestimation of erodible grain size, particularly in site 7 as it is located in a small tributary. Overestimation of transport potential in some sites may explain why seemingly energetic sites (eg. site 5) do not exhibit the highest shear stress.

5.4.4 Tracer Rock Verification

Although particle movement was generally predictable from tractive force calculations, some inconsistencies were clearly present. Many pebble-sized particles remained immobile in site 1 due to embedment of particles in fine sediment which increased protection from the energy of the moving water. Interestingly, the larger size class in site 1 exhibited similar proportions of movement potentially due to increased exposure to the flowing water. It is important to note that tractive force equations do not consider shielding and imbrication, two factors that reduce sediment movement downstream. Therefore, observations in site 1 were likely due to differences in embedment when deploying tracer particles. Tractive force calculations also do not account for other forces that can increase movement of sediment along the streambed, including impact force (ie. momentum transfer) and lift forces (ie. vertical velocity-gradient pressure force and upward turbulence force; Hickin 1995). There were several other sources of experimental error introduced in the hydraulic analysis and tracer rock study. Tractive force calculations were done based on stream geometry of three transects. This assumed that the average shear stress experienced along these transects represented the conditions of other parts of the site. Furthermore, while particles deployed were classified into general size classes, the particles still varied in weight, shape and size. Therefore, some particles in a size class could have mobilized at a lower flow compared to other particles due to its shape, weight, size, or orientation. Lastly, due to limitations of data collection during high flow, the stage-stage relation curve created did not capture the relationship between instream and gauge water levels at high flows (Appendix C). Therefore, there was some uncertainty with respect to using the curve to calculate the number of mobilizing events.

Despite inconsistencies arising from experimental error, the tracer rock study allowed for several conclusions to be made. With the exception of site 1, at least 70% of pebble-sized particles were mobilized in the study sites, confirming that placed gravels in bulk will not be stable. This provides further rationale for the installation of instream structures. Additionally, particles larger than expected were observed to move, which indicated that the tractive force equations underestimated shear stress at those sites. It is strongly recommended that any restoration works be sized with safety factors in place to withstand a greater than predicted shear stress.

5.4.5 Siltation

The rate of fine sediment accumulation measured in a short period of 12 days suggested that sources of fine sediment are abundant in the Upper Serpentine watershed and can degrade added gravel. Despite the cleaning effect of redd building, fine sediment can accumulate quickly after spawning. It is important to perform bank stabilization and install sediment catchment structures in order to protect newly added gravel from siltation during storms.

5.4.6 Barriers to Passage and Existing Spawning Gravel

Work on the culvert on 104 Avenue is strongly recommended if restoration works on sites 1 and 2 are to move forward. Currently, the culvert may be a barrier to passage and restoration of upstream sites will be pointless without alterations to the culvert.

There are pockets of suitable spawning gravel existing in the Upper Serpentine watershed, potentially as a result of previous restoration efforts. Areas around the Serpentine Enhancement Society, which is downstream of most project sites, contained some good quality spawning gravel. According to the Tynehead Hatchery director, a restoration project led by Alan Jonsson of Fisheries and Oceans Canada installed two rock weirs in August of 2017 to increase gravel retention above a fish fence that frequently became clogged by substrate (Lesley England, pers. comm., 2018). Spawners were observed using the newly created spawning habitat the following fall.

Many areas of the Upper Serpentine watershed still lacked well-sorted gravel beds, including the current project sites. Success of the rock weir installations at the Serpentine Enhancement Society provides good indication that a similar approach may be successful in restoring spawning habitat at some of the candidate sites.

5.5 Conclusion

Urban development of the Upper Serpentine watershed has resulted in changes in hydrologic and geomorphic processes within its waterways. Currently, the Upper Serpentine experiences high peak flows during precipitation events that causes scouring of spawning gravel. Furthermore, bank erosion from high flows delivers fine sediment downstream causing siltation of spawning gravel when the storm subsides. The gravel deployment program initiated by the City of Surrey has resulted in some improvements to the candidate sites. In many sites, the D_{50} of the surface gravel has increased towards a more suitable 20-50 mm from previous conditions (Dillon 2012). However, it appears that most of the deployed gravel had been mobilized downstream, which was consistent with the results from the hydraulic analysis and tracer rock study. The seemingly appropriate D_{50} sizes masked scour and fill processes and fine sediment delivery. Subsurface grains contained a high proportion of fine sediment, which contributes to compaction and raises concerns for egg survival.

Placed gravels that mobilized downstream could have deposited in areas that now provide spawning habitat for salmonids. Although some pockets of gravel were located, many areas, including candidate sites, were still lacking in sufficient spawning gravel (Urban Systems 2015; Lesley England, pers. comm., 2017). This suggests that erosion is still an ongoing issue in the Upper Serpentine River. Therefore, instream restoration using gravel supplementation must address the high shear stress experienced at the project sites. Restoration should also attempt to re-establish riffle-pool sequences that promote natural sorting of gravels. The subsequent chapter describes restoration treatments that aim to reduce tractive forces and promote long-term gravel retention. Furthermore, methods to reduce bank erosion and other watershed-level recommendations to restore hydrological processes are discussed.

6 Proposed Restoration Treatments

6.1 Desired Future Conditions

Determining realistic yet meaningful restoration goals require consideration of what the desired future conditions are in a changing landscape and a changing climate. Currently, the Upper Serpentine watershed has an average impervious surface cover of 29.8%, ranging from a low of 6.2% in Tynehead Regional Park to a high of 44.2% in the developed urban uplands (Urban Systems 2015). Based on existing community plans, the future ISC of the Upper Serpentine watershed will increase to 49.5%, with the developed urban uplands increasing to 64.0% ISC (Urban Systems 2015). Increased ISC will be exacerbated by increases in precipitation predicted for the Pacific Northwest (Mote and Salathe 2010).

These estimates pose clear challenges to stream restoration as it will not be possible to completely restore the hydrology of the river to its pre-urbanized state. Restoration goals, therefore, should aim to restore the Upper Serpentine River to a novel ecosystem that is resilient to these future changes and while producing self-sustaining wild salmonid populations. In order to achieve this, stormwater management must maximize green infrastructure in the watershed to mitigate the effects of increased development. Even under the best-case scenario, it would take years before these changes take place and become effective. Meanwhile, there is an urgent need for restoring streams to withstand an increasingly energetic hydrologic regime. Although it is not possible to restore the Upper Serpentine River to its pre-disturbed state, ecological restoration in urban landscapes plays an important role in improving human attitudes towards the natural landscape and achieving a positive urban-wildlife interface.

6.1.1 Restored Conditions and Processes

The main focus of this restoration plan is to create instream hydraulic conditions conducive to long-term retention of added gravels. Restoration treatments are centred around gravel addition accompanied by the use of instream boulder structures that function to dissipate water energy, increase gravel deposition, and increase bed roughness by creating more defined riffle-pool sequences. Currently, the substrate is well-mixed with some riffle-pool formation. This is consistent in urban systems where the descending limb of the hydrograph is steep, causing substrate to settle out quickly without much sorting. Having a more defined riffle-pool topography will generate heterogeneity and disruptions in the stream profile which has several benefits: 1) increased sorting of gravels, 2) creation of slow moving back eddies, 3) increased water exchange in gravels, 4) reduction of local gradient which promotes gravel deposition, and 5) dissipation of water energy. Bank stabilization is also prescribed to reduce fine sediment delivery downstream and to prevent further channel incision. Structures are designed with consideration of the urban landscape, where attention must be paid to avoid lateral erosion of property, flooding, and destruction of infrastructure. The following table summarizes the short-term conditions and processes this restoration plan aims to restore and long-term conditions and processes that could be achieved by improved stormwater management practices.

Table 8. Desired restored conditions and processes in the Upper Serpentine River and possible outcomes of the current restoration plan.

	Restored Conditions	Restored Processes
Short-term	• Increased spawning gravel • Increased inter-gravel flow • Increased habitat complexity • Increased bed roughness	• Increased water energy dissipation • Increased gravel retention • Reduced scour/erosion • Increased sorting of substrate • Reduction of fine sediment delivery
Long-term	• Increased spawning gravel • Improved water quality	• Reduced and slowed movement of stormwater into the Upper Serpentine mainstem and tributaries • Sediment and contaminant removal from stormwater prior to integration into waterways

6.2 Goals and Objectives

Overarching purpose: increase spawning habitat in the Upper Serpentine River

Goal 1: Restore instream hydrologic conditions such that they are conducive to long-term gravel retention

Objective 1.1: Install instream structures using Newbury weirs

Objective 1.2: Import spawning gravel according to recommended grain size distribution

Objective 1.3: Reduce impervious surface cover and increase stormwater management infrastructure in the watershed including rain gardens and bioswales

Goal 2: Reduce rate of fine sediment accumulation in spawning gravel

Objective 2.1: Stabilize stream banks where bank erosion is evident using dense willow staking with rock toe keys

Objective 2.2: Install sediment capture structures including rain gardens and bioswales

Goal 3: Restore fish access to Guildford Brook upstream of 104 Avenue culvert

Objective 3.1: Conduct culvert works to increase water depth and reduce gradient within culvert

Objective 3.2: Install structure downstream of the culvert to cause backwatering, reducing jump height and increasing pool depth

Goal 4: Increase education and outreach opportunities

Objective 4.1: Install interpretive signage around restoration sites or at access point entrances

Objective 4.2: Partner with SHaRP with restoration activities where heavy machinery is not being used

Objective 4.3: Consult with stakeholders, including nearby residents, park users, and park managers to increase awareness and receive feedback on restoration activities

6.3 Site Prioritization

The seven study sites each have unique characteristics and restoration challenges. Therefore, restoration treatments should be tailored to the specific needs and limitations of each site and prioritized in a sensible order. The table below summarizes the limitations to each study site and the recommended treatments.

Table 9. Site prioritization based on site limitations and recommended treatments.

Site	Limitation	Recommended Treatments	Priority
1	• Upstream of impassable culvert • Very low flows during periods of no precipitation • Heavily channelized: instream complexing may cause further lateral bank erosion • Difficult access	Phase 1: • Culvert works at 104 Avenue and 158B Street • Bank stabilization Phase 2: • Install Newbury weir (manually) • Excavation of channel bed may be necessary to increase minimum depth	Low
2	• Upstream of impassable culvert • Difficult access	Phase 1: • Culvert works at 104 Avenue and 158B Street Phase 2: • Install Newbury weir (manually)	Low
3	• Difficult access • Bank erosion	Phase 1: • Install Newbury weir (manually) • Bank stabilization	Medium
4	• Difficult access • Bank erosion	Phase 1: • Install Newbury weir (manually) • Bank stabilization	Medium
5	• Large-scale restoration and use of artificial structures may not align with the objectives of Tynehead Regional Park	Phase 1: • Consult with park managers to discuss restoration approaches • Install Newbury weir (using heavy equipment)	High
6	• Site unstable and undergoes frequent geomorphic changes due to LWD accumulation • Steep gradient (3%) makes gravel restoration difficult • Difficult access	• Restoration not recommended for this location	n/a
7	• Difficult access • Heavily channelized: instream complexing may cause further lateral bank erosion • Some instability	Phase 1: • Bank stabilization • Instream structures not recommended	Low

With the exception of site 5, all sites have difficult access for heavy equipment and will require manual construction of weirs. Spawning gravel restoration of sites 1 and 2 along Guildford Brook is not recommended until the culvert at 104 Avenue is assessed and reworked. Furthermore, site 1 does not exhibit hydrologic characteristics suitable for spawning, and may be more suitable as a rearing site. Further consultation should occur prior to restoration of site 1. Bank stabilization will occur in almost all sites, but particular emphasis should be placed on sites 1 and 7, which are heavily channelized. Lastly, site 6 is not a good candidate site for spawning gravel restoration due to its instability and steep gradient.

For sites that are not recommended for gravel works in the first year, bulk gravel addition could still be beneficial for education and monitoring purposes. Even if gravels are mobilized, it may prevent further downcutting of the stream channel. Bulk gravel addition should be done according to previous years' restoration works, and will not be discussed here. Based on the above prioritization, restoration should be carried out in three phases, with the first phase focusing on high and medium priority sites.

Table 10. Description of the three restoration phases to be carried out in the Upper Serpentine River. Phases 1 and 2 involve instream restoration treatments, while phase 3 focuses on watershed-level stormwater management

Phase	Action	Objective(s) Met	Year Performed
0	Consultation process	4.3	Ongoing
1	Bank stabilization of all sites, but focus on sites 1 and 7	2.1, 4.2	2018
	Gravel addition and instream structure installation at sites 3, 4, and 5	1.1, 1.2, 4.2	2018
	Install interpretive signage	4.1	2018
	Culvert assessment/rework	3.1, 3.2, 3.3	2018
	Bulk gravel addition for sites 1, 2, and 7 (not discussed in current report)	1.2, 4.2	2018
2	Gravel addition and instream structure installation at sites 1 and 2 (contingent on access to these sites being restored)	1.1, 1.2, 4.2	2019
3	Implement Upper Serpentine Integrated Stormwater Management Plan, including the installation of green infrastructure within the watershed.	1.3, 2.2	Ongoing

6.4 Instream Restoration Treatments

6.4.1 Newbury Weirs

Riffle construction using Newbury weirs are an increasingly implemented and successful rehabilitation technique in disturbed channels (Walker 2002). Newbury weirs involve large diameter rocks spanning across the entire stream, causing gravel accumulation upstream and pool formation downstream. Substrate scoured at the pool will be deposited at the tail end of the pool, creating spawning habitat in accelerating and downwelling waters. The Newbury weir has a steep crest and a gentler downstream slope of about 5:1-20:1, which directs water into the downstream the pool at a shallow angle (Figure 15; Newbury et al. 1997). The steep upstream slope lowers the gradient of the upstream area which in turn reduces local shear stress and promotes deposition of sediment. The structure is V-shaped to direct flow toward the centre of the stream, which reduces scour of banks and maintains a deep central pool downstream (Newbury et al. 1997). These riffle structures create slow back-eddies that cause additional gravel accumulation on the sides of the channels above and below the structure. The back-eddies generate areas of downwelling near the centre of the channel and upwelling at the sides of the channel. Back-eddies also provide important refuge areas for rearing juvenile salmonids (Newbury et al. 1997).

When placed at appropriate intervals, Newbury weirs create riffle-pool sequences that increase bed roughness and break up flow energy. Furthermore, the irregularities in the bed profile promotes more varied intergravel flows. Salmonids have been observed to preferentially spawn in areas with high water exchange. While chinook generally prefer downwelling water, chum often spawn in areas of upwelling (Vronskiy 1972, Tautz and Groot 1975). The geomorphic and hydraulic effects of Newbury weirs make them a good restoration treatment for disturbed channels in the Upper Serpentine. Newbury weirs were installed in a reach of the Upper Serpentine near Tynehead Hatchery north of 96 Avenue in August of 2017. In the following fall, salmon were observed spawning in the newly recruited gravels (Lesley England, pers. comm. 2018).

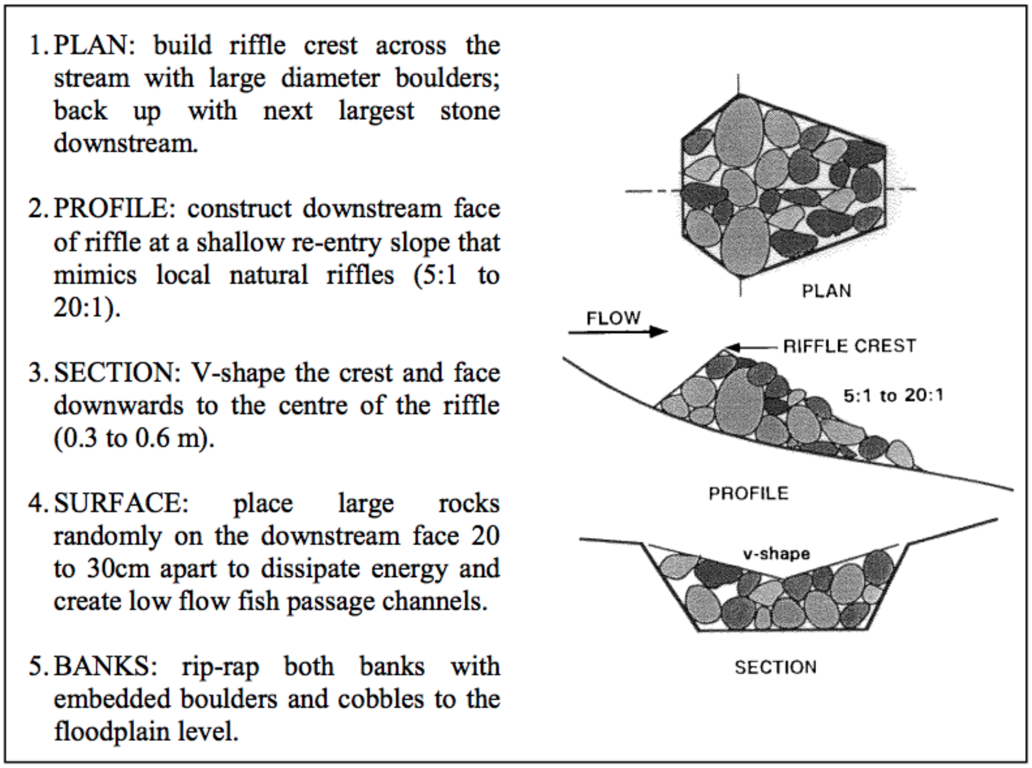


Figure 15. Design characteristics of a Newbury weir (video, Newbury Hydraulics 1996).

Spacing should follow that of natural streams, which is approximate six bankfull widths apart. In higher gradient headwater streams (ie. >5%), spacing may be shortened (Newbury et al. 1997). In disturbed streams, small drops and riffles may be apparent in the stream profile, and is a result of the stream attempting to re-establish a natural profile. In these cases, these features may provide guidance on where natural riffles are trying to establish, and are good candidate locations for constructed riffle structures (Newbury et al. 1997).

The energy losses of natural and constricted riffles ranged between 50 and 100% of the total streambed energy losses (Walker 2002). While energy reduction decreases scouring, the additional flow resistance caused by the riffle affects upstream water level and should be an important design consideration (Walker 2002). Riffle height calculations can be done to maintain upstream water level within bankfull level. In some cases, increasing water level may be a deliberate restoration technique where overtopping and reconnection to the floodplain is desired. In any event, riffle design should be conducted by a stream hydraulics engineer especially in areas with high flood risk (eg. urban areas). Sediment transport capacity will be reduced upstream of the constructed riffle as a result of the lower gradient, which is beneficial for incised and eroding urban streams (Walker 2002).

Newbury weirs can be constructed manually or with an excavator (Paul Cipywnyk, Byrne Creek Streamkeepers, pers. comm., 2018; Lesley England, pers. comm., 2018). Construction method will depend largely on site access for heavy machinery. Boulders should consist of angular rocks ranging from 250 to 450 mm. The minimum and maximum of this range are based on the highest erodible grain size calculated in all seven sites (164 mm) with a safety factor of 1.5 and 2.75, respectively. The larger sized boulders will function as anchors of the weirs, while smaller boulders will be used to fill the interstitial spaces in an interlocking configuration.

Predicted riffle stability was estimated for each site using tractive force calculations and a flood frequency curve constructed from peak discharges over the last 22 years (Appendix D). Calculations estimated that the median boulder size of the constructed riffles will remain stable in most sites up to a discharge with at least a 100-year return period. In site 5, the median boulder size is estimated to move with a 7.5-year flood. However, this does not take into account the drastic reduction of tractive force increases when water levels exceed bankfull and flood the riparian zone. Furthermore, using angular rocks interlocks smaller particles within a framework of larger anchor rocks which shields the smaller particles from the energy of the moving water.

Riffle stability predictions are rough estimates based on limited flow information and primitive stage-discharge relations. Furthermore, tractive force calculations are derived from simple flume experiments and do not account for the variety of external factors and stochastic forces that influence sediment transport in a natural stream. Therefore, it is important to monitor riffle integrity periodically to document changes and perform maintenance when needed.

6.4.2 Gravel Addition

Although gravels from upstream areas may naturally recruit behind the constructed weirs, it may be beneficial to add supplemental gravel behind the weirs due to the limited sediment sources in the upper reaches. Chinook excavate redds of around 18-43 cm in depth (Hawke 1978), while smaller fish will dig shallower redds (Hobbs 1937, Hardy 1963). Added gravel should extend 1/3 of the distance between constructed riffles and be at least 25 cm in depth unless limited by the final height of the constructed riffle. Bell (1986) recommended that grain size should range from 1.3 to 10.2 cm for anadromous salmon and trout. Specifically, 80% of the materials should be 1.3 to 3.8 cm, and the balance up to 10.2 cm.

6.4.3 Streambank Stabilization

Live staking is a simple soil bioengineering method that uses live cuttings to stabilize banks and reduce flow near the stream bank. Willow (*Salix* spp.) is a successful pioneer species native to Western Canada that can be easily grown from dormant stem cuttings (Polster 2017). Live willow stems can be harvested in large quantities without significant damage to the stand due to their ability to quickly grow new stems (Polster 2017). Cuttings are inserted into soft bank materials during the spring, and over the summer, root growth binds the unstable materials and above-ground growth slows flow and promotes sedimentation (Polster 2017). Cuttings should be inserted so that 3/4 to 7/8 of the length is underground (the drier the site, the larger fraction should be underground). Cuttings can be inserted vertically or diagonally as long as most of the length will remain moist. If possible, cuttings should be harvested during fall and winter when stored energy in the form of carbohydrates are at their highest in plants (Polster 2017). This stored energy enables plants to grow new roots and shoots before leaves have had a chance to develop and perform photosynthesis (Polster 2017). Just prior to planting, cuttings should be soaked for 48 hours and planted immediately after removal (Hunolt et al. 2013). Live staking can be implemented as a stand-alone treatment, but it does not protect against toe erosion. Most applications of bank bioengineering are paired with toe protection, which is commonly in the form of rocks (Figure 16). This method has been thoroughly tested in a wide range of conditions. The live stakes will provide aesthetics, shading, and reduces bank line velocity (Baird et al. 2015).

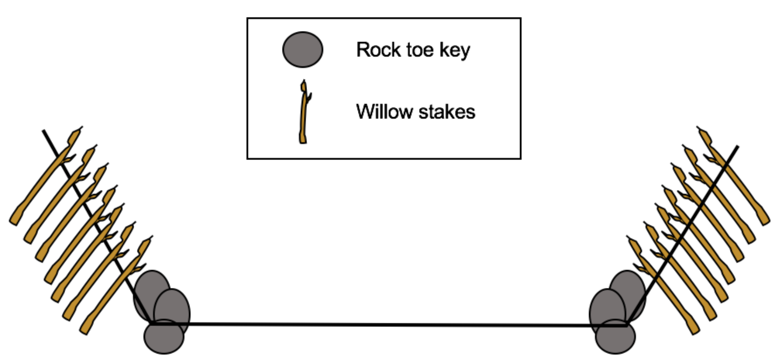
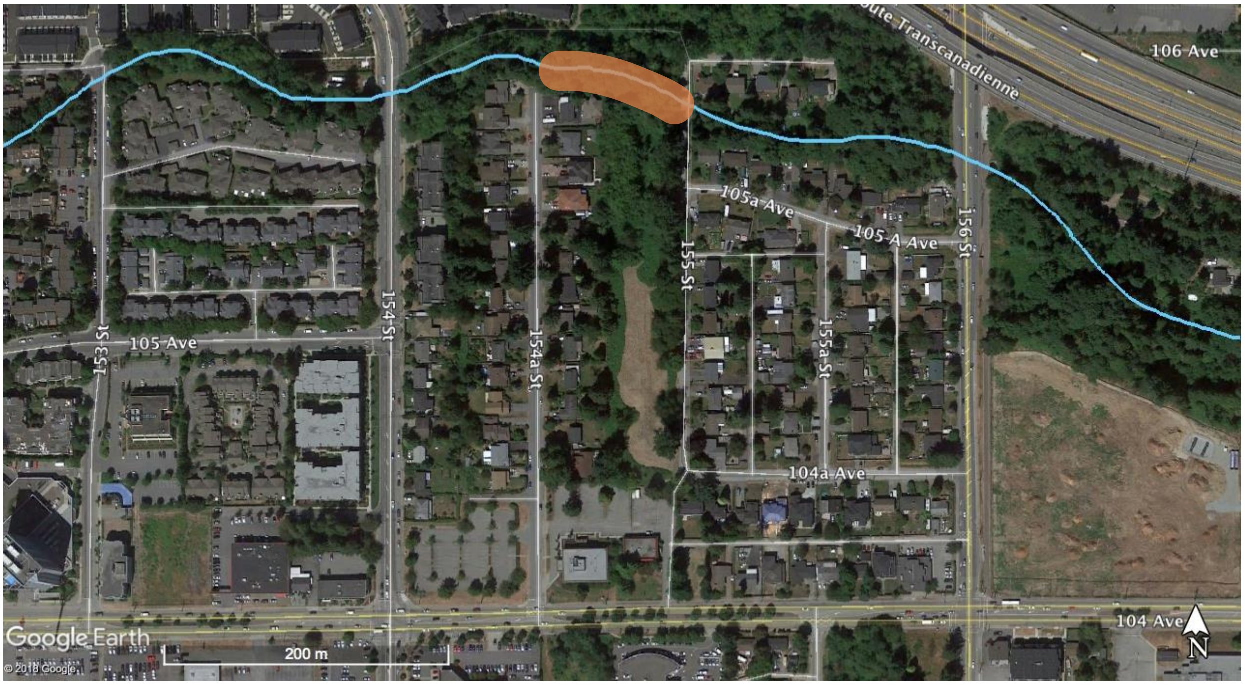


Figure 16. Cross-sectional view of bank stabilization treatment using willow stakes and a rock toe key.

6.5 Site-Specific Plans

The following figures depict conceptual site-specific plans. These plans will need to be reviewed, reworked, and finalized by a professional engineer. It is likely that further instream measurements will be required at the specific sites of the prescribed structures.

6.5.1 Site 1



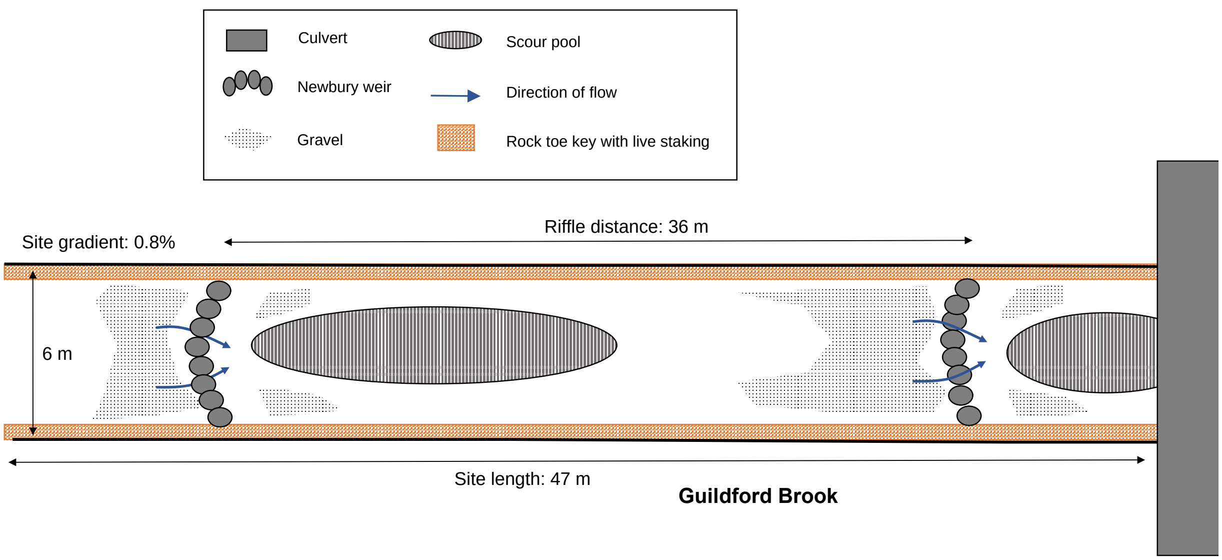
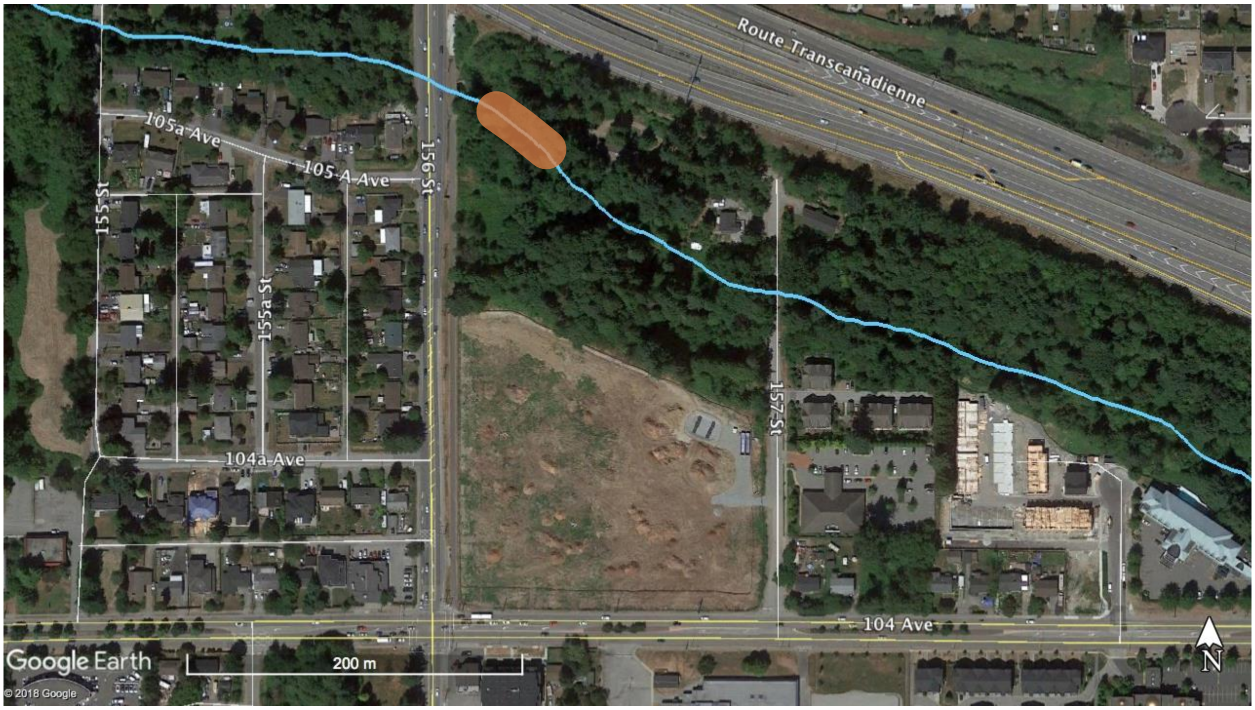


Figure 17. Top: location of site 1 (orange) within the context of surrounding roadways. Bottom: schematic of prescribed restoration treatments in site 1. The rock toe key and live staking will be carried out in phase 1, and the Newbury weirs will be installed in phase 2.

6.5.2 Site 2



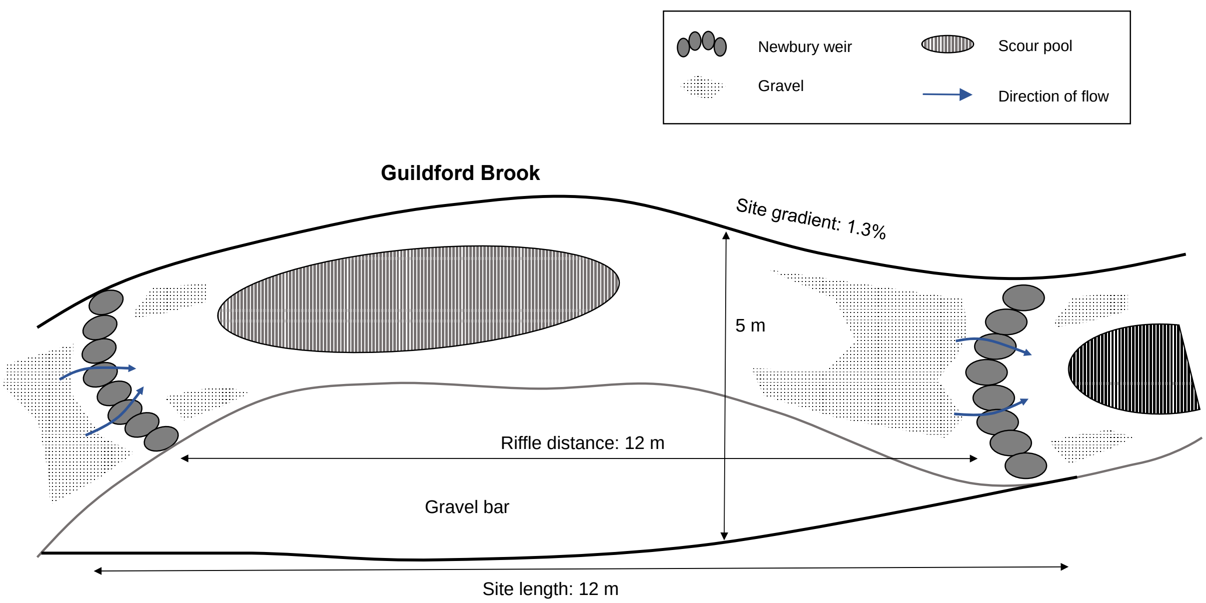


Figure 18. Top: location of site 2 (orange) within the context of surrounding roadways. Bottom: schematic of prescribed restoration treatments in site 2.

6.5.3 Site 3

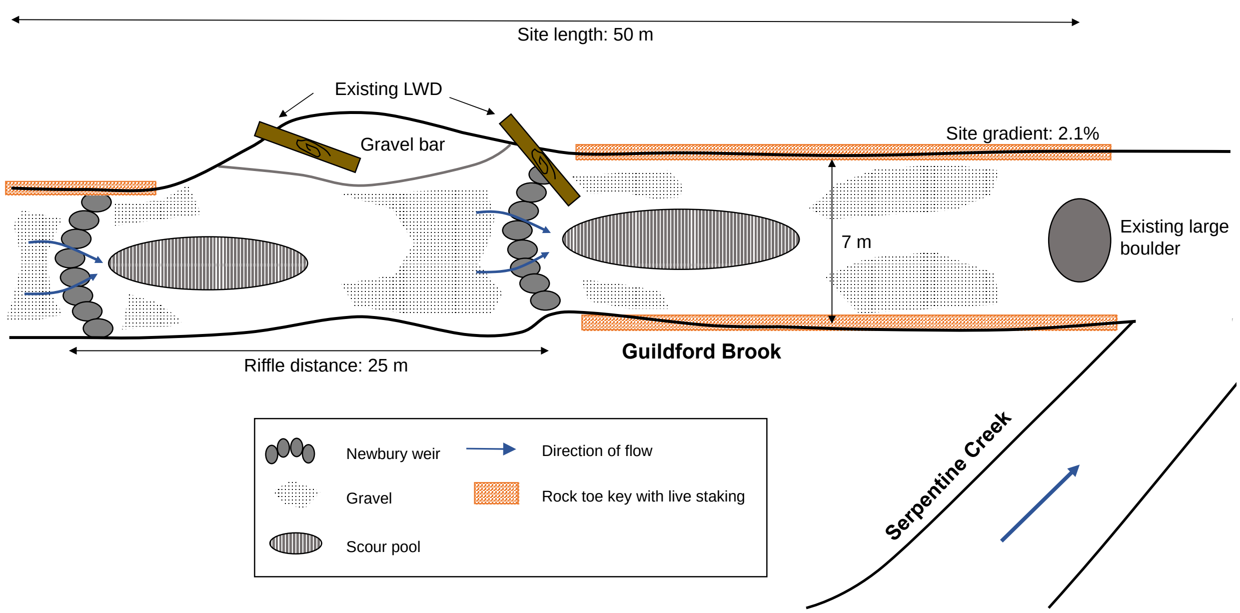
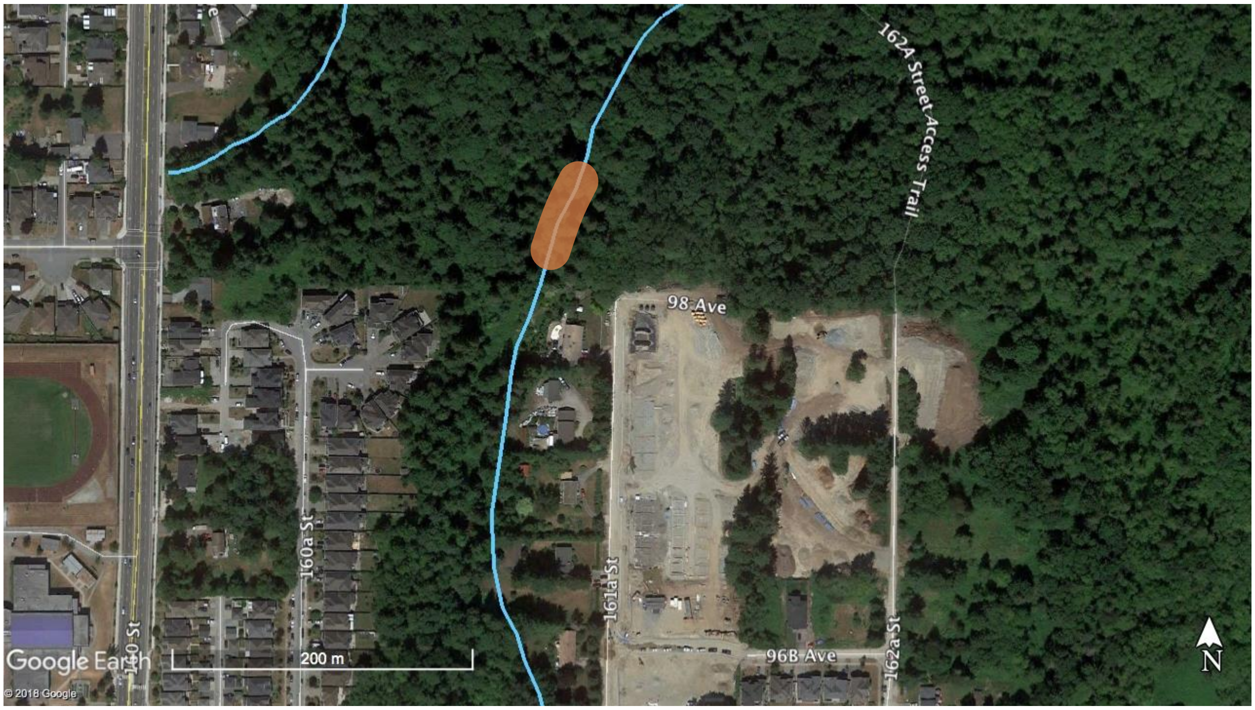


Figure 19. Top: location of site 3 (orange) within the context of surrounding roadways. Bottom: schematic of prescribed restoration treatments in site 3.

6.5.4 Site 4



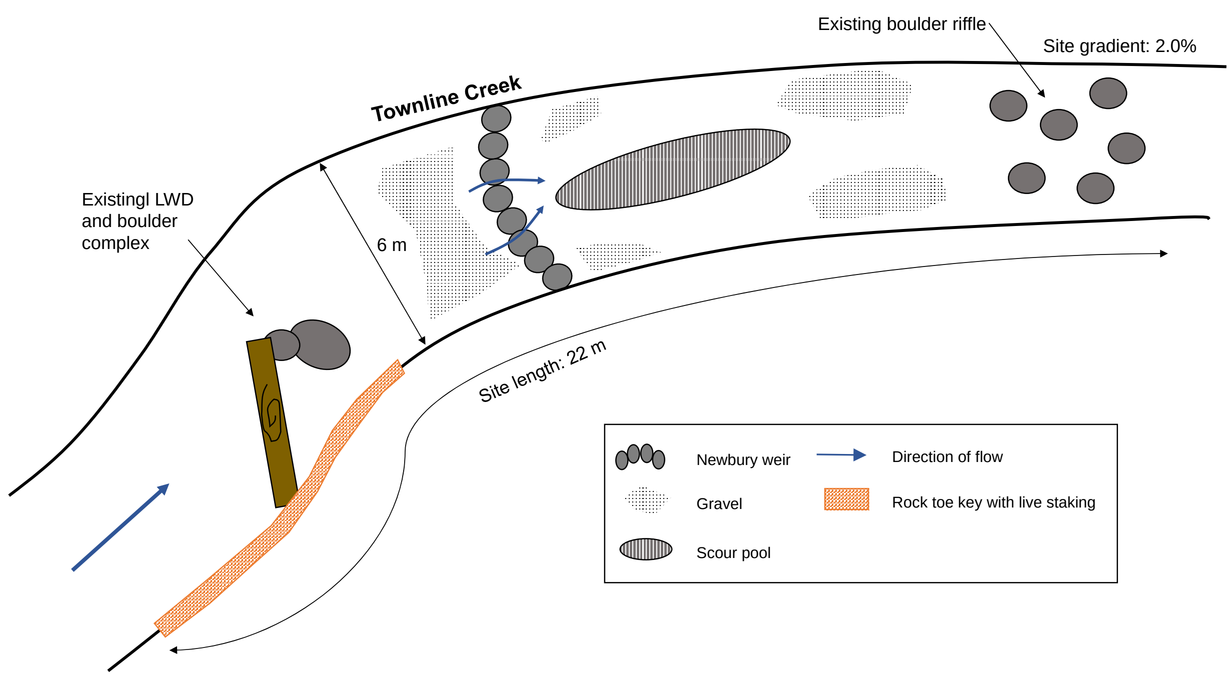


Figure 20. Top: location of site 4 (orange) within the context of surrounding roadways. Bottom: schematic of prescribed restoration treatments in site 4.

6.5.5 Site 5

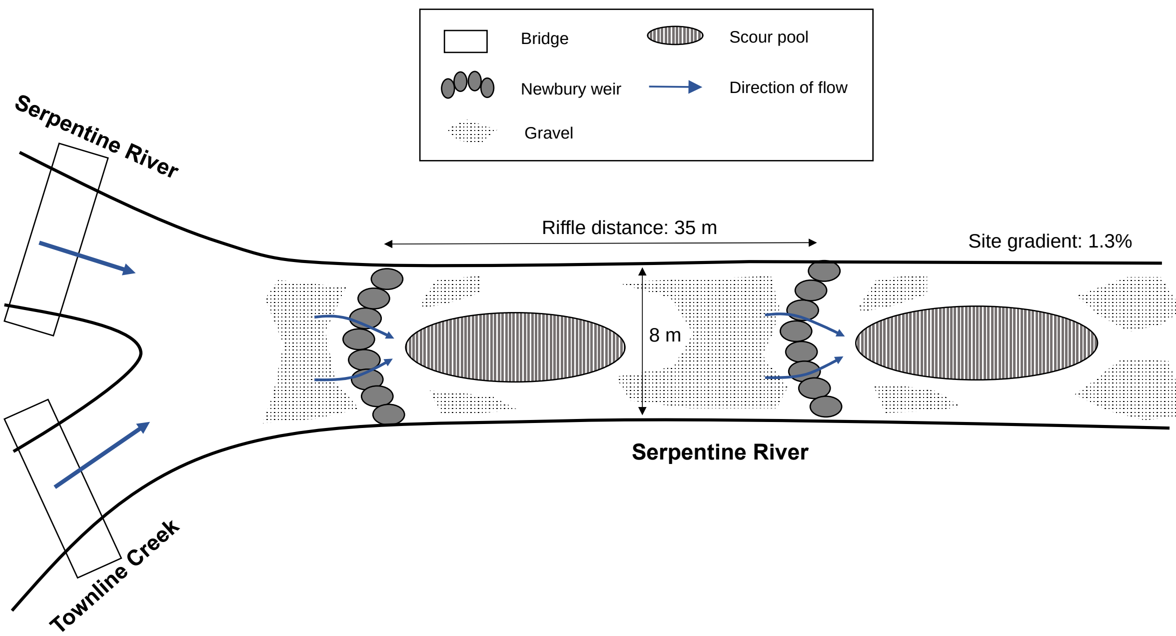


Figure 21. Top: location of site 5 (orange) within the context of surrounding roadways. Bottom: schematic of prescribed restoration treatments in site 5.

6.5.6 Site 7

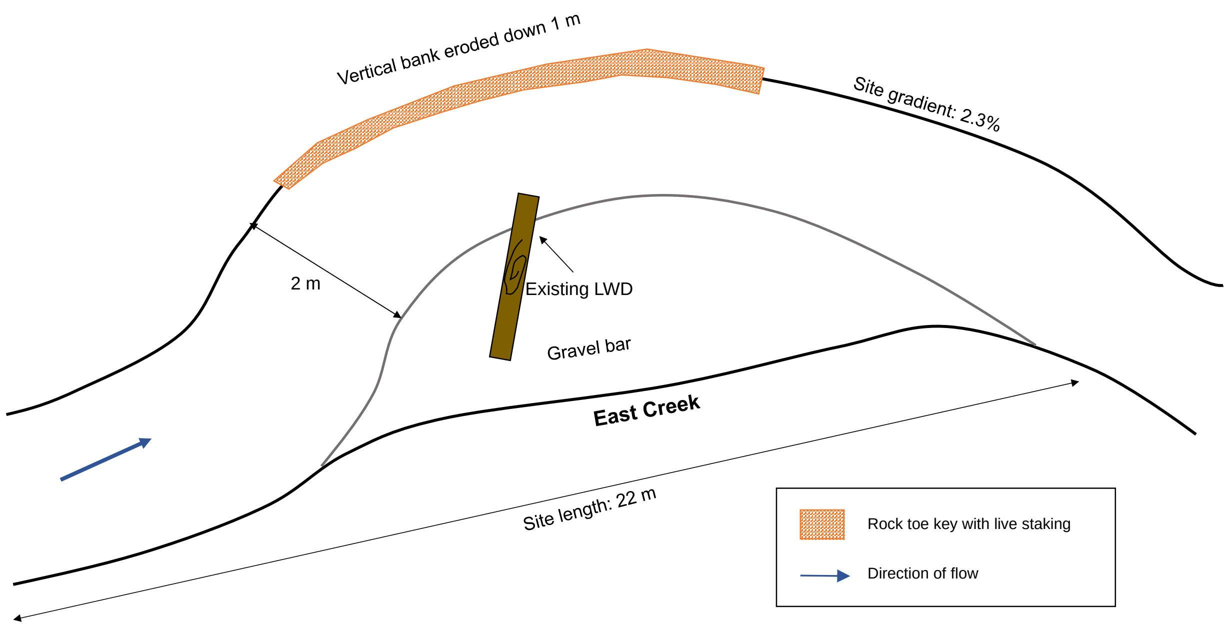


Figure 22. Top: location of site 7 (orange) within the context of surrounding roadways. Bottom: schematic of prescribed restoration treatments in site 7.

6.6 Biostandards for Estimating Restoration Benefits

Data synthesized from restoration studies estimates changes in salmonid production as a result of fish habitat restoration. An analysis of spawning gravel restoration using log weirs and deflectors estimated an average of 8.5-fold increase of returning adults following restoration (Keeley et al. 1996). This estimate should be viewed with caution because the restoration projects differed in effort and monitoring timeframe. Nonetheless, most restoration efforts significantly increased fish densities, indicating that restoration can have substantial positive effects on salmonid populations (Koning and Keeley 1997).

Using a similar method, changes in salmonid productivity were estimated for the current project. The proposed restoration treatments will increase spawning area in the Upper Serpentine by around 261 m^2, which can support 51 additional spawning pairs of chinook, 113 pairs of chum, or 93 pairs of coho. This translates to 147 returning adult chinook, 176 chum, or 424 coho annually. These estimates were calculated using published data on fecundity and survival, and are summarized in Table 11. It is important to note that when spawning habitat is limited, the number of spawning pairs is determined by territory size, which is roughly four times the redd size (Whyte et al. 1997). When this is the case, biological benefits will be reduced by a quarter.

Table 11. Estimated fish production calculated from a 261 m^2 increase in spawning habitat proposed by the current restoration plan.

Species	Redd size[a] (m^2)	Spawning pairs	Fecundity[b]	Fry	Freshwater survival[c]	Migrating fish	Marine survival[c]	Returning adults
chinook	5.1	51	6,107	311,457	0.086	26,785	0.0055[d]	147
chum	2.3	113	3,228	364,764	0.069	25,169	0.007	176
coho	2.8	93	3,103	288,579	0.015	4,329	0.098	424

[a]Whyte et al. 1997
[b]Beacham and Murray 1993
[c]Bradford 1995
[d]Lucchetti and White 1995

While biostandards are a useful tool that enables managers to quantify restoration benefits, the value of the current project extends beyond fish productivity estimates. Pilot projects aim to evaluate and fine-tune restoration methods at a small scale prior to large-scale implementation. Lessons learned and monitoring data from the proposed restoration efforts can be used to further the field of stream restoration ecology and set the stage for spawning habitat restoration in other candidate sites in the Serpentine River and beyond.

6.7 Watershed-scale Recommendations

6.7.1 Stormwater Management

In the long term, reduction of impervious surface cover and stormwater management upgrades will be required to restore the system's hydrology, which will then lead to improved sediment transport dynamics. However, development will continue in the Upper Serpentine catchment, increasing the ISC of developed areas to 64.0%. This will result in increased hydrologic stress to the Upper Serpentine waterways. Therefore, green infrastructure will become increasingly important to mitigate the effects of this increased ISC.

Rain gardens and bioswales are examples of green infrastructure that can effectively increase infiltration, intercept sediment, remove contaminants, and reduce impervious surface area when properly implemented (McIntyre et al. 2015). Green infrastructure and other stormwater management strategies are described in the Integrated Stormwater Management Plan for the Upper Serpentine watershed (Urban Systems 2015). Prioritization based on sub-basin and optimization of green infrastructure will increase efficiency in reducing stormwater effects on urban waterways, particularly when funding is limited.

6.7.2 Mitigation of Downstream Stressors

The agricultural lowland portion of the Serpentine River consists mainly of migration corridors for Pacific salmon. Due to alterations from dyking and construction of the sea dam, much of the lower reaches are void of riparian vegetation and cannot access their floodplain. Although dykes are important flood control structures, vegetation can be established along these dykes to provide shading during early fall when the adults migrate upstream. The sea dam is a migration barrier especially during years when migration months coincide with periods of little precipitation, causing the gates to be closed for extended periods of time. The salmon are then forced to hold in an area with little riparian shading during low flow, are more vulnerable to seal predation, and are exposed to low oxygen conditions due to fertilizer input from nearby farms. Prolonged exposure to low oxygen has caused episodic fish kills in the past (Backman and Simonson 1985).

To avoid future fish kills, it is recommended that access past the sea dam be considered a priority for restoration in the Serpentine River.

A similar problem at the Nicomekl River sea dam was addressed by Taft (2017). In his report, hydraulic modeling concluded that a strategically placed slot gate allowing continuous fish passage at the sea dam would minimally affect the upstream salinity profile. Hydraulic modeling and restoration recommendations from this report should be considered for the Serpentine River sea dam. Otherwise, an alternative method could be to assess the feasibility of constructing a fish ladder to allow fish passage without disruption of sea dam function.

7 Implementation

7.1 Planning

7.1.1 Engagement with stakeholders

Stakeholder engagement is an important process when planning restoration work because it recognizes the different land uses, strengthens relationships, and generates feedback from different perspectives. The Serpentine is a multi-use river. The lower portions of the river are dominated by agricultural use, while the upper portions are mainly residential. A large portion of the upper reaches is located within Tynehead Regional Park, a recreational space managed by Metro Vancouver. The Serpentine Enhancement Society is also located within the park. Engagement activities should target all the aforementioned interest groups to gather support for the proposed restoration plan and to settle any potential conflicts of interests. Engagement should highlight common benefits of the restoration work and include strategies to minimize negative effects, if any, to stakeholders.

Consultation with various stakeholder groups can be done in many ways, including direct correspondence, signage, workshops, and outreach events. The City of Surrey runs a student-led Salmon Habitat Restoration Program (SHaRP) each summer, in which outreach is an integral part of the program. The Serpentine Enhancement Society also hosts public fry release events in the late spring. It could be beneficial for these groups, along with Metro Vancouver, to partner and share information with respect to restoration works done on the Upper Serpentine watershed and to come up with an outreach and consultation plan to support future restoration activities.

7.1.2 Regulations and Permits

There are several Acts and Legislations that apply to restoration works described in this plan, including instream alterations, bank stabilization, water diversion, and fish salvage:

- Water Sustainability Act (Provincial)
- Fisheries Act (Federal)
- Species at Risk Act (Federal)
- Forest Practices Code (Provincial)
- Fish Protection Act (Provincial)
- Riparian Area Regulations (Provincial)

Project managers should be aware of these regulations, limitations they pose on restoration works, and the time required to obtain the necessary permits/approvals. There may also be municipal bylaws that may restrict work around a water course, and approvals should be obtained ahead of time from the Municipal Engineering Department.

7.1.3 Finalizing Weir Designs

A stream hydraulics engineer will need to visit the restoration sites and conduct site-specific measurements to determine exact location of weirs, riffle dimensions, and draw up finalized plans for the riffle construction. These plans should be provided well in advance so that workers and operators can familiarize themselves with the area and site plans.

7.1.4 Construction Budget

The following table summarizes the estimated cost for main construction tasks. A detailed budget can be found in Appendix E. Gravel and riffle boulder volumes were estimated using a riffle crest of 25 cm plus an additional 5 cm that is embedded into the stream. Materials for construction, such as boulders, have been donated toward similar restoration projects in the past which greatly reduces the cost. Therefore, nearby construction sites should be contacted to inquire about possible waste material that could be used for the current project. Not included are wages of personnel, as they will differ from project to project. Alternatively, an estimate of the number of workers and work days is provided (Table 13).

Table 12. Estimated construction costs based on preliminary site plans. Contingency value of 20% is based on a Class C Estimate recommendations according to the Guide to Cost Predictability in Construction (JFG/ICPT 2012).

Site 1		
Phase 1		
Bank Stabilization		$734.75
Phase 2		
Weir Construction		$3,062.00
	Site 1 Total	**$3,796.75**
Site 2		
Phase 2		
Weir Construction		$1,235.45
	Site 2 Total	**$1,235.45**
Site 3		
Phase 1		
Bank Stabilization		$558.15
Weir Construction		$2,620.55
	Site 3 Total	**$3,178.70**
Site 4		
Phase 1		
Bank Stabilization		$91.55
Weir Construction		$713.00
	Site 4 Total	**$804.55**
Site 5		
Phase 1		
Weir Construction		$4,692.25
	Site 5 Total	**$4,692.25**
Site 7		
Phase 1		
Bank Stabilization		$91.55
	Site 7 Total	**$91.55**
Miscellaneous and Resuable Items		
		$4,453.69
	Miscellaneous Total	**$4,453.69**
Totals		
Construction Subtotal		$18,252.94
Class C Contingency (20%)		$3,650.59
PST and GST (12%)		$2,628.42
TOTAL CONSTRUCTION COST		**$24,531.95**

Table 13. Estimated number of personnel and work days to carry out construction activities.

WAGES		
	No. of Personnel	Paid Days
Engineer	1	12
Qualified Environmental Professional	1	30
Project Manager	1	10
Workers	10 to 20	10

7.2 Implementing Restoration Treatments

7.2.1 Bank Stabilization

Bank stabilization should be supervised by a qualified environmental professional and the project manager. Rock toe keys must be imbedded below the thalweg to prevent undercutting. Shovels can be used to excavate the toe bank prior to rock installation. The rock toe key does not need to extend far up toward the banks because it will result in an unnatural rip-ripped appearance. Furthermore, live staking will occur in the main bank zone, which should take root and increase bank stability. Live stakes should be planted densely, around 0.25 m apart. Over 75% of the live cutting should be underground, and remain moist for most of year (Polster 2017). The number of live stakes planted per site should be recorded for monitoring purposes.

7.2.2 Weir Construction and Gravel Addition

Weir construction should be conducted during low flow periods and within fisheries work windows. The construction will be supervised by a qualified environmental professional, project manager, and engineer.

Several site preparation activities must be conducted prior to weir construction. To minimize disturbance to aquatic life, fish salvage must be carried out prior to instream works. Fish salvage can be conducted using seine nets and dip nets to transfer fish into buckets that are taken downstream for release. If a species at risk is expected to be present, the regional Ministry of Environment office should be contacted for more information. To allow excavation for boulder placement, the site will be dewatered by diverting water downstream using hoses and a gas-powered water pump. Sandbags can be placed upstream and downstream of the work site to aid in damming the stream and sediment control.

At this point, boulders will be placed either by excavator (site 5) or manually (all other sites). The streambed should be excavated around 5 cm so that the anchor rocks are imbedded. Anchor sites should also be excavated at the banks. In sites with no excavator access, manual wheelbarrows can be used to transport boulders down to the stream. A hand-winched crane may aid in lifting and placing of rocks. The riffle will then be constructed according to the specifications provided by the project engineer, using a surveyor’s level to determine riffle crest height. Smaller rocks should be placed along banks extending beyond the weir to prevent scouring and erosion.

After construction of the weir is completed, the sandbags and stream diversion can be removed. Finally, a 25-cm layer of gravel will be placed upstream of constructed weir for spawning habitat. Downstream of the weir, a scour pool will form and the scoured materials will naturally sort downstream of the pool.

7.2.3 Work Schedule

Table 14. Gantt chart summarizing sequence and timing of restoration tasks.

	Year 1										Year 2								
	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
PHASE 1																			
Permit applications																			
Site visits and completion of site plans by engineer																			
Material procurement																			
Outreach																			
Installation of signs																			
Delivery of boulders and gravels																			
Weir Construction and gravel addition (sites 3, 4, 5,)																			
Bank stabilization (all sites)																			
Monitoring (all sites, 5 years)																			
PHASE 2																			
Permit applications																			
Engineer finalize plan																			
Order materials																			
Outreach																			
Delivery of boulders and gravels																			
Weir Construction and gravel addition (Sites 1 and 2)																			

8 Monitoring

Monitoring is one of the most important aspects of restoration projects yet it is rarely conducted in sufficient detail or duration. While monitoring adds time and cost to projects, it is important for the improvement of future restoration projects and the field of restoration ecology. As mentioned previously, the value of the current project extends beyond its study sites because it serves as a pilot project for other candidate sites in the Serpentine River and other urban streams. Furthermore, there is little information on the effects of Newbury weirs on the physical and biological characteristics of streams, which also presents an opportunity to critically evaluate its usefulness to spawning habitat restoration.

8.1 Metrics of Success

The following metrics of success were developed to help guide monitoring activities in assessing whether restoration is successful in meeting its goals. Typical response times for stream restoration projects range from 1-5 years post-restoration (Roni et al. 2002). Therefore, monitoring should be conducted annually for at least 5 years post restoration to capture changes in spawning habitat, salmonid production, bank vegetation, and structural integrity of weirs. If funding permits, monitoring over 10 years would produce valuable data on the longevity of restoration benefits.

Metrics of success for spawning habitat were developed based on requirements outlined in section 3. Gravel should be relative free of large cobbles and fine sediment, and have a minimum depth of 20 cm. Scour depth should not exceed 10 cm at any time because it risks the excavation of redds. Survival of willow live cuttings can be high (75-95%) if soils remain moist for most of the growing season (Randall 2014). Although some movement of boulder structures are expected, the functions of the weirs and rock toe keys should not be compromised.

Table 15. Metrics of success of restoration treatments for year 1, year 3, and year 5 post-restoration.

Treatment	Year 1 Metric	Year 3 Metric	Year 5 Metric
Newbury weir construction and gravel addition	Some boulders have shifted into a new stable position without affecting the functions of the weir	Some boulders have shifted into a new stable position without affecting the functions of the weir	Some boulders have shifted into a new stable position without affecting the functions of the weir
	Gravel depth decreases by <2 cm	Gravel depth decreases by <4 cm	Gravel depth decreases by <5 cm
	Scour depth <10 cm	Scour depth <10 cm	Scour depth <10 cm
	<5% of substrate over 102 mm	<10% of substrate over 102 mm	<15% of substrate over 102 mm
	<5% of substrate under 1 mm	<10% of substrate under 1 mm	<15% of substrate under 1 mm
Rock toe key with live staking	No movement of boulders resulting in exposure of bank toe	No movement of boulders resulting in exposure of bank toe	No movement of boulders resulting in exposure of bank toe
	80% survival of all live cuttings	75% survival of all live cuttings	70% survival of all live cuttings

8.2 Baseline Monitoring

Baseline monitoring should be done prior to restoration in order to quantify site changes pre- to post-restoration. A strong monitoring plan should include a control site, so that a before-after-control-impact (BACI) design can be implemented to compare natural changes in the control site to changes in the restored sites. However, finding an appropriate control site is difficult in a river where sites are not truly independent from one another due to their connectivity and influence from upstream sites, and if close enough in proximity, downstream sites. In the past, sites at a short distance upstream from restoration sites have been used as control sites due to similarities of the site environment. Unfortunately, upstream sites differ greatly from restoration sites of this project, largely due to the presence of anthropogenic structures (ie. bridges, culverts, riprap). An alternate solution is to conduct baseline monitoring of the restoration sites for several years prior to restoration. This will document natural changes in the sites which can be compared to changes post-restoration. Although error will be introduced from temporal variation, this method is the best available option.

Because spawning habitat requirements are well documented in literature from laboratory and field experiments, reference conditions derived from literature will be used in lieu of a reference site.

8.3 Physical Monitoring

The metrics of success were based primarily on physical changes in the restoration sites for several reasons. While the ultimate goal of the project is to increase salmonid production in the Serpentine River, biological responses are not good indicators of project success due to the multitude of variables that influence population size, including oceanic productivity, predation dynamics, and other stressors in the watershed. In other words, it is difficult to tell without conducting largescale baseline monitoring with control sites whether the biological response is due to the restoration activity or another factor. On the other hand, instream restoration directly affects the physical characteristics of the study sites, which can provide a quantitative assessment of spawning habitat, as well as an indirect measure of the effects of sediments on incubating eggs and alevin. If resources are limited, monitoring of gravel depth and size should be prioritized, as they are the most relevant parameters affected by restoration. If enough funding exists, other parameters that are considered key spawning requirements should be monitored to ensure continued suitability of sites for spawning.

8.3.1 Gravel Depth and Sediment Budget

The primary goal of this restoration plan is to provide sufficient gravel of the proper depth and size for spawning. Scouring of gravels during high flows may result in loss of gravel over time. Even if gravel refills from upstream sources, scour and fill events can excavate redds and be a contributing cause of mortality of incubating eggs and alevin. Therefore, measurement of scour and fill will not only provide detailed information about the changes in the streambed over time, but also a rough estimate of sediment budgets at each site.

Sliding-bead monitors are strings of plastic beads that are implanted into the streambed to measure scour and fill events without excavation of the monitor. High flows scour the streambed and expose the beads to the flow of the water. Because the beads are buoyant, they slide upward to the end of the cable (Figure 23). The length of beads excavated represents the depth of scour. Fill can be determined by measuring the length of cable above the streambed in relation to the length at time of installation. After monitoring, the sliding-bead monitor can be reset in the streambed and reused for the next round of monitoring. The sliding-bead monitors should be installed in areas upstream of constructed weirs and downstream of pools, where gravels are expected to accumulate. Monitors should be installed along two transects, one upstream of the constructed weir and one downstream of the scour pool, with three to four monitors along each transect. Monitors have a high recovery rate and are inexpensive to construct (Nawa and Frissell 1993). An experienced two-person crew can install around eight devices within a day (Nawa and Frissell 1993). Nawa and Frissell 1993 describes the construction and installation process in detail. Well-defined markers, such as aluminum tags driven into trees or surveyor's stakes, should be placed on either side of the stream. Gravel depth monitoring should be conducted at least once a year after the rainy season.

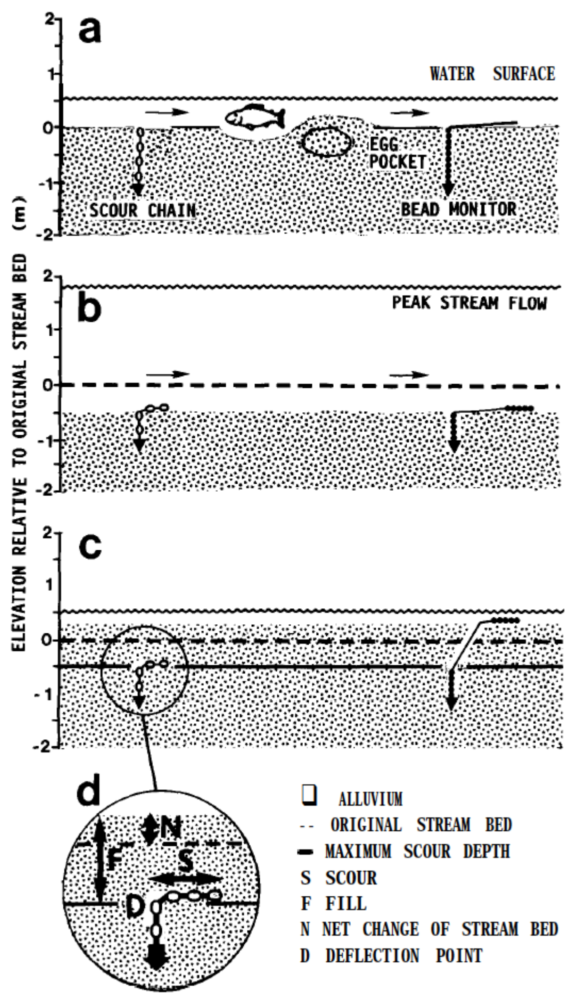


Figure 23. Scour and fill measured by a scour chain and sliding bead monitor. (a): Before peak flow. (b): Maximum scour during peak flow. Exposed beads slide to the end of the cable. Redd and eggs have been excavated and washed downstream. (c): Sediment deposition after peak flow. (d): measurements of scour and fill recorded by a scour chain (Nawa and Frissell 1993).

8.3.2 Gravel Size

Surface and subsurface grain size analysis should be conducted according to the methods described in section 5.2.3. The same transects used in gravel depth monitoring can be used for gravel size. For surface grain size, 100 pebbles should be collected across each transect. For subsurface grain size, volumetric samples should be collected at intervals of 1.5 m. Grain size distribution should be analyzed for fine sediment content and compared to the recommended spawning size range of 13 – 102 mm. Gravel size monitoring should be conducted once a year.

8.3.3 Geomorphic Changes

Riffle construction will likely cause geomorphic changes to the downstream channel. Specifically, a scour pool should form immediately downstream followed by sorting of gravels. To track the changes in these geomorphic features, cross-sectional channel surveys should be conducted once a year along each riffle, pool, and spawning pad. Percent riffle and pool in relation to the length of the reach should also be measured.

8.3.4 Other Parameters

Temperature, dissolved oxygen, velocity, and depth measurements should continue to be monitored along the same transects to ensure that the spawning area is meeting all physical requirements. To better understand the effects of fine sediment accumulation on intergravel permeability, a hand-powered vacuum pump apparatus described by Saiki and Martin (1996) can be constructed to measure gravel porosity.

8.4 Biological Monitoring

8.4.1 Spawning Activity and Redds

Despite earlier mentions of the unreliability of biological monitoring data, biological monitoring is still valuable in assessing overall project success. Most importantly, use of newly restored spawning habitat must be confirmed by spawning activity or presence of redds. During spawning season, surveys of study sites should be conducted at least once a week for the purpose of recording spawning activity and redds.

8.4.2 Fry Surveys

During each spring, fry surveys should be conducted at each restoration site and compared to escapement numbers obtained by the Serpentine Enhancement Society. Although fry numbers can be influenced by a variety of factors, there is value in documenting overall ratios of fry production to adult escapement in the previous fall, as it provides a rough estimate of changes in reproductive success. Methods and effort spent for fry surveys and adult fish counts should be standardized to produce accurate data.

8.4.3 Vegetation

A visual examination of the live cuttings should be conducted once a year to determine survival rates of each site. Survival rates will be determined by the number of dead cuttings divided by the number of cuttings planted in total.

8.5 Structural Integrity

Structures should be examined during monitoring events to detect needs for repair. Some movement of the rock weir is expected, but major repairs are necessary if the riffle crest no longer functions to accumulate gravel at the upstream end. Rock toe keys should also be examined to ensure that rock movement has not exposed the toe bank to the flow of water.

8.6 Photomonitoring

Photos are one of the best ways to communicate restoration results. Photos should be taken from the same position with a clear landmark in the background for scale. This can be achieved by installing photomonitoring markers at the restoration sites. Photos can be taken during monitoring events to show changes over time.

8.7 Maintenance

If the structural integrity of the weirs is compromised due to boulder movement, tractive force calculations should be redone, and replacement by larger boulders may be necessary to repair damages. If the gravel depletion occurs at a rate that is too quickly, supplemental gravel should be placed as needed. Fine sediment accumulation within the gravels may continue without installation of sediment catchment structures within the watershed catchment. Rock toe keys should be repaired if movement of rocks exposes the toe zone to erosion. A second iteration of live staking can be done if there is failure to achieve target survival.

9 Conclusion

Urbanization has drastically altered the Upper Serpentine River and its surrounding landscape. The resulting change in hydrology, stream geomorphology, and water quality has degraded what once was high quality spawning habitat for salmonids. Despite previous efforts to add supplemental gravel, the seven study sites were still in a state of gravel deficit. The substrate was well-mixed with little riffle-pool topography, conditions that are indicative of a disturbed system. Hydraulic analysis of the study sites showed that spawning gravels will be mobilized during modest storms. Furthermore, fine sediment sources from the watershed and bank erosion were readily available and accumulated quickly in the streambed. A culvert along Guildford Brook at 104 Avenue is a barrier to fish passage and should be reworked prior to restoration of upstream sites.

Restoration goals were set with consideration of future changes in the landscape and climate. The Upper Serpentine watershed will increase in ISC and experience wetter winters. Thus, restoring the hydrology of the Upper Serpentine River to its pre-urbanized state will not be possible. Instead, restoration should aim to restore to a novel ecosystem that is resilient to the future changes while still producing wild self-sustaining salmonid populations. In order to achieve this, restoration should aim to alter site-specific hydraulics in the meantime while stormwater management strategies are being improved.

Gravel addition was prescribed along with instream structures to reduce tractive forces and increase gravel retention within the study sites. Newbury weirs, or constructed riffles, were proposed due to their ability to increase flow resistance, trap spawning gravels, and re-establish riffle-pool sequences that promote natural sorting of gravels. Newbury weirs also add irregularities in the stream profile, which generates intergravel flows. Bank stabilization using dense live staking with a protective toe key was prescribed to reduce further channel incision and siltation. In the long-term, it was recommended that the City of Surrey should address other watershed-level priorities including passage through the Serpentine sea dam, monitoring for urban contaminants, and installing green infrastructure to intercept and filter surface runoff.

The proposed treatments are relatively inexpensive, and if successful, will increase salmonid production in the Serpentine River. However, the value of the current project extends beyond fish productivity estimates. Monitoring data can be used inform future urban stream restoration projects and contribute to the continual improvement of restoration techniques. If the

Newbury weirs are successful, this restoration treatment can be expanded to other sites along the Serpentine River and other rivers situated in an urban landscape. Future research should be directed towards the effects of riffle construction on sediment transport dynamics so that the effects of restoration on habitat processes, not just form, are better understood. Measuring changes in sediment budget after riffle construction can provide useful information on how often supplementary gravels are required. Although theoretical models of constructed riffles have been done in the past, continued field verification should be done to better quantify the uncertainties that arise from unpredictable environments.

The conservation and recovery of wild Pacific salmon is becoming increasing urgent as anthropogenic stressors increase with urban growth. As urbanized centres continue to encroach on productive streams, there is a greater need to reduce human impact on these valued ecosystems and the keystone species that live within them. Restoration projects in urban areas are often overlooked and given low priority due to the extent of degradation of some of these ecosystems. However, this is a dangerous attitude to adopt as it perpetuates the degradation of urban environments. Instead, focus should be shifted towards achieving a positive human-wildlife interface through restoration, respectful consultation, and education.

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Appendix A

Table A1. Number of samples not included in the subsurface grain size analysis due to particles being too large or too small.

Site	Total sampling locations	Number of locations where samples were taken	Number of locations not sampled due to sizes too large (>100 mm)	Number of locations not sampled due to sizes too small (sand)
1	16	9	3	4
2	7	6	0	1
3	23	16	6	1
4	7	6	1	0
5	9	5	4	0
6	3	3	0	0
7	5	5	0	0

Appendix B

Table B1. Fish passage scoring based on Field Assessment for Determining Fish Passage Status of Closed Bottom Structures (MOE 2011).

Criteria	Score
Culvert length <15 m = 0 15-30 m = 3 >30 = 6	0*
Embedded score No continuous embedment = 10 Continuous embedment <20% pipe diameter or <30 cm deep = 5 Continuous embedment >20% of piper diameter or >30 cm deep = 0	10
Outlet drop score <15 cm = 0 15-30 cm = 5 >30 cm = 10	10
Culvert slope score <1% = 0 1-3% = 5 >3% = 10	5*
Stream width ratio (channel width/culvert width) <1.0 = 0 1.0-1.3 = 3 >1.3 = 6	6
TOTAL	**31**

*based on conservative estimates

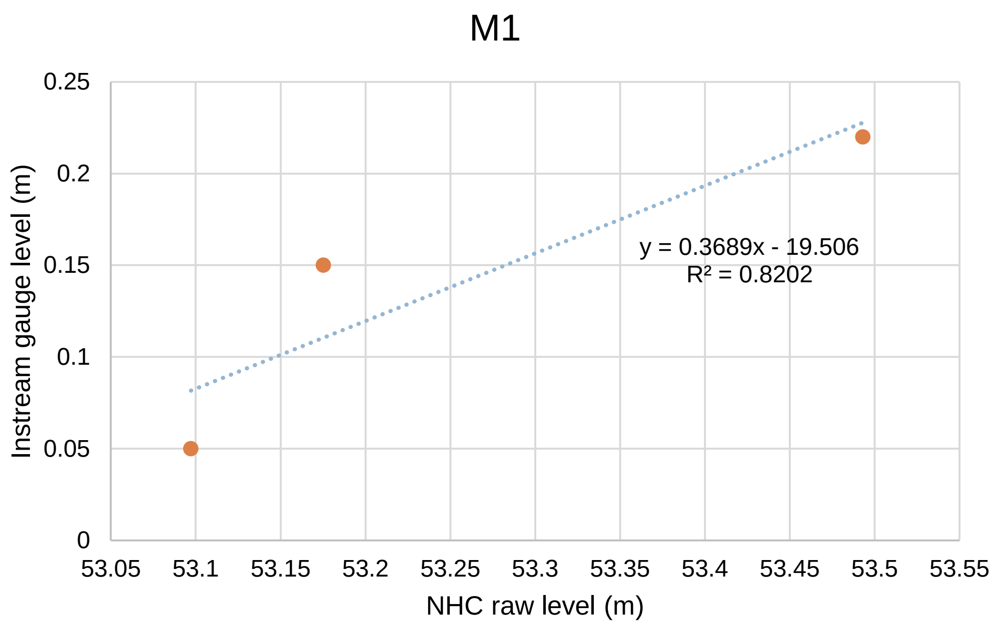
Final Score Results

0-14 = passable

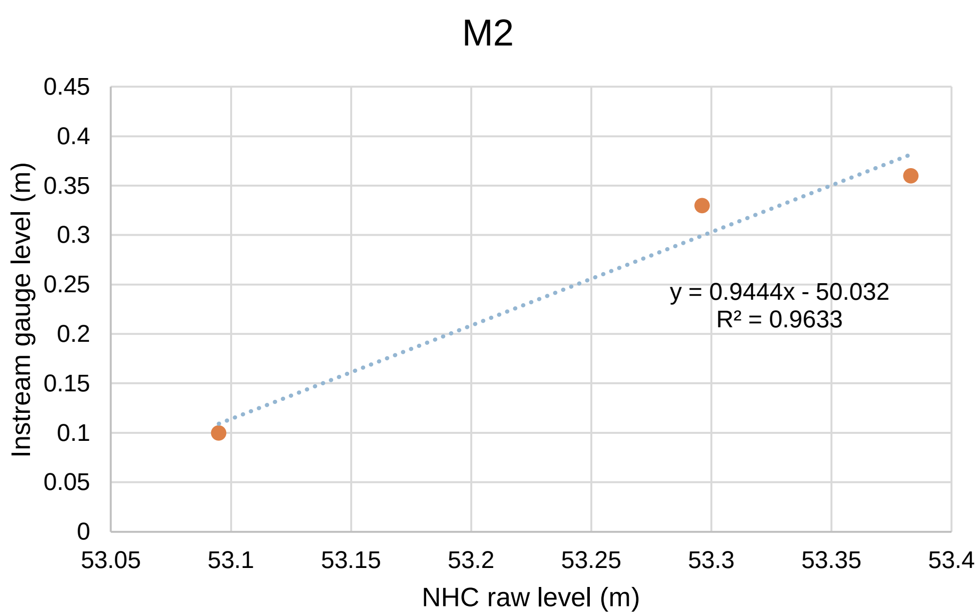
15-19 = potential barriers

>20 = barrier

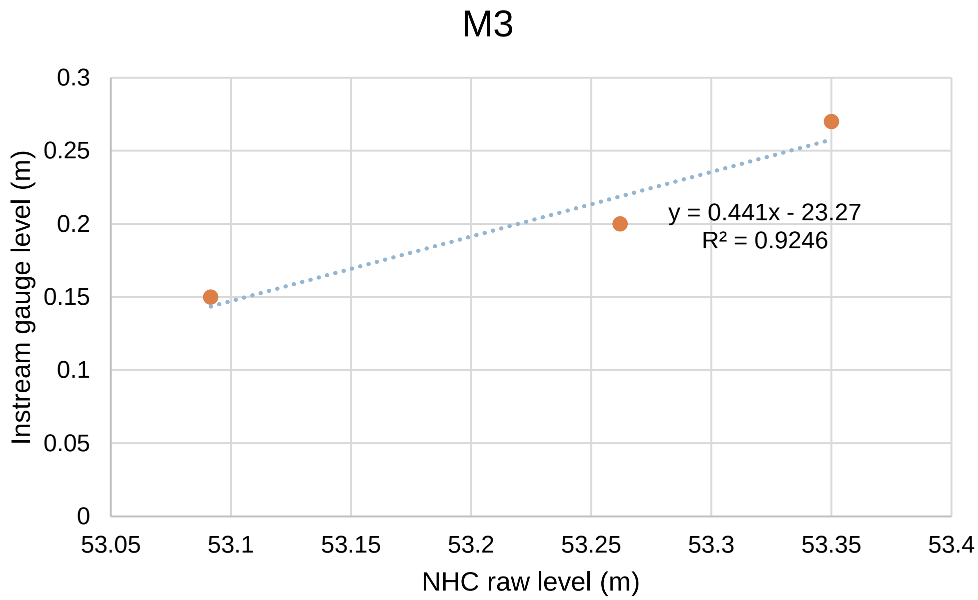
Appendix C

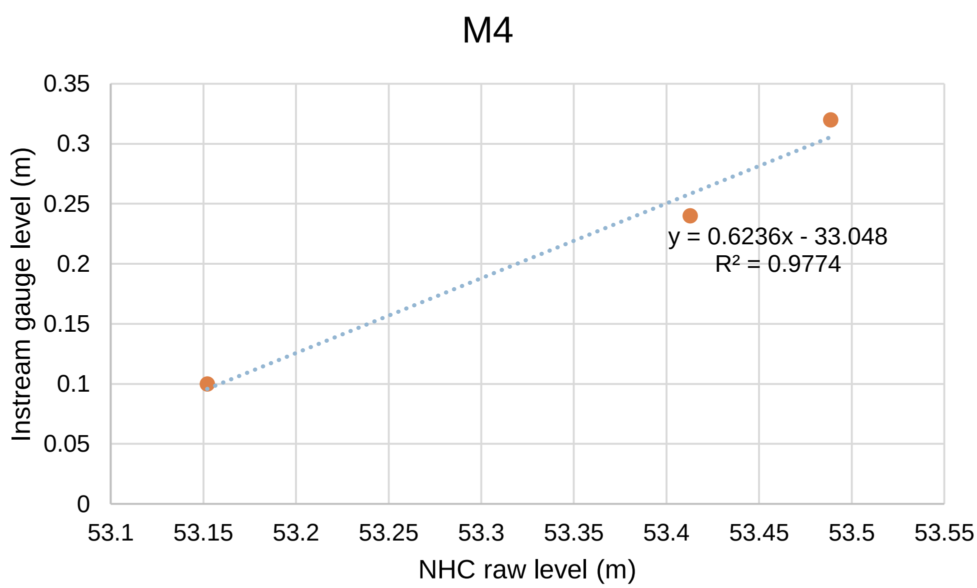


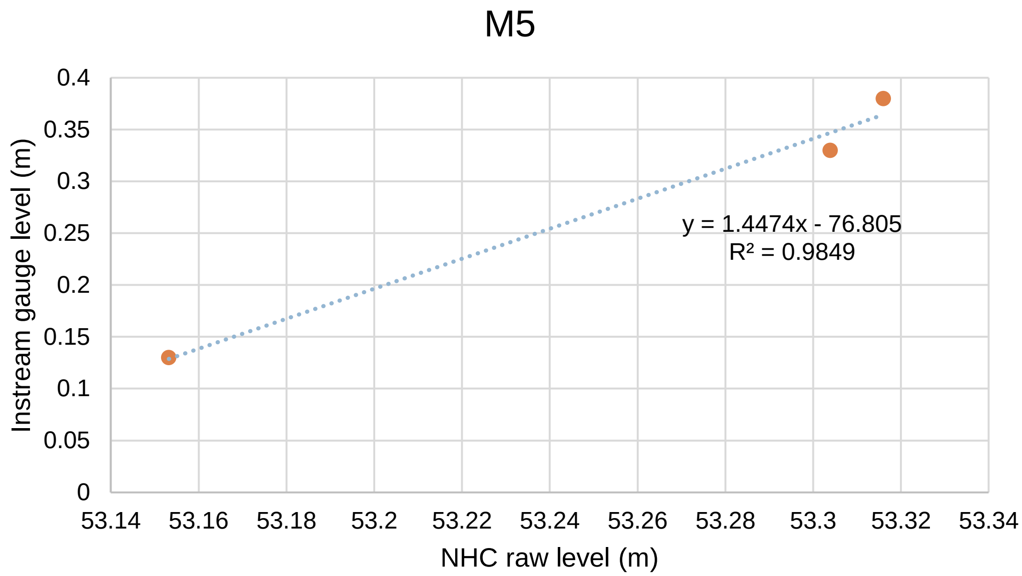
M1
y = 0.3689x - 19.506
R² = 0.8202
Instream gauge level (m)
NHC raw level (m)
0.25
0.2
0.15
0.1
0.05
0
53.05
53.1
53.15
53.2
53.25
53.3
53.35
53.4
53.45
53.5
53.55



M2
y = 0.9444x - 50.032
R² = 0.9633
Instream gauge level (m)
NHC raw level (m)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
53.05
53.1
53.15
53.2
53.25
53.3
53.35
53.4


M3
y = 0.441x - 23.27
R² = 0.9246
Instream gauge level (m)
NHC raw level (m)
0
0.05
0.1
0.15
0.2
0.25
0.3
53.05
53.1
53.15
53.2
53.25
53.3
53.35
53.4


M4
y = 0.6236x - 33.048
R² = 0.9774
Instream gauge level (m)
NHC raw level (m)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
53.1
53.15
53.2
53.25
53.3
53.35
53.4
53.45
53.5
53.55



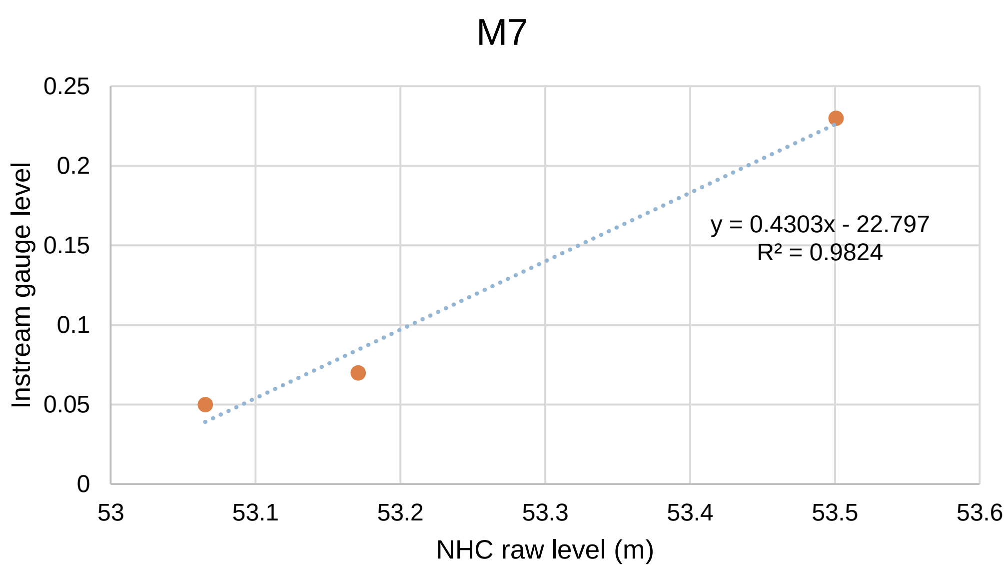


Figure C1. Stage-stage relation curve created by relating instream gauge levels to water levels monitored by the flow gauge installed at Serpentine River at 104 Avenue (FlowWorks 2018).

Appendix D

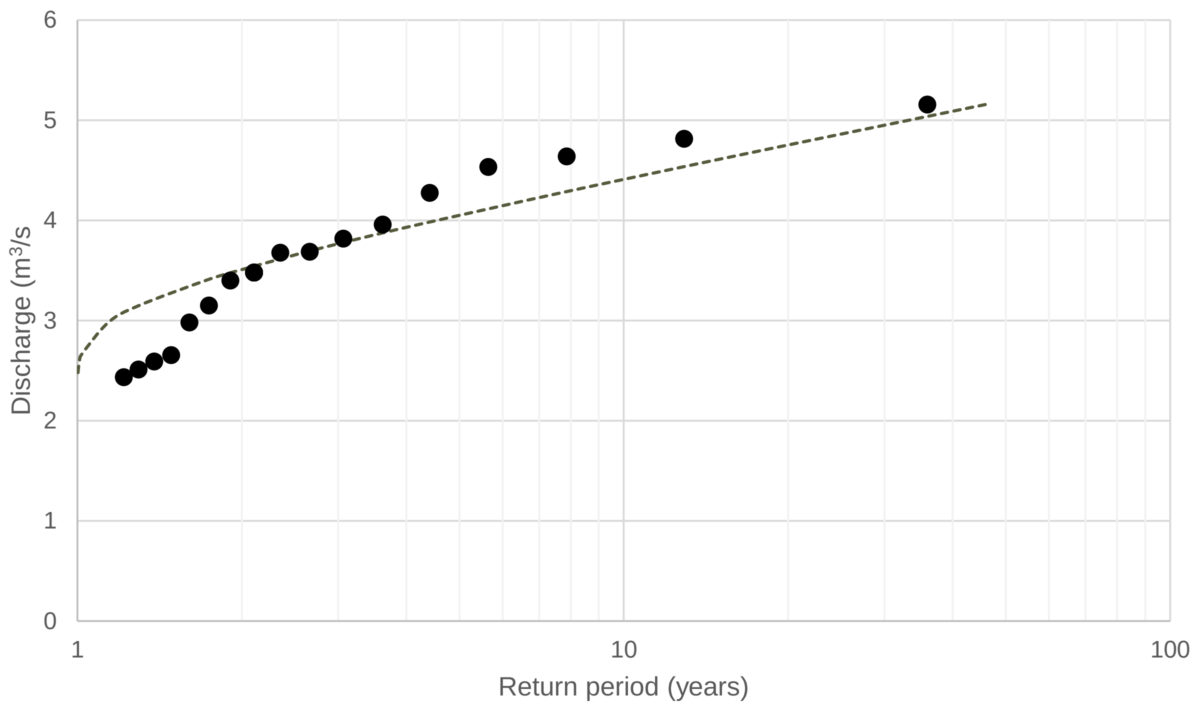


Figure D1. Flood frequency curve constructed from annual peak discharges from 1996 to 2017 at the 104 Avenue flow station. The dashed line represents the theoretical Gumbel distribution and the black circles represent the fit of peak annual streamflow to the Gumbel distribution.

Appendix E

Site 1

Table E1. Construction cost of site 1.

PHASE 1				
Bank stabilization				
Item	**Qty**	**Unit**	**Unit Cost**	**Subtotal**
Boulders (9.1 m^3)	25	tonne	$20.05	$501.25
Delivery	25	tonne	$8.30	$207.50
Willow stakes	4	bundle (of 50)	$6.50	$26.00
			Total	**$734.75**
PHASE 2				
Weir Construction				
Item	**Qty**	**Unit**	**Unit Cost**	**Subtotal**
Boulders (7.2 m^3)	20	tonne	$20.05	$401.00
Boulder delivery	20	tonne	$8.30	$166.00
Gravel (36 m^3)	60	tonne	$28.00	$1,680.00
Gravel Delivery	60	tonne	$12.50	$750.00
Gas powered water pump	1	day	$65.00	$65.00
			Total	**$3,062.00**
			Site Subtotal	$3,796.75
			Class C Contingency (20%)	$759.35
			PST and GST (12%)	$546.73
			TOTAL	**$5,102.83**

Site 2

Table E2. Construction cost of site 2.

PHASE 2				
Weir Construction				
Item	**Qty**	**Unit**	**Unit Cost**	**Subtotal**
Boulders (6.1 m^3)	17	tonne	$20.05	$340.85
Boulder delivery	17	tonne	$8.30	$141.10
Gravel (10 m^3)	17	tonne	$28.00	$476.00
Gravel Delivery	17	tonne	$12.50	$212.50
Gas powered water pump	1	day	$65.00	$65.00
			Total	**$1,235.45**
			Site Subtotal	$1,235.45
			Class C Contingency (20%)	$247.09
			PST and GST (12%)	$177.90
			TOTAL	**$1,660.44**

Site 3

Table E3. Construction cost of site 3.

PHASE 1				
Bank stabilization				
Item	**Qty**	**Unit**	**Unit Cost**	**Subtotal**
Boulders (6.8 m^3)	19	tonne	$20.05	$380.95
Delivery	19	tonne	$8.30	$157.70
Willow stakes	3	bundle (of 50)	$6.50	$19.50
			Total	**$558.15**
Weir Construction				
Item	**Qty**	**Unit**	**Unit Cost**	**Subtotal**
Boulders (8.3 m^3)	23	tonne	$20.05	$461.15
Boulder delivery	23	tonne	$8.30	$190.90
Gravel (28 m^3)	47	tonne	$28.00	$1,316.00
Gravel Delivery	47	tonne	$12.50	$587.50
Gas powered water pump	1	day	$65.00	$65.00
			Total	**$2,620.55**
			Site Subtotal	$3,178.70
			Class C Contingency (20%)	$635.74
			PST and GST (12%)	$457.73
			TOTAL	**$4,272.17**

Site 4

Table E4. Construction cost of site 4.

PHASE 1				
Bank stabilization				
Item	**Qty**	**Unit**	**Unit Cost**	**Subtotal**
Boulders (1.1 m^3)	3	tonne	$20.05	$60.15
Delivery	3	tonne	$8.30	$24.90
Willow stakes	1	bundle (of 50)	$6.50	$6.50
			Total	**$91.55**
Weir Construction				
Item	**Qty**	**Unit**	**Unit Cost**	**Subtotal**
Boulders (3.4 m^3)	10	tonne	$20.05	$200.50
Boulder delivery	10	tonne	$8.30	$83.00
Gravel (5 m^3)	9	tonne	$28.00	$252.00
Gravel Delivery	9	tonne	$12.50	$112.50
Gas powered water pump	1	day	$65.00	$65.00
			Total	**$713.00**
			Site Subtotal	$804.55
			Class C Contingency (20%)	$160.91
			PST and GST (12%)	$115.86
			TOTAL	**$1,081.32**

Site 5

Table E5. Construction cost of site 5.

PHASE 1				
Weir Construction				
Item	**Qty**	**Unit**	**Unit Cost**	**Subtotal**
Boulders (9.3 m^3)	25	tonne	$20.05	$501.25
Boulder delivery	25	tonne	$8.30	$207.50
Gravel (46.4 m^3)	77	tonne	$28.00	$2,156.00
Gravel Delivery	77	tonne	$12.50	$962.50
Gas powered water pump	1	day	$65.00	$65.00
Excavator and operator	1	day	$800.00	$800.00
			Total	**$4,692.25**
			Site Subtotal	$4,692.25
			Class C Contingency (20%)	$938.45
			PST and GST (12%)	$675.68
			TOTAL	**$6,306.38**

Site 7

Table E6. Construction cost of site 7.

PHASE 1				
Bank stabilization				
Item	**Qty**	**Unit**	**Unit Cost**	**Subtotal**
Boulders (1.1 m^3)	3	tonne	$20.05	$60.15
Delivery	3	tonne	$8.30	$24.90
Willow stakes	1	bundle (of 50)	$6.50	$6.50
			Total	**$91.55**
			Site Subtotal	$91.55
			Class C Contingency (20%)	$18.31
			PST and GST (12%)	$13.18
			TOTAL	**$123.04**

Miscellaneous and Reusable Items

Table E7. Cost of miscellaneous and reusable items.

Steel pointed rods	10	each	$13.00	$130.00
Hand-winched crane	1	each	$410.95	$410.95
Hoses (4" by 100')	3	each	$72.88	$218.64
Seine net	1	each	$61.99	$61.99
Dip nets	5	each	$11.99	$59.95
Sandbags	100	each	$4.00	$400.00
Interpretive posters	6	each	$100.00	$600.00
Shears	5	each	$17.00	$85.00
Wheel barrow	10	each	$94.98	$949.80
Laser Level Kit	1	each	$484.00	$484.00
Gloves	7	pack (of 3)	$16.98	$118.86
Shovels	10	each	$15.98	$159.80
Buckets	10	each	$3.97	$39.70
Flagging tape	3	each	$7.47	$22.41
Eslon measuring tape	3	each	$35.95	$107.85
Pin flags	2	pack (of 100)	$12.57	$25.14
High Visibility Vests	20	each	$14.99	$299.80
Hard Hats	20	each	$13.99	$279.80
			TOTAL	**$4,453.69**
			Site Subtotal	$4,453.69
			Class C Contingency (20%)	$890.74
			PST and GST (12%)	$641.33
			TOTAL	**$5,985.76**