# The effects of canopy closure on precipitation throughfall: Ecological restoration considerations for Spanish Bank Creek

**by**

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## APPROVAL

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## EXECUTIVE SUMMARY

Since the 1860s the watershed of Spanish Bank Creek has experienced many ecological disturbances due to extensive old-growth logging and urban development. Most notably, these disturbances have altered the vegetative composition and hydrology throughout the watershed. The historic old-growth forest has been replaced by species typical of earlier seral stages, as well as invasive species such as English ivy (*Hedera helix*). This disturbed vegetation mosaic is characterized by an arrested ecological trajectory that perpetuates degraded conditions. Urban development has eliminated over a third of the historic length of Spanish Bank Creek and storm drains were installed to direct residential drainage into the stream. The combination of a disturbed forest and degraded hydrology intensifies runoff and associated sediment transport, and decreases the hydraulic retention time of the watershed. This has led to a significant decline in abundance of chum, coho, and cutthroat salmonids in Spanish Bank Creek.

Previous research has established how trees partition precipitation into throughfall, stemflow, and interception, however there are few studies examining the effects of canopy closure on throughfall within the context of ecological restoration. Thus, the objective of this paper is to determine if increasing canopy closure can be used as a restoration model to decrease throughfall, and consequently increase the hydraulic retention time of the watershed. Results indicated that greater canopy closure was associated with decreased precipitation throughfall.

From these results I formulated a restoration goal and several treatments that would increase canopy closure, and also ameliorate the degraded vegetative composition and hydrology of the watershed. The restoration treatments prescribed in this paper constitute five years of physical enhancements from which self-sustaining biological processes will continue to restore ecosystem function and structure.

Successful implementation of these restoration treatments will positively affect regional biota, as well as users of the Pacific Spirit Regional Park who come to recreate, learn, and connect.

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## ACKNOWLEDGEMENTS

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Thank you Krissie Saba and Phil Climie for your field assistance and company.

Last but not least I want to thank the Musqueam Nation for allowing me to learn on their ancestral lands. I hope that I will be able to reciprocate the favour one day.

# CHAPTER 1: INTRODUCTION

## 1.1 SITE LOCATION

The watershed of Spanish Bank Creek is located within the 763 hectare Pacific Spirit Regional Park (PSRP) of greater Vancouver. The PSRP was established in 1989, and was designated as an environmentally sensitive area in 1991 (Kahrer, 1991; Page and Eymann, 1994). The PSRP is located within the boundary of the unincorporated community of the University Endowment Lands between the University of British Columbia (UBC) campus, and the City of Vancouver.

Spanish Bank Creek flows north from Chancellor Boulevard for approximately one kilometer, then flows under NW Marine Drive, and terminates at the tidally influenced estuary of Burrard Inlet (*Figure 1*).

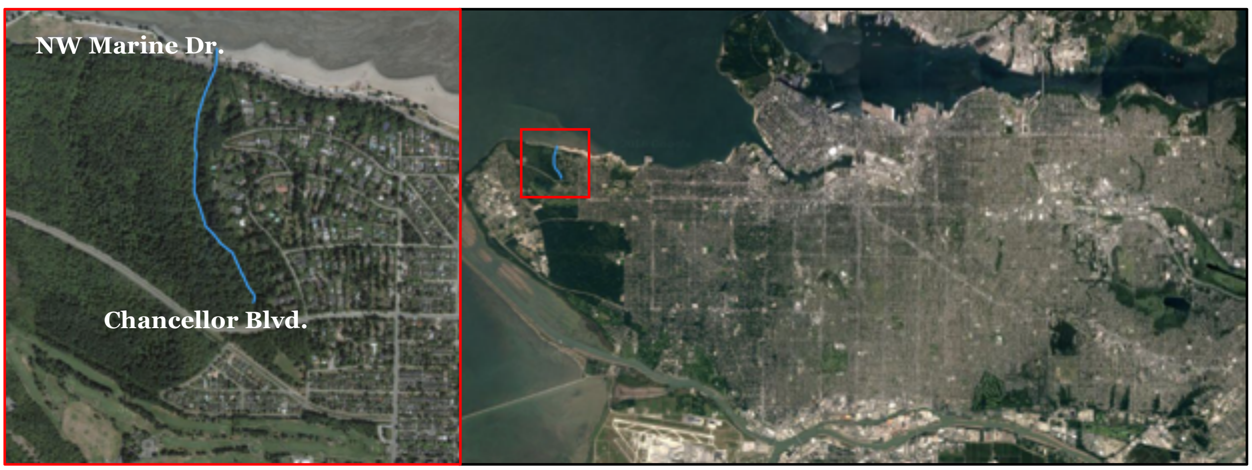


**Figure 1**: The location of Spanish Bank Creek within greater Vancouver. The stream runs through the PSRP, which is located between the University of British Columbia campus and the City of Vancouver (QGIS Development Team, 2009).

## 1.2 PROJECT OVERVIEW

A significant quantity of inorganic sediment appears to be present within the lower reaches of Spanish Bank Creek that are north of NW Marine Drive (*Figure 2*). This sediment can negatively affect fish and invertebrates, hinder stream productivity, and impede fish passage (Birtwell, 1999; Suttle, *et al.*, 2004). The watershed of Spanish Bank Creek has experienced significant ecological disturbance due to historic logging and urbanization from the 1860s to the 1940s (Kahrer, 1991). Generally, ecosystems are defined as a specific plant community and its associated topography, soil, and climate (Green and Klinka, 1994). Logging and urbanization within the watershed have altered the plant communities of the project site, as well as the hydrology, thus affecting the topography. This has degraded the ecological expression of the watershed to the point where human intervention is required. Restoration efforts will focus on mitigating ecological stressors that have manifested as a result of over 150 years of disturbances throughout the watershed and surrounding region.

**Figure 2**: A thick layer of inorganic sediment has accumulated behind a downed tree that has fallen across Spanish Bank Creek. Longitudinally, this sediment has accumulated for approximately 15 m upstream of the downed tree (Reynolds, 2016).

## 1.3 THE MUSQUEAM

Spanish Bank Creek runs through traditional Musqueam First Nations territory. The Musqueam have occupied several locations throughout the Greater Vancouver Region for thousands of years, and have never relinquished their rights and title to their ancestral territories throughout greater Vancouver. Their ancestral territory includes Vancouver, North Vancouver, South Vancouver, Burrard Inlet, New Westminster, Burnaby, Richmond, and parts of Delta (*Appendix A*). The forests throughout the PSRP were historically used by the Musqueam for hunting, and the beaches along the north coast of Point Grey were used for harvest of marine resources (GVRD, 2000). At least a dozen culturally significant sites have been identified within or near Spanish Bank Creek, including middens, camp sites, villages, artifact sites, and trails (Macdonald, 1992).

Any work conducted within Musqueam territory will require consultation and collaboration with the Musqueam Fisheries Department, as well as the Musqueam Treaty, Lands, and Resources Department regarding archaeological concerns (*Appendix B*).

## 1.4 PRINCIPAL CLIENTS

The principal clients involved in this restoration project are Metro Vancouver, Department of Fisheries and Oceans Canada, the Ministry of Forests, Lands and Natural Resource Operations, Spanish Bank Streamkeepers, and the Pacific Spirit Park Society (*Appendix B*). Any plans for work performed within the watershed around Spanish Bank Creek will require approval from Metro Vancouver, Fisheries and Oceans Canada, and the Ministry of Forests, Lands and Natural Resource Operations to ensure that outcomes are aligned with the goals of all three institutions. It is recommended that works performed be in collaboration with the Spanish Bank Streamkeepers and the Pacific Spirit Park Society. Inclusion of these two volunteer organizations is essential to promote stewardship and public engagement.

## 1.5 WILDLIFE

The Coastal Western Hemlock Biogeoclimatic Ecosystem Classification (BEC) zone commonly has a greater diversity and abundance of ecological niches than any other BEC zone (Meidinger and Pojar, 1991). In addition, the Fraser Lowlands of this BEC zone are home to the greatest diversity of birds, amphibians, and reptiles in BC. Black-tailed deer (*Odocoileus hermionus*), black bear (*Ursus americanus*), grizzly bear (*Ursus arctos*), and gray wolf (*Canis lupus*) are the most abundant large mammals that are typically found in this BEC zone. Anecdotal evidence suggests that around the late 1800s there were elk (*Cervus canadensis*), deer (*Cervidae spp.*), cougar (*Puma concolor*), bear (*Ursidae spp.*), wolves, lynx (*Lynx canadensis*), snowshoe hare (*Lepus americanus*), skunk (*Mephitidae spp.*), porcupine (*Erethizontidae spp.*), weasel (*Mustela spp.*), muskrat (*Ondatra zibethicus*), and beaver (*Castor canadensis*) within the region of Vancouver (Macdonald, 1992). Many of these mammals have been displaced due to urban development (Meidinger and Pojar, 1991).

Currently, mammals found within the PSRP include coyote (*Canis latrans*), skunk, raccoon (*Procyon lotor*), Douglas squirrel (*Tamiasciurus douglasii*), mole (*Scapanus spp.*), vole (*Arvicolinae spp.*), and mice (*Apodemus spp.*, *Mus spp.*, and *Pewmyscus spp.*) (PGL, 2013). Amphibians and reptiles include salamander (*Caudata spp.*), newt (*Pleurodelinae spp.*), toad (*Anaxyrus spp.*), frog (*Anura spp.*), and garter snake (*Thamnophis spp.*) species. The PSRP has been described as the largest remaining greenspace within Metro Vancouver excluding the mountains north of Burrard Inlet, providing resting, foraging, roosting, and nesting opportunities for over 156 species of migratory and non-migratory birds (IBA Canada, 2017). In 1995 the PSRP was named an Important Bird Area (IBA) due to a large nesting colony of Great Blue Herons that have since moved elsewhere (PGL, 2013).

There are many plants, animals, and ecological communities at risk in BC that could potentially be found within the project site (*Appendix C*). This information was compiled using British Columbia's Conservation Data Centre Ecosystem Explorer (BC Conservation Data Centre, 2017). Ecosystem managers should be cognizant of the direct and indirect effects of any work conducted on the project site to these plants, animals, and ecosystems.

## 1.6 HISTORICAL CONTEXT

### *1.6.1 Logging in the Pacific Spirit Regional Park*

Significant logging has occurred within the Pacific Spirit Regional Park. In the 1860s European settlers began selectively logging the old-growth forest (Kahrer, 1991). Over the following one hundred years, several more iterations of logging occurred. By the 1900s the most valuable timber had already been removed from the forest. From 1912 to 1923, 65 timber sale licenses were issued. Timber harvested under these licenses consisted mostly of dead and downed trees and second growth. The purpose of these licenses was to reduce the fire hazard associated with logging debris and to derive any remaining timber revenue for the Forest Branch. Through World War I (1914 to 1918) and the Great Depression (1929 into the 1930s), illegal subsistence logging occurred within the forest. By 1933, 180 timber permits were issued per week by the Forest Branch, targeting dead and downed trees. Through the 1940s, timber permits were issued at the request of local residents. Forest fires were a constant concern due to build-up of logging debris. Fires were selectively ignited to diminish fuel throughout the forest. One such occasion occurred on 13 July 1919 when a fire was ignited that got out of control. Two days later a backfire was lit to halt progression (Thompson, 1985). A total of 500 acres of the forest was burned (Kahrer, 1991). In 1910 the watershed of Spanish Bank Creek was clear-cut and burned (Thompson, 1985). In the years following, the watershed was used as a dairy farm.

Despite the extensive history of logging within the forest, very few records exist. However, anecdotal evidence suggests that in the 1850s, Vancouver's largest trees were approximately 1,000 years old, some of which were over 100 m tall (Macdonald, 1992). Tree species consisted of Douglas-fir (*Pseudotsuga menziesii*), cedar (*Cedrus spp.*), hemlock (*Tsuga spp.*), pine (*Pinus spp.*), spruce (*Picea spp.*), maple (*Acer spp.*), and yew (*Taxus spp.*). This is consistent with records from a timber survey conducted in 1869 that indicated that tree species present near Spanish Bank Creek included fir, hemlock, cedar, and yew (Kahrer, 1991). Records from the 1920s indicated that the forest was composed of patches of dense second growth that was often deciduous and burnt, as well as some areas of mature forest and accumulations of logging debris. A timber survey was conducted southeast of the PSRP in 1932 that indicated that trees present were green alder (*Alnus viridis*), fir, hemlock, and some soft maple, with an average diameter at breast height of 30 to 35 cm. Another survey in 1941 indicated that the tree species were primarily composed of second growth cedar, hemlock, and alder (*Alnus spp.*). The forests of the Endowment Lands were designated as a regional park in 1989, thereby assuming the title of the Pacific Spirit Regional Park (Kahrer, 1991).

*1.6.2 Urban Encroachment*

Between 1907 and 1908 the framework for establishing the University of British Columbia was organized, and in 1910 the final location of the UBC campus was determined (Kahrer, 1991). Two million acres of land were endowed to UBC to develop funds for the university. This agreement was revised in 1923 under the University Loan Act. The two million acres across British Columbia (BC) were substituted for 2,900 acres surrounding the UBC campus. These 2,900 acres constitute the current day extent of the PSRP and the unincorporated community of the University Endowment Lands (Kahrer, 1991). Urban areas such as the residential neighbourhood of Little Australia and the University Golf Course have steadily encroached into the watershed, resulting in Spanish Bank Creek being shortened significantly from its historic extent (*Figure 3*).

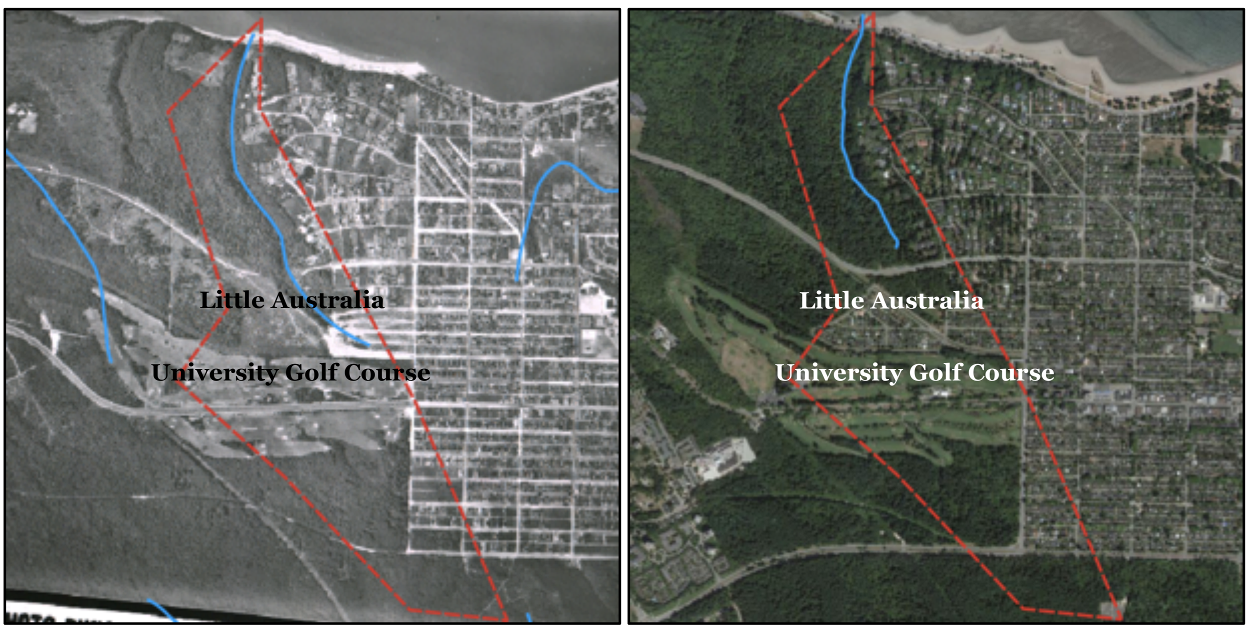


**Figure 3**: Comparison between a 1932 airphoto and a current satellite image. The historic stream course of Spanish Bank Creek has been superimposed on the airphoto (left), and the current extent of Spanish Bank Creek has been superimposed on the satellite image (right). The approximate historic watershed extent is outlined in the dashed red line. Urbanization has encroached into the watershed, and Spanish Bank Creek has been shortened from approximately 1.5 km in length to its current length of 1.025 km (QGIS Development Team, 2009).

Historically, the Greater Vancouver Region used to be a mosaic of stream courses. Through analysis of historic maps from 1880 to 1920, approximately 124 km of streams and creeks used to flow through what is now the municipality of Vancouver and the University Endowment Lands (Lesack and Proctor, 2011; PIBC, 1998). Many of these watercourses were home to various species of Pacific salmon (*Oncorhynchus spp*.). As of 1998, as few as 10 km of streams and creeks were available for use by Pacific salmon. This equates to approximately 12% of previously identified 1880 to 1920 stream length that was available in 1998 for Pacific salmon at various life stages. Spanish Bank Creek itself used to support healthy populations of coho salmon (*Oncorhynchus kisutch*), chum salmon (*Oncorhynchus keta*), and cutthroat trout (*Oncorhynchus clarkia*) less than 100 years ago (Page and Eymann, 1994). Considering the regional, and site-specific context, there is an opportunity for restoration of populations of salmonids at Spanish Bank Creek. In addition, the presence of salmon within the watershed of Spanish Bank Creek will have compounding positive effects on aquatic and terrestrial productivity because salmon-derived nutrients are utilized by nearly all trophic levels of coastal ecosystems (Schindler *et al*., 2003).

### *1.6.3 Previous Restoration*

In 1994, restoration recommendations were prepared to re-establish salmonids at Spanish Bank Creek (Page and Eymann, 1994). At the time, fish could only access Spanish Bank Creek from Burrard Inlet through an 83 m-long culvert. The recommendations examined the possibility of daylighting a section of the culvert and restoring the riparian vegetation around the lower reaches of the stream. Work was conducted in 1999 following these recommendations. The sections of culvert recommended for daylighting by Page and Eymann (1994) were restored, as well as several other lower reaches of Spanish Bank Creek.

In 2004 an off-channel pond was dug out and connected to Spanish Bank Creek, just south of NW Marine Drive. This off-channel pond was designed to provide refuge for fish and other aquatic species during high winter flows and low summer flows.

## 1.7 ECOLOGICAL STRESSORS: FILTERS TO RECOVERY

### *1.7.1 Invasive Species*

Within the PSRP English ivy (*Hedera helix*), English holly (*Ilex aquifolium*), Japanese knotweed (*Fallopia japonica*), policeman's helmet (*Impatiens glandulifera*), and Himalayan blackberry (*Rubus armeniacus*) have been identified (Page, 2006). Furthermore, these five species have been categorized as a management priority by Metro Vancouver due to their ability to compete for resources and disperse over large areas. Several varieties of English ivy have been identified within the PSRP. Therefore, English ivy will herein after be referred to as *Hedera*.

A particularly abundant invasive species within the watershed of Spanish Bank Creek is *Hedera*. On 8 July 2016 I identified a potential source of invasive species entering the watershed. It appears that the home owner or residential landscape crews have been dumping garden clippings over their fence into the watershed (*Figure 4*). This is a cheaper and faster alternative to hauling the clippings to the transfer station. There is a subsequent lack of vegetative species diversity (Biggerstaff and Beck, 2007) at this location of the watershed. In addition, there is also miscellaneous refuse including old bikes, bags, and furniture, indicating the use of this location as a dumping site for more than just garden clippings. Several footpaths navigate this section of the watershed, leading down to the ravine of Spanish Bank Creek and terminating once the terrain steepens and the vegetation thickens. There are several other residences along the eastern edge of the watershed that are also dumping their garden clippings into the ravine of Spanish Bank Creek.

**Figure 4**: Sources of invasive species in the watershed of Spanish Bank Creek. Garden clippings have been dumped over the fence from a private residence into the watershed of Spanish Bank Creek (left). This general area is highly invaded with invasive *Hedera* (right; Reynolds, 2016).

*Hedera helix* is a species that is native to Eurasia and was introduced to North America several hundred years ago (Ingham and Borman, 2010). *Hedera* seeds have a high rate of survival and establishment even in mature forest stands, demonstrating its shade tolerance (Laskurain, Escudero, Olano, and Loidi, 2004). In terms of the ecology of forests, *Hedera* can be troublesome in several ways. It can cover the forest floor in a dense monoculture, and can climb mature trees, thus smothering the canopy of the tree and potentially causing tree mortality (Ingham and Borman, 2010; Yang *et al.*, 2013). At the ecosystem scale, over significant time and space, presence and abundance of *Hedera* can direct succession to an alternative pathway, and can result in local extirpation of native seed sources (Fierke and Kauffman, 2006).

*1.7.2 Hydrological Alterations*

Vegetation and soils naturally function to mitigate storm water runoff during significant precipitation events (Asadian and Weiler, 2009). Vegetation intercepts precipitation, thereby storing water and increasing the hydraulic retention time of water entering the watershed. In addition, vegetation interception protects the soil surface from the energy of falling precipitation. Rainsplash erosion can lift as much as 37 Mg/ha of soil into the air (Polster, 2014). Vegetation also increases the rate of infiltration into the soil (Shen, *et al.*, 2017). Historic logging throughout the watershed of Spanish Bank Creek has decreased native species diversity and cover, as well as associated precipitation interception and stemflow potential. Urbanization has increased impervious surfaces throughout the watershed, thereby increasing the storm water runoff volume and rate (Sanders, 1986; Stephens *et al.*, 2002). Thus, historic logging and urbanization have created conditions that negatively affect the ability of the vegetation and soils to mitigate storm water runoff.

While logging in the PSRP has not occurred in nearly a century, land-uses are constantly evolving in response to socioeconomic patterns. Approximately 5% of BC is suitable or available for development (Stephens *et* al., 2002). Limited land for development, when combined with projected population growth, will result in rural areas becoming suburban, and urban areas developing further. This will increase land imperviousness (Chabaeva *et al.*, 2004). Therefore, it is likely that the residential areas around the watershed of Spanish Bank Creek will experience further development and increased imperviousness in response to socioeconomic fluctuations. This will result in increased runoff and decreased infiltration into the soils of the forest around Spanish Bank Creek (*Figure 5*). The effect that this has on stream hydrology is demonstrated by a comparison of hydrographs from a stream derived from urban runoff, and a stream derived from rural runoff (*Figure 6*).

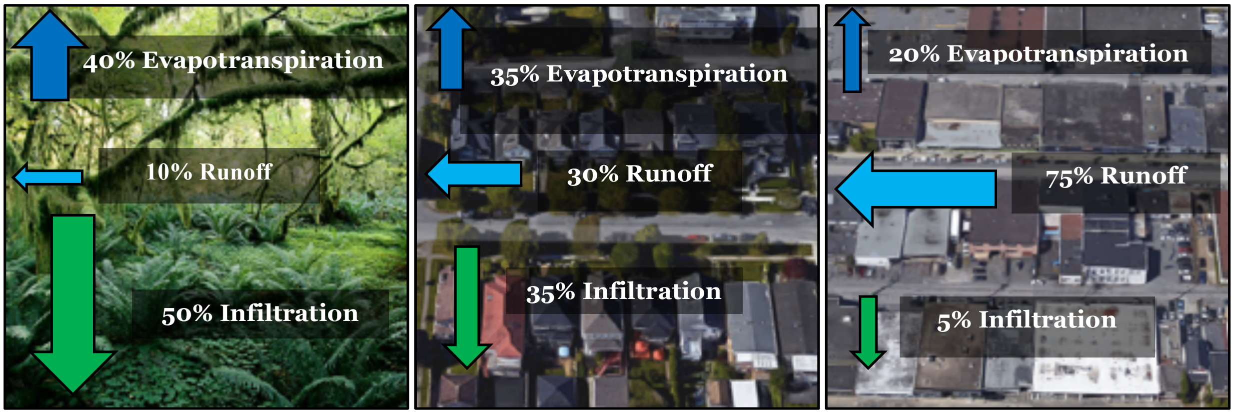


**Figure 5**: Runoff volume increases with expansion of impervious surfaces (Adapted from Stephens *et al.*, 2002). Natural forests have 0% impervious surfaces and approximately 10% runoff (left; Eastcott and Momatiok, 2014). Residential use areas have approximately 30 – 50% impervious surfaces and 30% runoff (middle; Google Maps, 2017). Commercial use areas can have up to 100% impervious surfaces and approximately 75% runoff (right; Google Maps, 2017).

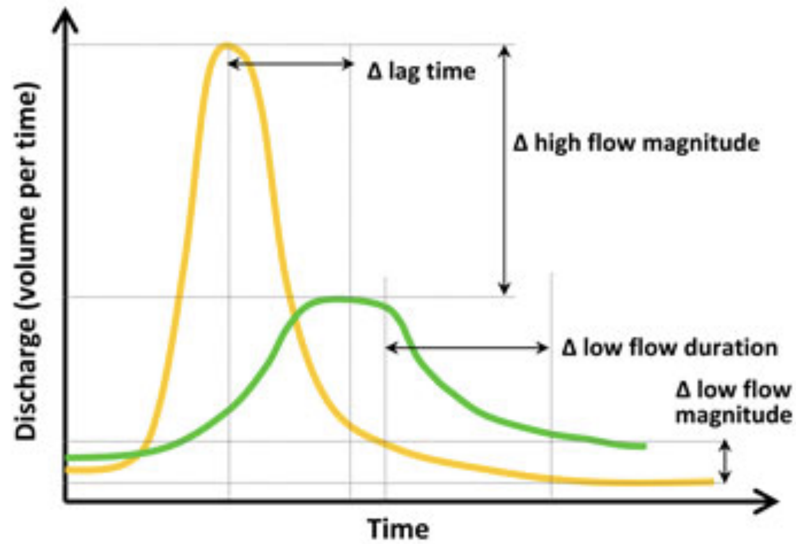


**Figure 6**: A typical hydrograph for streams derived from rural and urban runoff (US EPA, 2016). Generally, urban runoff produces streams that experience a greater total discharge, a greater peak flow, and a more rapid increase in discharge in response to a precipitation event (yellow line) compared to streams derived from rural runoff (green line). Urban runoff streams also typically have a lower base flow compared to rural runoff streams (Liu *et al.*, 2014; Lefrançois, 2015).

# CHAPTER 2: RESEARCH STUDY

## 2.1 RESEARCH OBJECTIVE

Considerable research has been conducted studying the relationship between various tree species and the partitioning of rainfall into throughfall, stemflow, and interception losses (Crockford and Richardson, 1990; Domingo *et al.*, 1998; Link *et al.*, 2004; Llorens and Domingo, 2007). However, there are few studies examining the ecological context and implications of these relationships for restoration.

The objective of my research is to investigate the relationship between canopy closure and precipitation throughfall with an ecological restoration perspective. Results of this research are particularly useful within the context of creating management frameworks for novel or hybrid ecosystems that are hydrologically degraded and are unlikely to be restored to historic conditions. For the watershed of Spanish Bank Creek, the results of this research will assist in development of a restoration plan.

## 2.2 RESEARCH QUESTION

In the watershed of Spanish Bank Creek, topographical conditions are dominated by eroding rills and gullies that rapidly mobilize water as runoff and decrease the hydraulic retention time of the watershed (*1.7.2 Hydrological Alterations*). It is widely understood that water is one of the primary causes of erosion (Polster, 2014). In most forested ecosystems, precipitation is the primary hydrologic input and, as a function of climate, interacts with the pedology, lithology, vegetation, slope, and drainage area resulting in a varied topography that is often characterized by erosion (Dewitte, *et al.*, 2015). Vegetation has the ability to mitigate the effect that precipitation has on rates of erosion (Hartanto *et al.*, 2003; Pypker *et al.*, 2005; Shen *et al.*, 2017; Zhou *et al.*, 2008), and stream embeddedness has been found to be negatively associated with forest cover (Opperman *et al.*, 2011). Therefore, vegetation throughout the watershed of Spanish Bank Creek can ameliorate conditions that perpetuate further production of rills and gullies and associated runoff. Thus, within the context of ecological restoration, it is the interface between precipitation and vegetation that is of primary importance in understanding and mitigating the immediate concerns of rill and gully erosion and associated accretion of sediment in the lower reaches of Spanish Bank Creek. Due to the possible restoration implications of this relationship, I formulated the following research question:

*What is the relationship between canopy closure and precipitation throughfall at forested sites within the watershed of Spanish Bank Creek?*

## 2.3 METHODS

### *2.3.1 Hydrology*

Following the methods described in the United States Department of Agriculture's Urban Hydrology for Small Watersheds Technical Release 55 (Cronshey *et al.*, 1986), I calculated the peak rate of discharge for the watershed of Spanish Bank Creek. The formula used is as follows:

$$q_p = q_u * A_m * Q$$

where:

$q_p$: peak discharge

$q_u$: unit peak discharge

$A_m$: drainage area

Q: runoff

To ground-truth the accuracy of this model in calculating stream discharge, I measured flow velocity using a float on 24 March 2017. I measured flow velocity in two reaches in Spanish Bank Creek. To correct for stream bed roughness associated with sandy-gravel substrates, I multiplied the measured stream velocity by a correction coefficient of 0.85 (Hooper and Kohler, 2000). To obtain a stream discharge measurement, flow velocity was then multiplied by the stream cross-section (*2.4.6 Fish Habitat Assessment Procedure*).

*2.3.2 Vegetation*

Under the biogeoclimatic ecosystem classification system, the watershed of Spanish Bank Creek is classified as Coastal Western Hemlock very dry maritime, eastern variant (Forest Analysis and Inventory Branch, 2016). To quantify the current state of the composition of the forest throughout the ravine surrounding Spanish Bank Creek I delineated six transects on either side of the stream for a total of 12 transects. The transects were perpendicular to streamflow, and spanned the approximate width of the ravine of Spanish Bank Creek. Along each transect I recorded up to three dominant vegetative species at the tree layer (> 5 m height), as well as the shrub layer (< 5 m height). I also estimated canopy closure visually along each transect using the line-intercept method described by Bonham (2013). These estimates were then corrected using cover category mid-points to mitigate bias. Lastly, *Hedera* presence along the ground and within canopies of trees was estimated visually along each transect using a coding protocol (*Table 1*).

**Table 1**: Coding protocol for mapping *Hedera* along twelve transects throughout the ravine of Spanish Bank Creek. The first code, Not Detected through D, corresponds to percent ground cover of *Hedera* along a transect. The second code 0 through 4, corresponds to percent tree coverage of *Hedera* along a transect. An example code is B3, and would correspond to 38% ground cover, and 63% tree cover of *Hedera*.

| **Code 1** | **Code 2** | | |
|---|---|---|---|
| **% Ground Coverage** | **% Tree Coverage** | **% Interval** | **Cover Mid-points** |
| Not Detected | 0 | 0% | 0% |
| A | 1 | 0-25% | 12.5% |
| B | 2 | 26-50% | 38% |
| C | 3 | 51-75% | 63% |
| D | 4 | > 75% | 87.5% |

*2.3.3 Topography*

Rebar staking was conducted along the streambank of Spanish Bank Creek to quantify rates of erosion or accretion. Two 1.27 cm diameter rebar stakes were pounded into the forest floor on either side of Spanish Bank Creek along each of the 12 transects used for sampling vegetation (*2.3.2 Vegetation*). The distance from the farthest stake to the streambank was measured using an eslon tape, pulled tight along the forest floor. The second rebar stake between the farthest stake and the streambank was used as a guide to ensure that measurements were taken at a constant vector. The rebar was installed, and initial measurements were taken between 24 October and 4 November 2016. On 22 January 2017 measurements were taken for the second time to see if there were any changes to the streambanks of Spanish Bank Creek. Along these transects I also measured the distance from the streambank to the top of the ravine using my handheld Garmin Global Positioning System unit, as well as the slope using a clinometer.

Lastly, I walked the length of Spanish Bank Creek on 4 November 2016 and mapped the locations where runoff was entering the stream.

*2.3.4 Sediment Transport*

As mentioned in *2.4.3 Topography*, the results of the rebar staking and mapping of runoff inputs into Spanish Bank Creek indicate the downward movement of soils to lower elevations of the watershed. To quantify the rate of sediment loading into Spanish Bank Creek, I installed 15 sediment accumulators in Spanish Bank Creek. Before installation I drilled fifteen 0.16 cm holes into the bottom of each container and then filled them with clean 1.9 cm crushed gravel for drainage and to create void interstitial spaces. On 14 November 2016 the sediment accumulators were installed in Spanish Bank Creek at three locations throughout the length of the stream (*Figure 7*). Five of the accumulators were installed at each of the three locations, totalling 15 sediment accumulators. The tops of the containers were installed to be flush with the natural grade of the stream. At each of the three locations, the five containers were placed in a pentagon formation with approximately 40 cm between each of the containers.


**Figure 7**: Fifteen sediment accumulators were installed in Spanish Bank Creek. The sediment accumulators were installed in Spanish Bank Creek at locations denoted as top, middle, and bottom (left; QGIS Development Team, 2009). Five accumulators were installed at each of the locations, for a total of 15 accumulators (right; Reynolds, 2016).

On 30 December 2016 I collected the sediment accumulators from Spanish Bank Creek. To remove water weight from the samples I emptied the contents from each waterproof bag into individual baking dishes and baked the samples in the oven for 30 minutes at 230 °C. After 30 minutes I stirred the dish contents to homogenize the moisture gradient and then baked them for 15 more minutes. After the samples were removed from the oven I let them cool to room temperature. Once cooled I separated the 1.9 cm crushed gravel from the accumulated sediment and then weighed the individual samples using a digital scale that is accurate to 0.1 grams.

### *2.3.5 Water Quality*

Fisheries and Oceans Canada performed water quality sampling 17 times over 14 months between 2007 and 2008 at a low reach of Spanish Bank Creek. Specific methods of sampling and data collection are unknown. Other locations around UBC and Point Grey were also tested for comparison. The parameters tested included temperature, dissolved oxygen, and pH.

### *2.3.6 Fish Habitat Assessment Procedure*

A Fish Habitat Assessment Procedures (FHAP) Level 1 was conducted on 21 October 2016 (Adapted from Johnston and Slaney, 1996). I walked the length of Spanish Bank Creek and measured habitat type, gradient, bankfull depth, water depth, bankfull width, wetted width, bed material type, large woody debris (LWD), disturbance indicators, barriers to fish passage, and riparian vegetation parameters such as type, structure, and canopy closure. LWD is defined as being greater than 1 m in length, with a diameter greater than 0.1 m (Fetherston *et al.*, 1995). Parameters were measured using an eslon tape, wading staff, clinometer, and visual estimation. This data was then compiled in a Microsoft Excel spreadsheet.

### *2.3.7 Canopy Closure and Precipitation Throughfall*

I established three locations within the watershed of Spanish Bank Creek to collect canopy closure and precipitation throughfall data (*Figure 8*). At each of the three locations, six measurement sites were set up, for a total of 18 measurement sites. The measurement sites were set up in a two-by-three grid formation at each location, with 25 m between each site, as approximated by my handheld Garmin Global Positioning System unit.


**Figure 8**: From each of the three study locations, A, B, and C, I measured canopy closure and precipitation throughfall. Data was collected between 28 November 2016 and 4 December 2016 (QGIS Development Team, 2009).

I measured canopy closure at each of the measurement sites on 4 December 2016, using a spherical crown densiometer, facing each of the cardinal directions. On 28 November 2016 there was no precipitation in the forecast so I used this day to set up rain gauges at each of the measurement sites. The rain gauges were made out of empty two-liter soda bottles. The tops were cut off and then inverted into the body of the bottle to act as a funnel, and to minimize evaporation over the measurement period. Using elastic bands, I strapped the rain gauges to a 1.27 cm diameter rebar stake that was pounded vertically into the forest floor. Overhanging shrub vegetation was removed from the field of influence on the rain gauges so that the only vegetation effects on the quantity of throughfall collected were from the tree layer. On 4 December 2016 there was no precipitation in the forecast so I returned to collect my rain gauge data. The rain gauges were left out to collect precipitation throughfall for a total of 6 days, including the set-up and collection days. Using a 100 mL graduated cylinder I measured the quantity of throughfall that had collected in each of the rain gauges. I recorded this data in my field notebook where it was then transferred to a Microsoft Excel spreadsheet.

For canopy closure, 72 measurements were recorded using the spherical crown densiometer. Four measurements were recorded for each measurement sites corresponding to the four cardinal directions. The four measurements from each cardinal direction were averaged for each measurement site, resulting in mean canopy closure for each of the 18 measurement sites, expressed as a percent. For precipitation throughfall, 17 measurements were recorded. At location B, one of the rain gauges was found to be knocked over on the day of data collection. This data was therefore negated, resulting in five measurements of precipitation throughfall for location B, compared to six measurements at locations A and C. Precipitation throughfall at each measurement site is expressed in mL.

Statistical analysis was conducted using R version 3.3.2 and RStudio version 1.0.1.3.6. For data analysis I conducted a simple linear regression on untransformed data to validate the research hypothesis that increased canopy closure would result in decreased precipitation throughfall.

Using a significance level ($\alpha$) of 0.05 I performed the following test statistic:

$$F = MSreg / MSE$$

where:

MSreg: mean square of the regression

MSE: mean square of the error

The following hypotheses were tested:

$H_0$: $\beta = 0$

$H_1$: $\beta \neq 0$

## 2.4 RESULTS AND DISCUSSION

### *2.4.1 Hydrology*

The watershed model yielded a two-year peak discharge of 0.13 $m^3/s$. When this value is divided by the mean cross-section of Spanish Bank Creek (*2.4.6 Fish Habitat Assessment Procedure*), the result is a two-year peak flow of 0.8 m/s.

The float method of flow velocity measurement yielded a mean flow velocity of 1.95 m/s. When multiplied by the 0.85 correction coefficient, the result is a corrected flow velocity of 1.66 m/s. Multiplying this value by the mean cross-section of Spanish Bank Creek as determined in *2.4.6 Fish Habitat Assessment Procedure*, this yields a discharge of 0.26 $m^3/s$. This measured discharge is two times greater than the two-year peak discharge calculated using the watershed model previously used. Therefore, either the model is unable to accurately calculate the input parameters of Spanish Bank Creek, or I significantly underestimated the drainage area and drainage inputs that enter the stream. An assumption I made for the two-year peak discharge calculation was that the drainage area does not include the University Golf Course or any other areas south of the residential area of Little Australia. I made this assumption because it is unknown how much water the golf course uses for irrigation. However, it is likely that there is a robust watering and drainage system for the entirety of the golf course. There is also known to be groundwater input into Spanish Bank Creek. Thus, the difference between the calculated two-year peak discharge (0.13 $m^3/s$) and the measured discharge (0.26 $m^3/s$) is likely derived from the University Golf Course irrigation and groundwater inputs into Spanish Bank Creek.

Historically the hydrologic inputs into Spanish Bank Creek were derived from precipitation due to being located within a dense forest. In Vancouver, the annual precipitation is approximately 1200 mm (Hambly *et al.*, 2012). Precipitation that does not infiltrate into the forest floor produces surface runoff. This can be problematic because water is commonly one of the principal causes of soil erosion in various ecosystems (Luffman *et al.*, 2015). In the 1920s and 1930s, encroaching urbanization from the University Golf Course and Little Australia altered the drainage patterns within the watershed (*1.6.2 Urban Encroachment*). Currently, there are three culvert outfalls that drain into the watershed of Spanish Bank Creek (*Figure 9*). The primary culvert input of Spanish Bank Creek is a 341.6 m-long culvert that discharges just north of Chancellor Boulevard. This culvert receives inputs from the University Golf Course, and also drains 12.8 ha of Little Australia (A. Galbraith, personal communication, 25 November 2016). In addition, this culvert has penetrated the groundwater table somewhere along its 341.6 m length. This is supported by results from water quality testing (*2.4.5 Water quality*). A secondary culvert drains the north-west corner of Little Australia. This culvert outfall terminates at a ditch just north of Chancellor Boulevard, and the water drains into the forest. The water from this culvert appears to infiltrate into the forest floor except during significant or sustained rainfall events, where a rill has formed in the forest floor. Where this rill meets the steeper slopes of the ravine of Spanish Bank Creek a gully has formed. A third culvert drains a 4.7 ha park that is just north of Little Australia. Just below this culvert's outfall the forest floor is a mosaic of concrete slabs that were probably placed there in an attempt to mitigate erosion (Kahrer, 1991). As a result of these culverts directing storm water in the watershed, discharge in Spanish Bank Creek is tightly coupled to precipitation events. This has led to concerns regarding water quality associated with storm water and golf course drainage (DFO, 1999).

**Figure 9**: Three culverts drain into the watershed of Spanish Bank Creek. These culverts are indicated by the dashed lines. The polygons indicate the approximate areas that the culverts drain and are paired to the culverts according to colour. The yellow polygon is 12.8 ha, and the purple polygon is 4.7 ha (QGIS Development Team, 2009).

*2.4.2 Vegetation*

For the shrub layer (< 5 m height), the dominant primary species recorded was deer fern (*Blechnum spicant*), the dominant secondary species was Bigleaf maple (*Acer macrophyllum*), and the dominant tertiary species was again deer fern. For the tree layer (> 5 m height), the dominant primary species recorded was equally western hemlock (*Tsuga heterophylla*) and Bigleaf maple. The dominant secondary species was Bigleaf maple, and the dominant tertiary species was alder (*Alnus spp.*). After applying the cover category mid-points for each canopy closure measurement, mean canopy closure was 40%, with a range of 12.5 – 63%.

*Hedera* was present along nine of the twelve transects sampled throughout the watershed (*Figure 10*). Of these nine transects, *Hedera* was present in the tree layer along seven transects. This means that *Hedera* was found along 75% of the transects, and was in the canopies of trees along 58% of the transects. Of the transects with *Hedera* present, 78%

had *Hedera* in the canopies of at least one tree. This indicates *Hedera* has a tendency to climb trees once it has established as ground cover.


**Figure 10**: *Hedera* was mapped along transects through the ravine of Spanish Bank Creek on 30 November 2016. Transects are colour coded corresponding to percent ground cover of *Hedera* along transects. Tree coverage of *Hedera* is labelled as a percent or not detected (QGIS Development Team, 2009).

### *2.4.3 Topography*

The sum of streambank change from the rebar staking was accretion by 3.9 cm, with a mean of 3.3 cm. Values ranged from -4.0 to 11 cm. Nine of the 12 streambanks indicated accretion rather than erosion. Therefore, over the measurement time period, it is likely that upslope sediments were transported down the ravine to the banks of Spanish Bank Creek at a greater rate than the stream could erode and mobilize the sediments from the streambank (*Figure 11*). Mean slope on the east bank of the ravine was 75%, and on the west bank it was 78%. The total area of the ravine was measured at approximately 12 ha, and extends approximately 70 m on either side of Spanish Bank Creek. The topography of the watershed beyond the steep slopes of the ravine is undulating as is typical of glacially formed landforms (GVRD, 1991).

**Figure 11**: Soils throughout the watershed are eroded and transported to lower elevations. An upturned root wad from a downed tree exemplifies the sandy soils throughout the watershed of Spanish Bank Creek (left). Significant supply of sediment modifies channel morphology (right; Reynolds, 2016).

One limitation and possible source of error in the rebar staking method is that there is no way of regulating the microtopography between the stakes and the streambank. Thus, pulling the eslon tape tight over the forest floor could yield various results based on changes to presence or absence of small woody debris and vegetation between measurements.

Rills and gullies that flow into Spanish Bank Creek are the most common erosional formation that is present within the watershed. In conjunction with soil erosion, there is a subsequent redistribution of sediment to a lower elevation of the watershed that can negatively affect ecological structure and function of terrestrial and aquatic ecosystems. Some of the ways that eroding landscapes can affect forested ecosystems are by steepening topography, limiting moisture and nutrient storage and availability, and reducing rates of weathering (Milodowski *et al.*, 2015; Shen *et al.*, 2017). These characteristics of eroding landscapes negatively affect vegetative communities, thereby perpetuating further soil erosion.

From the streambank mapping, total of 34 inputs were identified (*Figure 12*). Of these 34 inputs, 32 were derived from runoff, and two were derived from drainage pipe outfalls that drain into Spanish Bank Creek. The 32 runoff inputs were likely derived from upslope rills and gullies that are present throughout the watershed. The majority of these rills and gullies are located a significant distance from culvert outfalls. This indicates that the hydrological input that is causing these rills and gullies and associated runoff inputs is derived from precipitation.

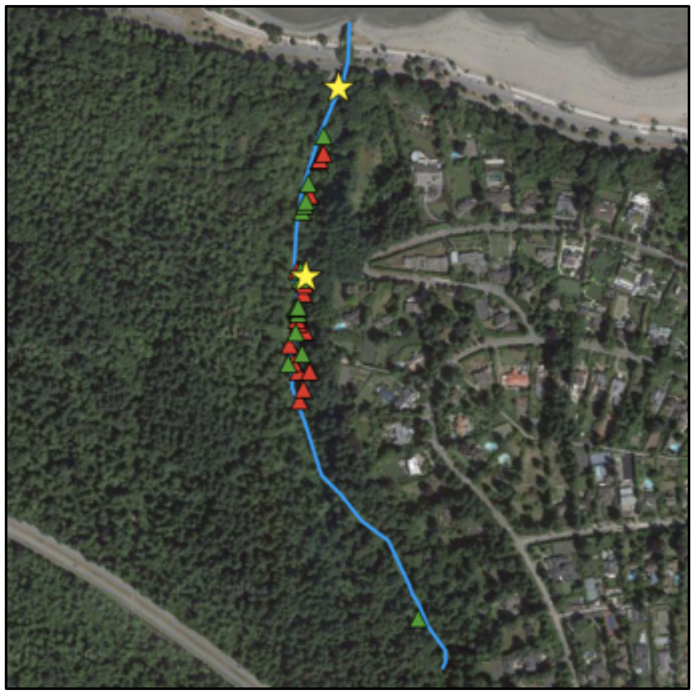

**Figure 12**: A map of inputs into Spanish Bank Creek. Green triangles represent the 14 runoff inputs from bank left, red triangles represent the 18 runoff inputs from bank right. Yellow stars represent the two drainage pipe inputs into Spanish Bank Creek. Field work was conducted on 4 November 2016 (QGIS Development Team, 2009).

### *2.4.4 Sediment Transport*

The mean weights from the top, middle, and bottom sampling stations were 327.2, 290.8, and 340.4 g respectively (*Table 2*). Values ranged from 264.1 – 417.1 g for the top sampling location, 252.7 – 327.1 g for the middle sampling location, and 270.5 – 415.3 g for the bottom sampling location. The mean of the entire sampling set was 319.5 g, with a range of 252.7 – 417.1 g. The bottom sampling location had the largest mean of the three locations. Logically this is expected because a lower reach of a stream generally has a larger input drainage area compared to a higher reach of a stream.

**Table 2**: Results of the sediment accumulator sampling of sediment deposition in Spanish Bank Creek. Sediment accumulator 5 could not be located when collecting data, as indicated by NA* in the data table. Results are in grams.

| Sample | Top (g) | Middle (g) | Bottom (g) |
|---|---|---|---|
| 1 | 291.3 | 311.0 | 270.5 |
| 2 | 357.9 | 327.1 | 415.3 |
| 3 | 417.1 | 252.7 | 342.7 |
| 4 | 264.1 | 272.4 | 332.0 |
| 5 | 305.8 | NA* | 341.3 |
| **Mean (g)** | **327.2** | **290.9** | **340.4** |
| **Total Mean (g)** | | | **319.5** |

Spanish Bank Creek is 1.025 km long, and has an average wetted width of 1.74 m (*2.4.6 Fish Habitat Assessment Procedure*). This means that Spanish Bank Creek has a surface area of 17.8 km$^2$. Each of the sediment accumulators has a surface area of 0.0089 m$^2$ (8 cm wide, 11.5 cm long, and rounded corners with a radius of 2 cm). Assuming that the mean of the 14 sediment accumulators (319.5 g) is a representative sample of actual bed accumulation, this means that over 46 days (15 November 2016 to 30 December 2016), 639 t of sediment was accumulated in Spanish Bank Creek. For each day of the study period this equals approximately 13.9 t of sediment.

Assuming that sand has a bulk density of 1600 kg/m$^3$, this corresponds to a 2.2 cm-deep accumulation of sand over the entire surface area of Spanish Bank Creek. It is possible that actual sediment accumulation is even greater than sediment accumulation that was measured. Sediment particles may be in a constant state of entrainment such that it appears as though significant deposition of sediment is occurring; however, the majority of the sediment will not be deposited until flow velocity decreases at lower reaches. Sediment may completely fill a sediment accumulator as a precipitation event mobilizes sediment into Spanish Bank Creek, but once the sediment has been moved to a lower reach the particles deposited in the accumulator may immediately become entrained and transported again. This is termed re-suspension due to turbulence within the accumulators (Hedrick *et al.*, 2013).

Soils throughout the watershed of Spanish Bank Creek appear to be largely composed of glaciofluvial sands (*Figure 11*; GVRD, 2000; Clague *et al.,* 1998; Clague, 1975). As described in the Udden-Wentworth scale of particle sizes, these glaciofluvial particles are likely between 0.5 – 2 mm in diameter (coarse sand to very coarse sand; *Figure 13*, left). According to the Hjulstrom curves (*Figure 13*, right), mean flow velocities greater than approximately 0.1 m/s will entrain nearly all particles within this diameter interval.

| Classification | Particle Size (Diameter mm) |
|---|---|
| Boulder | > 256 |
| Cobble | 64 - 256 |
| Pebble | 4 - 64 |
| Gravel | 2 - 4 |
| Very coarse sand | 1 - 2 |
| Coarse sand | 0.5 - 1 |
| Medium sand | 0.25 - 0.5 |
| Fine sand | 0.125 - 0.25 |
| Very fine sand | 0.062 - 0.125 |
| Silt | 0.004 - 0.062 |
| Clay | < 0.004 |

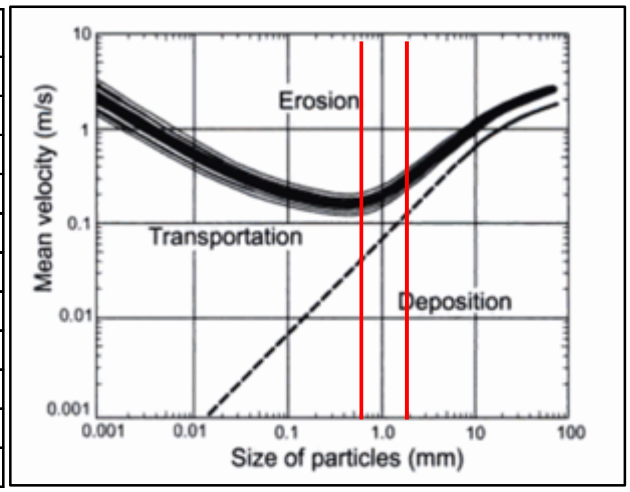


**Figure 13**: The Udden-Wentworth scale and Hjulstrom curves (Wentworth, 1922; Gordon *et al.*, 2004). The Udden-Wentworth scale of particle size classification (left), indicates that the sandy soils around Spanish Bank Creek are likely 0.5 – 2 mm in diameter. According to the Hjulstrom curves (right), particles of these dimensions, as illustrated between the vertical red lines, will be transported or eroded by flow velocities greater than approximately 0.1 m/s.

This suggests that most of the upslope soils that enter Spanish Bank Creek are in a state of entrainment until particles settle at the shallower grades of the lower reaches. This means that measured sediment accumulation is only a portion of the total sediment accumulation throughout Spanish Bank Creek.

Flow velocity was measured at 1.66 m/s on 24 March 2017. According to the Hjulstrom curve, this flow velocity would transport or erode particles up to approximately 50 mm in diameter. On the Udden-Wentworth scale this corresponds to particles in the pebble size classification. As recorded at the Vancouver International Airport, there was 6.6 mm of precipitation on 24 March 2017 (Environment Canada, 2017a). From the 1981 to 2010 Canadian Climate Normals weather station at UBC, mean precipitation for the month of March was 195.1 mm (Environment Canada, 2017b). This corresponds to a daily precipitation mean of 6.3 mm. If flow velocity is primarily a function of precipitation inputs into Spanish Bank Creek, then it is likely that flow velocities of 1.66 m/s are typical during the month of March.

Presence of extensive sediment aggradation throughout the lower reaches of Spanish Bank Creek indicates a significant input of soil into the stream, and that the sediment budget is in disequilibrium. Furthermore, this suggests that sediment transport dynamics within Spanish Bank Creek are capacity-limited rather than supply-limited (Gray and Simões, 2008), where capacity refers to the maximum sediment size that can be mobilized by flow velocity. Simply, the rate of sediment supply is greater than the rate of sediment transport out of Spanish Bank Creek into Burrard Inlet. Understanding this dynamic relationship between sediment supply and capacity is important within the context of restoring the watershed-scale functions and structures that will regulate sediment dynamics and mitigate significant aggradation.

### *2.4.5 Water Quality*

From the 17 samples, temperature in Spanish Bank Creek was significantly cooler than temperatures recorded at three nearby storm drains over the 14 months (*Figure 14*). Mean temperature in Spanish Bank Creek was 9.0 °C, with a range of 3.9 – 12.9 °C. Mean water temperature measured at three nearby storm drains was 17.6, 18.5, and 17.2 °C, and ranged from 10.5 – 22.1 °C. These results indicate that it is likely that there are groundwater inputs into Spanish Bank Creek that moderate stream temperature year-round. This is supported by the fact that Spanish Bank Creek flows year-round despite a lack of precipitation inputs throughout many summer months.

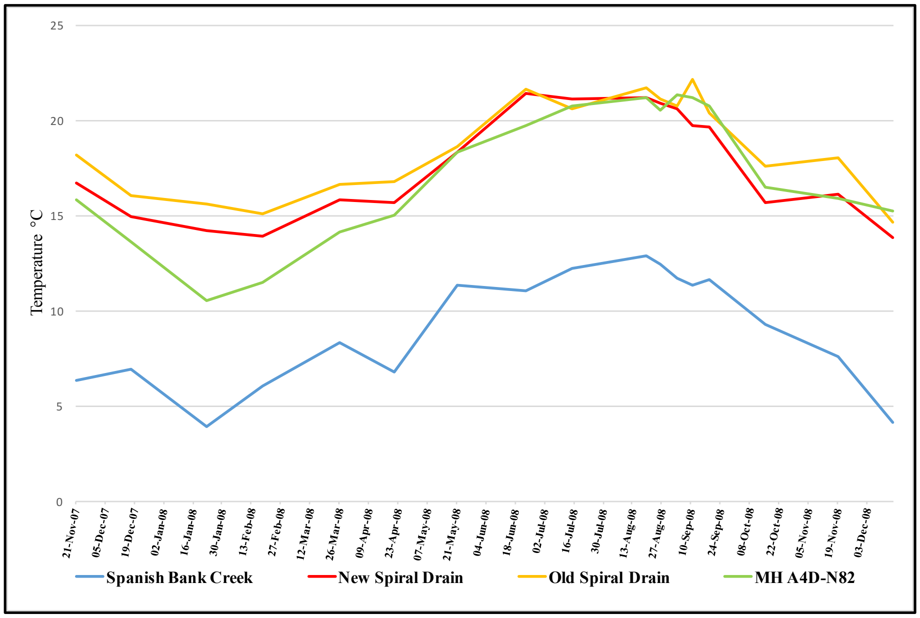


**Figure 14**: Temperature measured in Spanish Bank Creek and three nearby sites from November 2007 to December 2008**.**

In terms of the biological thresholds of potential salmonids in Spanish Bank Creek, the temperatures recorded were within both the upper and lower lethality limits, and approximately a third of the year (June to September 2008) was within the preferred temperature range for all three species of salmonids (*Table 3*).

**Table 3**: Lower and upper lethal temperature limits for chum, coho, and cutthroat salmonids (Bjornn and Reiser, 1991). Over the measurement period from November 2007 to December 2008, temperatures in Spanish Bank Creek stayed within the upper and lower lethal temperature limits for these three species of salmonids.

| Species | Lower Lethal Limit (°C) | Upper Lethal Limit (°C) | Preferred Range (°C) |
|---|---|---|---|
| chum salmon | 1.7 | 26.0 | 12.0 – 14.0 |
| coho salmon | 0.5 | 25.4 | 12.0 – 14.0 |
| cutthroat trout | 0.6 | 22.8 | 10.0 – 13.0 |

The mean pH recorded in Spanish Bank Creek was 7.3, with a range of 6.4 to 7.5 (*Figure 15*). The optimal pH range for Pacific salmon is between 6.5 – 8.5 (OWEB, 1999). Only one measurement was below the optimal lower limit between 2007 and 2008. This indicates that pH within Spanish Bank Creek from November 2007 to December 2008 was not a limit to production for salmonids. Lastly, each pH measurement from Spanish Bank Creek was less than pH measured at each of the other three storm drains. This is explained by the fact that many forests are characterized by acidic soils due to decomposition of organic matter (Forestry Commission, 2011).

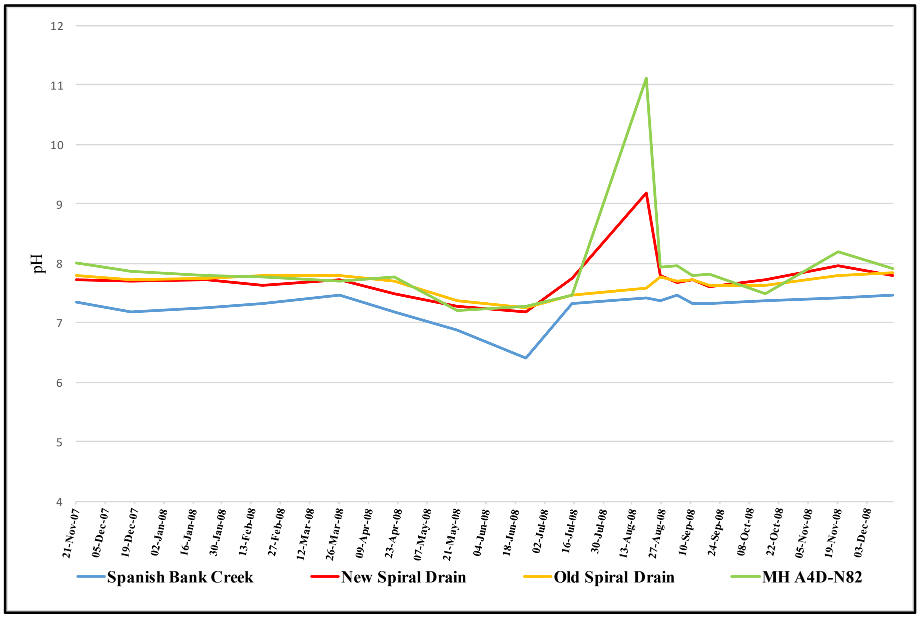


**Figure 15**: pH measured in Spanish Bank Creek and three nearby sites from November 2007 to December 2008.

Mean dissolved oxygen measured in Spanish Bank Creek was 10.8 mg/L, with a range of 9.7 – 12.0 mg/L (*Figure 16*). Salmonid embryos display slight production impairment below 9.0 mg/L (Carter, 2005). This means that levels of dissolved oxygen in Spanish Bank Creek from November 2007 to December 2008 were well within the optimal range for salmonids.

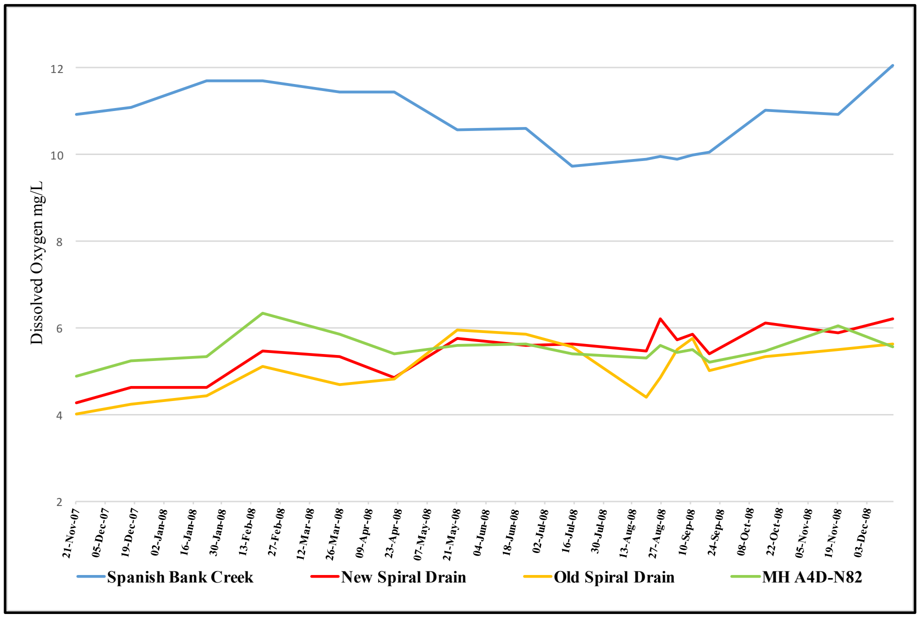


**Figure 16**: Dissolved oxygen measured in Spanish Bank Creek and three nearby sites from November 2007 to December 2008.

From November 2007 to December 2008, dissolved oxygen measured in Spanish Bank Creek was significantly greater than dissolved oxygen measured in the three nearby storm drains. This is likely due to the extensive riffle zones throughout Spanish Bank Creek (*2.4.6 Fish Habitat Assessment Procedure)* that aerate the flowing water.

It is unknown whether significant changes within the watershed of Spanish Bank Creek have occurred between 2008 and 2017 that would affect temperature, pH, and dissolved oxygen throughout Spanish Bank Creek.

*2.4.6 Fish Habitat Assessment Procedure*

The dominant morphological unit of Spanish Bank Creek was riffle zones, with a mean gradient of 2.6% and a range of 1 – 3.5%. The mean bankfull water depth was 0.35 m with a range of 0.25 – 0.60 m, and the mean water depth was 0.09 m with a range of 0.02 – 0.17 m. The mean bankfull width of the stream recorded was 3.25 m with a range of 1.45 – 5.35 m, and the mean wetted width was 1.74 m with a range of 0.40 – 2.85 m. The dominant and sub-dominant bed materials were sand and gravel, respectively.

The average number of LWD pieces per reach was 12, with a range of 1 – 22 pieces per reach. In terms of the proportions of the LWD in each of the diameter categories, 47% of LWD was between 20 – 50 cm, 37% was between 10 – 20 cm, and 16% was greater than 50 cm. The three most common disturbance indicators in Spanish Bank Creek were eroding banks, extensive riffle zones, and extensive sediment wedges at the margins of the stream. The dominant riparian vegetation was at the shrub stage, with an average estimated canopy closure of 24%. The range estimated for canopy closure was 10 – 40%.

There were three potential barriers to fish passage identified within Spanish Bank Creek. The first potential barrier is at the mouth of Spanish Bank Creek (*Figure 17*). Access to Spanish Bank Creek from Burrard Inlet is only possible during high tides.

**Figure 17**: Oceanic tides render Spanish Bank Creek inaccessible except during high tides. At low tide the ocean recedes several kilometers and Spanish Bank Creek is inaccessible (left). Only at high tides is Spanish Bank Creek accessible from Burrard Inlet (right; Reynolds, 2016)

Following the recommendations of Page and Eymann (1994), restoration to the lower reaches of Spanish Bank Creek was conducted to re-grade the mouth of the stream to 4.7 m above chart datum. This means that between September to December (approximately when Pacific salmon return to their natal streams) 2016, 21% of the total days had a high tide that was equal to or greater than 4.7 m chart datum (*Table 4*). Assuming a water depth of 0.1 m (mean of 0.09 m during FHAP Level 1) flowing out from Spanish Bank Creek, 38% of the total days had a high tide that was equal to or greater than 4.6 m chart datum.

**Table 4**: Access to Spanish Bank Creek during chum and coho spawning months was limited in 2016. Denoted below are the number of days from September to December 2016 that had high tides that were greater than or equal to 4.6 and 4.7 m above chart datum.

| **Relative to Chart Datum** | **2016** | | | | |
|---|---|---|---|---|---|
| | **September** | **October** | **November** | **December** | **% of Total Days** |
| >/= 4.6 m | 2 | 7 | 12 | 25 | 38% |
| >/= 4.7 m | 0 | 0 | 7 | 18 | 21% |

The second possible impediment to fish passage was identified at the lower reaches of Spanish Bank Creek below NW Marine Drive (*Figure 18*). As Spanish Bank Creek is aggrading at the lower reaches (*2.4.4 Sediment Transport*).

**Figure 18**: The lower reaches of Spanish Bank Creek have been filled with sediment. Installed in 2000, the concrete box culvert pictured above is 6 m long, 1.2 m tall, and 1.8 m wide (left; Hollick-Kenyon, 2002). After 16 years only a fraction of the culvert is passable due to build-up of sediments (right; Reynolds, 2016).

The culvert pictured above is 1.2 m tall and 1.8 m wide. Assuming that the culvert was installed to 1978 British Columbia culvert design guidelines of installation of the culvert 0.31 m below grade (Dane, 1978), 26% of the culvert cross-section would have been buried in the substrate. I recorded measurements of the north and south end of the culvert on 3 March 2017. On the south end of the culvert, approximately 50% of the width of the culvert has been blocked by a cedar stump that is buried in the substrate. In the thalweg to the right of the stump the distance from the substrate to the top of the culvert was 0.6 m. This corresponds to approximately 75% of the culvert cross-section being buried in sediment or blocked by the cedar stump.

At the north end of this culvert the distance from the substrate to the top of the culvert was 0.27 m. This corresponds to 78% of the culvert being buried in the substrate. If the culvert was installed 0.31 m below grade (Dane, 1978), then the height from the substrate to top of the culvert would have been 0.89 m. The current measurement of 0.27 m means that 0.62 m of sediment has aggraded over the last 17 years since installation. Water depth at the north end of the culvert was measured at 0.04 m, thereby constituting a possible barrier to adult returning salmon. If the cedar stump was not blocking approximately 50% of the south end of the culvert then it is likely that the distance from the substrate to the top of the culvert, as well as water depth would be more similar to measurements recorded from the north end of the culvert.

Approximately 20 m upstream from the concrete box culvert is a wood stave culvert that is 0.90 m in diameter and 20 m in length. This culvert extends under NW Marine Drive. The downstream (north) end of the culvert terminates at a pre-cast concrete headwall (*Figure 19*). Access to the culvert has been impeded by accretion of sediment. Measured on 16 March 2017, the height from the thalweg substrate to the top of the inside edge of the culvert was 0.40 m. This corresponds to 43% of the total cross-sectional area of the culvert that is passable by fish. This measurement assumes that the thalweg is a representative depth for all measurements along the profile of the substrate within the culvert. However, the thalweg typically scours into the substrate, resulting in deeper water depths compared to stream sections not within the thalweg. Therefore, it is probable that there is less than 43% of the total cross-section of the culvert that is passable by fish. If the culvert was installed to 1978 British Columbia culvert design guidelines (Dane, 1978) and the culvert was installed 0.31 m below grade, then 70% of the total cross-sectional area of the culvert was initially passable by fish. Compared to this design parameter, only 61% of the cross-sectional area of the culvert is now passable by fish.

**Figure 19**: A pre-cast concrete headwall was installed at Spanish Bank Creek. The pre-cast concrete headwall is located at the north end of the wood stave culvert that spans under NW Marine Drive (left). Accretion of sediment has filled in the lower reaches of Spanish Bank Creek, thereby impeding flow through the wood stave culvert (right; Reynolds, 2016).

Lastly, due to the greater stream velocities associated with winter precipitation events it is likely that some the sediment at the mouth of the culvert was washed out around the approximate time of measurement. Over the summer low-flow months, decreased stream velocities result in less tractive forces entraining and washing out sediments, thereby resulting in a potentially greater proportion of the culvert that is blocked by sediment. To fully understand how culverts with impeded flow respond to changing watershed conditions will require monitoring (*3.6.4 Culvert Metrics*).

### *2.4.7 Canopy Closure and Precipitation Throughfall*

Mean canopy closure was 50% across all measurement sites with a range of 7 – 84%. Mean precipitation throughfall was 359 mL, with a range of 159 – 684 mL. Histograms indicate that residuals were approximately normally distributed, with no apparent heteroscedasticity (*Figure 20*). The p-value for the F-statistic was less than 0.05 (*Table 5*). Thus, the null hypothesis can be rejected. The calculated $R^2$ coefficient value was 0.4. These results indicate that the relationship between canopy closure and precipitation throughfall is significant, and that the linear regression model accounts for approximately 40% of the variability in the data. In addition, these results suggest a negative relationship between canopy closure and precipitation throughfall. As canopy closure increases, precipitation decreases (*Figure 21*).

**Table 5**: ANOVA of the regression model and residuals for canopy closure and precipitation throughfall data that was collected in the fall of 2016.

| | **df** | **SS** | **MS** | **F** | **Significance F** |
|---|---|---|---|---|---|
| Regression | 1 | 126583.1131 | 126583.113 | 10.1494951 | 0.006139412 |
| Residual | 15 | 187077.9458 | 12471.8631 | | |
| Total | 16 | 313661.0588 | | | |

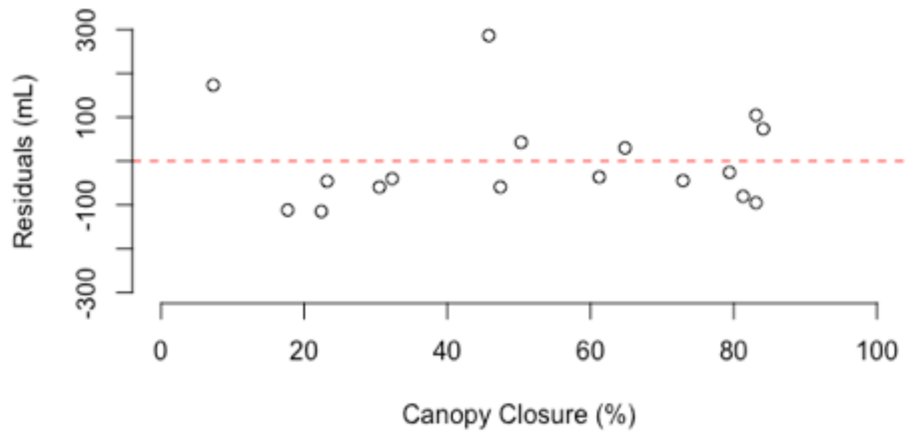


**Figure 20**: A plot of residuals indicates that data is approximately normally distributed, with no apparent heteroscedasticity.

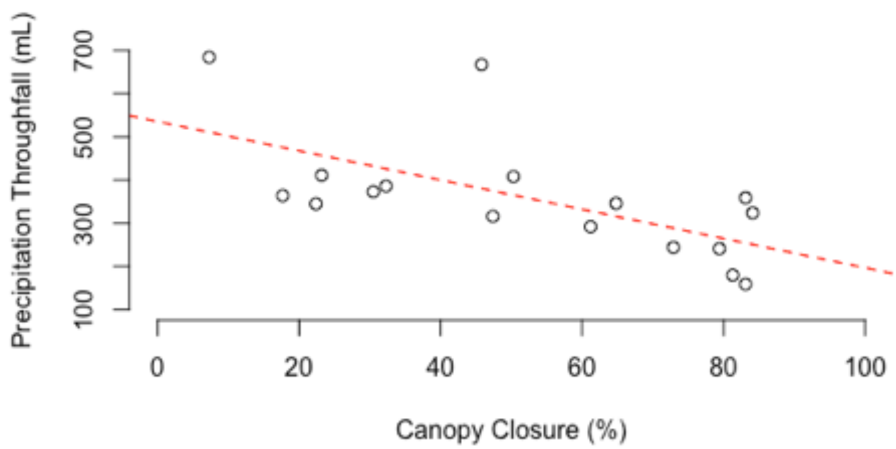


**Figure 21**: A plot of the relationship between canopy closure and precipitation throughfall, as measured at the three locations, A, B, and C, in the watershed of Spanish Bank Creek.

Based on Thompson's (1985) study conducting field surveys to map the vegetation associations throughout the PSRP we can relate vegetation associations to the canopy closure and precipitation throughfall results (*Table 6*).

**Table 6**: At the three measurement locations, as the vegetation associations increase (towards late succession species assemblage), canopy closure increases and precipitation throughfall decreases. While this is an interesting trend, the sample size is too small to draw meaningful conclusions.

| Location | Canopy Closure (%) | Precipitation Throughfall (mL) | Association (Thompson, 1985) | Association Title (Thompson, 1985) |
|---|---|---|---|---|
| A | 48.8 | 406.7 | 6 | Vine maple – red elderberry |
| B | 20.4 | 430.4 | 2 | Red alder - salmonberry |
| C | 80.6 | 251.2 | 10 | W. hemlock – *Mnium glabrescens* |

While my data was collected in the fall (28 November 2016 to 4 December 2016) when deciduous trees lose their leaves, this is an ideal time of the year to conduct this research. Vancouver experiences the greatest volume and intensity of rainfall during the fall and winter months. Therefore, it is in the fall and winter that the watershed of Spanish Bank Creek would experience the most runoff and associated erosion. This is supported by findings from a study conducted in North Vancouver in 2007 and 2008 (Asadian, 2010). In this study, gross precipitation was partitioned into interception, stemflow, and throughfall for common Vancouver, BC tree species. Results indicate that coniferous tree species divert 46.6% of gross precipitation as interception and stemflow during the winter, and 64.5% of gross precipitation during the summer. Deciduous tree species divert 25.1% of gross precipitation as interception and stemflow during the winter, and 42.4% of gross precipitation during the summer. Comparison between coniferous and deciduous trees during winter months indicates that 21.5% of gross precipitation could be diverted from directly falling on the forest floor by facilitating succession from a deciduous forest to a coniferous forest. This would decrease the amount of energy impacting the forest floor as rainsplash erosion, and would increase the hydraulic retention time of the watershed.

# CHAPTER 3: RESTORATION

## 3.1 ECOLOGICAL TRAJECTORY

Currently, the ecological trajectory of the watershed of Spanish Bank Creek is at a disturbed ecological state due to the compounding effects of various invasive species dominating the landscape and hydrologic alterations that increase storm water runoff. These ecological stressors have degraded the vegetation and soils of the watershed, thereby producing conditions that support erosion. Erosion can function as a bottom-up control on aboveground biomass and forest structure (Milodowski *et al.*, 2015). Generally, vegetation mitigates erosion by enhancing shear strength of the soil with rooting structures, increased soil infiltration, decreased rates of runoff, and intercepting precipitation (Shen *et al.*, 2017). Thus, a degraded forest state can contribute to erosion, resulting in a further degraded vegetation composition. A positive feedback loop has the potential to develop between soil erosion and vegetation degradation.

In 1983 and 1984, Thompson (1985) conducted field surveys throughout the PSRP to determine the vegetative associations within the park. Twenty associations were identified and mapped (*Figure 22*). The numbers 1 – 13 correspond to vegetative associations ranking from early succession to late succession.


| Association | Title |
|---|---|
| **1** | hardhack - salmonberry - fireweed |
| **2** | red alder - salmonberry |
| **3** | bitter cherry - willow - trailing blackberry |
| **4** | bigleaf maple - spiny wood fern |
| **5** | cascara - mountain ash - deer fern |
| **6** | vine maple - red elderberry |
| **7** | red alder - western red cedar - red huckleberry |
| **8** | Douglas-fir - bracken -*Stokesiella oregana* |
| **9** | Douglas-fir - salal -*Plagiothecium undulatum* |
| **10** | western hemlock - *Mnium glabrescens* |
| **11** | western red cedar - English holly |
| **12** | western hemlock - Douglas-fir -*Stokesiella praelonga* |
| **13** | western red cedar - western hemlock - sitka spruce |

**Figure 22**: Vegetation associations throughout the PSRP were mapped in 1982 and 1983 by Thompson (1985; left). Within the watershed of Spanish Bank Creek, these associations range from hardhack, salmonberry, and fireweed (1) to western hemlock, *Mnium glabrescens* (10; right; Thompson, 1985).

A similar survey to Thompson (1985) was conducted in 2007 to assess changes to the vegetation within the PSRP (Super *et al.*, 2013). The results of the second iteration of surveys indicate that throughout the entire park, succession is occurring moderately slowly. This is a common phenomenon, as urban impacts often arrest or modify successional trajectories (Matlack, 1997). As described by Suding and Hobbs (2009), ecosystems are the expression of a multitude of non-linear functional and structural dynamics. Impacts, anthropogenic or otherwise, can produce unexpected changes and can result in an ecosystem crossing thresholds from which recovery is challenging (Polster, 2014).

## 3.2 DESIRED FUTURE CONDITIONS

Over the last century and a half, the watershed of Spanish Bank Creek has experienced significant disturbance from logging and urbanization that has altered the vegetation and hydrology. The historic old-growth forest has been largely replaced by species typical of earlier successional stages and invasive species such as *Hedera*. This, in combination with an altered watershed hydrology, exacerbates storm water runoff and erosional processes. A major consideration when performing restoration is determining what ecological state to restore to. Ecosystems are dynamic and constantly changing, thereby producing a variable suite of conditions (Walker *et al.*, 2007). Thus, attempting to restore the watershed of Spanish Bank Creek to a specific set of conditions in space and time is particularly challenging, especially considering the proclivity of urban watersheds for novel or hybrid species assemblages (Hobbs *et al.*, 2009). Instead, restoration effort should be focused on restoring ecosystem function and structure that will in turn produce favourable ecological conditions (Clewell and Aronson, 2013). To construct favourable conditions in the watershed of Spanish Bank Creek without addressing the true filters to recovery (i.e., *Hedera* and hydrologic alteration), is analogous to a doctor treating symptoms rather than causes of symptoms. In consideration of this, a restoration goal and associated objectives were formulated in the following section that will initiate a successional trajectory and mitigate harmful impacts from over 150 years of logging and urban encroachment in the watershed.

## 3.3 GOALS AND OBJECTIVES

### *3.3.1 Goal 1: Restore the Forest to a Resilient, Self-replacing Native Composition*

To achieve this goal, first we must understand what these terms mean. Resilience is the ability of an ecosystem to absorb disturbances or stressors without a dramatic alteration to ecological function or structure (Holling, 1973). Ecosystems have a limit to their resilience, and once the thresholds of resilience have been exceeded, ecosystems shift to an alternate expression of function and structure. Restoring a measure of resilience to ecosystems is fundamentally important for any successful restoration project, especially in an urban context such as the watershed of Spanish Bank Creek, with spatially and temporally extensive ecological stressors (*1.7 Ecological Stressors: Filters to Recovery*).

However, in conjunction with a resilient forest, vegetation in the watershed must be restored towards a self-replacing native composition. Successful restoration can be described as initial physical enhancement such that further restoration can be replaced by self-sustaining biological processes (Tongway and Ludwig, 2011; *Figure 23*). In ecology, this is the definition of self-replacement. Invasive species commonly alter species composition, biodiversity, structure, function, and trophic cascades such that self-sustaining biological processes are severely impaired (Polster, 2014). Thus, removal of invasive species is a prerequisite to achieving an ecological state of self-replacement.

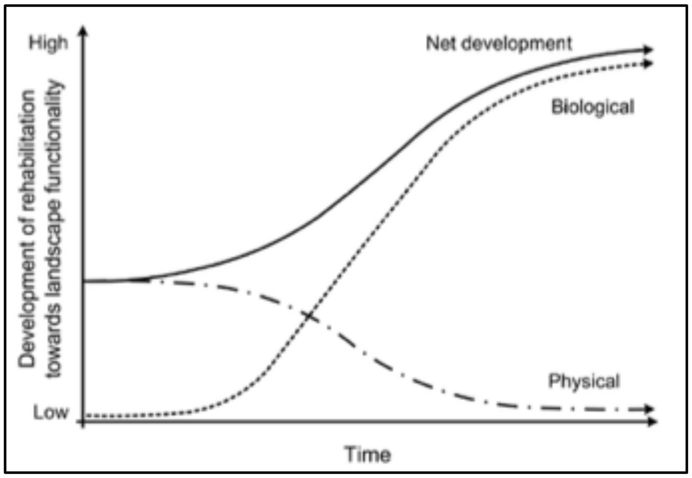


**Figure 23**: Restoration is often described as physical enhancement such that biological processes can eventually continue the restoration process (Tongway and Ludwig, 2011). Net ecological development continues after physical enhancement ceases.

### *3.3.2 Objective 1: Reduce Hedera in Tree Canopies Throughout the Watershed of Spanish Bank Creek*

Some of the possible control methods for *Hedera* include manual removal, prescribed burning, insects and fungi, grazing, and chemical application (Reichard, 2000). There is a lack of significant literature investigating best management practices of these control methods, as well as a lack of discussion regarding results over long-term trials. However, several of these methods are not suitable for the watershed of Spanish Bank Creek. Prescribed burning is not recommended due to close proximity to residential and recreational areas. Use of insects and fungi to control *Hedera* have not been studied enough to warrant consideration. The palatability and success of grazing animals in controlling *Hedera* has been documented (Ingham and Borman, 2010). They found that goat browsing caused a significant decline in *Hedera* over two years. This is a treatment possibility that warrants future consideration, however I have concerns regarding coyote dens in the project site, as well as the fact that a group of goats roaming through the watershed would disturb and mobilize a large volume of soil on the already unstable slopes of the ravine. Chemical application has been documented as a successful control method. However, it is not recommended due to the high annual rainfall and susceptibility of native species within the watershed to deleterious effects of various chemicals. Furthermore, the watershed and estuary are high-use recreational areas for humans and their pets. Lastly, manual removal of *Hedera* can be conducted by two main methods. The first is pulling the plant from the forest floor, and the second is cutting the vines that grow vertically up the trunks of invaded trees. Cutting these vines rapidly kills the portions of *Hedera* that are in the tree (Reichard, 2000). This second method of manual removal will be used to reduce cover of *Hedera* from trees throughout the watershed of Spanish Bank Creek due to its proven effectiveness, as well as its low risks and cost compared to other control methods.

Many invasive species such as *Hedera* are pioneer species that rapidly colonize disturbed landscapes. Thus, successional advancement throughout the forest can be used as a management tool to mitigate the availability of disturbed landscapes (Polster, 2014). Reduction of *Hedera* cover from the trees throughout the watershed will be conducted as a long-term restoration treatment to facilitate the ecological progression from a disturbed mosaic of *Hedera* and deciduous trees to a mixed-conifer forest that is more typical of a coastal western hemlock temperate rainforest. A study by Thomas (1980) found that *Hedera* is tolerant of shade, but growth is stimulated by light. In addition, *Hedera* began to slowly decline in heavy shade. These findings further support the need to increase canopy closure throughout the watershed of Spanish Bank Creek.

### *3.3.3 Objective 2: Mitigate Watershed Runoff and Associated Transport of Sediment into Spanish Bank Creek*

Soil bioengineering is defined as the use of vegetation in solving issues relating to instability (Polster, 2014), and combines environmental and technical engineering approaches (Bischetti *et* al., 2012). One of the primary advantages of soil bioengineering techniques is that structures implemented are capable of self-regeneration, and generally increase in stability over time as vegetation matures (Evette *et al.*, 2009). Historically, there is evidence of soil bioengineering techniques from as early as 28 BC, as willow baskets were buried to repair dykes in China, and willow branches were woven together to create fences in Europe (Bischetti *et al.*, 2012). Modern day techniques follow the same principles that have been successfully used for millennia. Soil bioengineering techniques will be used to stabilize slopes throughout the watershed of Spanish Bank Creek, thereby mitigating runoff and associated transport of sediment into the stream.

Species to be used for the soil bioengineering techniques will be black cottonwood (*Populus trichocarpa*) and willow (*Salix spp.*) for low bench sites, black cottonwood and red-osier dogwood (*Cornus stolonifera*) for medium bench sites, and black cottonwood for high bench sites (Green and Klinka, 1994; Polster, 2014). Besides physically slowing down the rate of mobilization of runoff and sediment, these species ameliorate harsh conditions and create cool and moist understory conditions that are suitable for later-successional species such as western hemlock and western red cedar to establish (Clewell and Aronson, 2013; Polster, 2014). This initiates a successional trajectory, and is known as the facilitation principle. Ecological facilitation may act to offset competition by undesirable species (Polster, 2014).

### *3.3.4 Objective 3: Enhance Benthic Conditions in the Lower Reaches of Spanish Bank Creek*

While the first two objectives are designed as long-term solutions to the processes that are creating undesirable instream conditions at the lower reaches of Spanish Bank Creek, this objective is a short term solution to enhance instream conditions. The mouth of Spanish Bank Creek was designed to be at 4.7 m above chart datum (Page and Eymann, 1994). However, assuming installation of the culvert 0.31 m below grade, measurements from the culvert that spans under the footbridge indicate that as much as 0.62 m of sediment may have aggraded in the lower reaches of Spanish Bank Creek. Therefore, the mouth of Spanish Bank Creek could be greater than 5.3 m above chart datum.

The pre-cast concrete headwall was installed at 6.1 m above chart datum (Page and Eymann, 1994). Thus, assuming that the mouth of Spanish Bank Creek was designed to be 4.7 m above chart datum, this corresponds to an elevational rise of 1.4 m. The distance from the mouth of Spanish Bank Creek to the pre-cast concrete headwall is approximately 65 m. This equates to a slope of 2.2%. If the mouth of Spanish Bank Creek is now approximately 5.3 m above chart datum, this equates to a current slope of 1.2%. Decreased slope decreases stream flow velocities, thereby enabling greater deposition of sediment that is transported through Spanish Bank Creek. Accumulation of fine sediment in the lower reaches of the stream negatively affect salmonids of all life stages, as well as benthic invertebrate communities (Birtwell, 1999; Suttle *et al.*, 2004). Specifically, a decreased abundance of benthic invertebrates results in a diminished rate of nutrient cycling, primary productivity, decomposition, and translocation of materials (Wallace and Webster, 1996). Even the presence or absence of a single species of benthic invertebrate can cause significant changes to ecosystem structure and function (Covich *et al.*, 1999). Thus, decreased benthic invertebrate productivity has cascading negative effects on other aquatic species, the riparian ecotone, and the forest of the PSRP (Helfield and Naiman, 2001).

## 3.4 RESTORATION TREATMENTS

The following restoration treatments are designed to establish an ecological trajectory that will facilitate transition into a forested state that is defined by the restoration goal as a resilient, self-replacing native composition. Before any restoration treatments are performed, baseline conditions should be quantified using the methods outline in *3.6 Monitoring*. This restoration plan consists of five years of treatments (*Table 7*), and treatments are delineated into three phases based on their associated objective. A restoration treatment budget is located in *Appendix D*.

**Table 7**: Restoration will be conducted in three phases over five years. Phase 1 and 3 will be conducted each year, and phase 2 will be conducted once.

| Phase | Year(s) Performed | Objective |
|---|---|---|
| 1: Sever climbing *Hedera*... | 1 – 5 | 1: Reduce *Hedera* in canopies... |
| 2: Soil bioengineering... | 1 | 2: Mitigate runoff and sediment transport... |
| 3: Remove sediment... | 1 – 5 | 3: Enhance benthic conditions... |

### *3.4.1 Phase 1: Sever Climbing Hedera Vines Around the Stems of Invaded Trees Throughout the Watershed of Spanish Bank Creek*

This restoration treatment will be conducted in accordance with the objective to reduce *Hedera* in tree canopies throughout the watershed of Spanish Bank Creek. My research on the relationship between canopy closure and precipitation throughfall indicates that there is a negative relationship between canopy closure and precipitation throughfall in the watershed of Spanish Bank Creek. Reduction of *Hedera* from the canopies of trees throughout the watershed will mitigate the deleterious effects that *Hedera* has on native vegetation, thus increasing canopy closure of native tree species over time. As a result, this will decrease precipitation throughfall, and decrease rainsplash erosion due to a diminished rate of precipitation input that directly impacts the forest floor. In addition, a denser canopy results in greater slope stability (Keim and Skagset, 2003).

Specifically, reduction of *Hedera* from tree canopies will occur every year for five years, will target tree stands within and on the periphery of the ravine of Spanish Bank Creek (*Figure 24*). Ideally, every tree throughout the watershed of Spanish Bank Creek will be treated each year. However, this is unrealistic. Instead, this restoration treatment will occur every year, with the objective to treat every tree throughout the watershed of Spanish Bank Creek at least once by year five.

**Figure 24**: Priority treatment locations for removal of *Hedera* from the canopies of tree throughout the watershed of Spanish Bank Creek. The first priority is the red polygon that is approximately 4 ha. The second priority the orange polygon that is approximately 6.4 ha. The third priority is the yellow polygon that is approximately 3 ha. The last priority is the green polygon that is approximately 5.3 ha (QGIS Development Team, 2009).

*Hedera* vines that are climbing trees will be cut around the entire circumference of invaded trees from the ground to approximately head height. Severed vines will be left on the ground to desiccate. Field work will be conducted in the summer, after *Hedera* has already expended stored energy into new growth.

### *3.4.2 Phase 2: Install Brush Layers Where Runoff Flows Initiate Upslope of Spanish Bank Creek*

This restoration treatment will be conducted in accordance with the objective to mitigate watershed runoff and associated transport of sediment into Spanish Bank Creek. Brush layers are composed of live cuttings that are typically 1.5 – 4 m long, and aid in regenerating vegetation where most species have a hard time establishing (Polster, 2014). Specifically, brush layers will be installed within the forest of Spanish Bank Creek where runoff flows initiate and slope failures have the potential to occur. The species to be used for brush layer installation at the watershed of Spanish Bank Creek is black cottonwood due to its tolerance for a range of moisture conditions (Green and Klinka, 1994). For installation of brush layers where runoff initiates upslope of Spanish Bank Creek, 1,000 black cottonwood cuttings will be required.

### *3.4.3 Phase 2: Install Live Gully Breaks Where Runoff Has Scoured into the Forest Floor*

This restoration treatment will be conducted in accordance with the objective to mitigate watershed runoff and associated transport of sediment into Spanish Bank Creek. Live gully breaks are typically installed in gullies to slow down the velocity of entrenched runoff (Polster, 2014). Species to be used for gully break installation will be black cottonwood and red-osier dogwood, due to their tolerance for moist conditions (Green and Klinka, 1994). Installation of gully breaks in each of the gullies throughout the watershed will require 500 black cottonwood cuttings and 500 red-osier dogwood cuttings. Each of the cuttings should be between 1.5 – 4 m long (Polster, 2014).

### *3.4.4 Phase 2: Install Live Stakes Where Runoff Enters Spanish Bank Creek*

This restoration treatment will be conducted in accordance with the objective to mitigate watershed runoff and associated transport of sediment into Spanish Bank Creek. Live staking will be conducted where the 32 runoff inputs enter Spanish Bank Creek (*Figure 12*) as the upslope rills and gullies meet the gentler slopes of the stream's floodplain. The primary species to be used for the live staking will be *Salix spp.* and black cottonwood because of their tolerance for moist conditions (Green and Klinka, 1994; Polster, 2014). Installation of live stakes at each of the 32 runoff inputs into Spanish Bank Creek will require 250 black cottonwood cuttings, and 250 *Salix spp.* cuttings.

A total of 2,500 live cuttings will be required to complete all three soil bioengineering techniques at each of the 32 runoff inputs into Spanish Bank Creek and associated rills, gullies, and locations of runoff initiation (*Figure 25*). If *Salix spp.* and red-osier dogwood cannot be sourced, black cottonwood can be used for all the soil bioengineering techniques due to its ability to survive in a range of moisture conditions (Green and Klinka, 1994). The live cuttings should be soaked in water for 48 hours prior to installation, and should be planted immediately after removal from soaking (Hunolt *et* al., 2013). Where and when it is possible, live cuttings should be harvested during the dormant season. When planting, most (75 – 85%) of the length of the cuttings should be buried in soil (Polster, 2014). Phase two of restoration will be conducted just one time, with minor maintenance thereafter if needed. Installation of bioengineering structures will be conducted in the fall and winter, when plants are dormant (Polster, 2014). This will increase the chances of meeting the metrics-of-success for this restoration treatment (*3.5 Metrics-of-Success*). However, work during significant precipitation events should be avoided due to significant loss of soils and generally hazardous conditions for field work. Bioengineering structure designs are located in *Appendix E*.

**Figure 25**: Location within Spanish Bank Creek where the soil bioengineering techniques will be installed. Brush layers will be installed upslope (yellow polygon), live gully breaks will be installed midslope (orange polygon), and live stakes will be installed downslope (red polygon) along the edge of Spanish Bank Creek (QGIS Development Team, 2009).

### *3.4.5 Phase 3: Remove Sediment from the Lower Reaches of Spanish Bank Creek*

Removal of sediment from the lower reaches of Spanish Bank Creek will be conducted north of NW Marine Drive, in accordance with the objective to enhance benthic conditions in the lower reaches of Spanish Bank Creek. Removed sediment will be discarded in the estuary of Spanish Bank Creek.

There are three primary locations where sediment will be removed from the lower reaches of Spanish Bank Creek (*Figure 26*). The first location is just north of the pre-cast concrete headwall of the culvert that spans under NW Marine Drive, as seen in Figure 19. Removal of sediment will be conducted to increase water flow and fish passage through the culvert. On 16 March 2017, water depth in the thalweg of the north end of the culvert was 0.4 m. The culvert itself is 0.9 m in diameter. This indicates that sediment was blocking more than 50% of the cross-section of the culvert. It is likely that sediment will further block the culvert during summer low flow periods. As recommended by Dane (1978), water depth in culverts should be maintained above 0.23 m for fish passage. If sediment continues to accumulate at the lower reaches of Spanish Bank Creek, fish passage at this culvert could be further impeded. To ensure fish passage through this culvert, water depth along the substrate profile should be maintained at a depth greater than 0.45 m at the pre-cast concrete headwall.


**Figure 26**: Locations of sediment removal for the lower reaches of Spanish Bank Creek. The first priority is the culvert under the footbridge (red star). The second priority is the pre-cast concrete headwall at the north end of the wood stave culvert (orange star), and the last priority is the mouth of Spanish Bank Creek to re-grade the lower reaches of Spanish Bank Creek (yellow star; QGIS Development Team, 2009).

The second location of sediment removal at the lower reaches of Spanish Bank Creek is at the culvert under the footbridge (*Figure 18*). Sediment removal will be conducted to increase the depth of water in the culvert to at least 0.23 m under low flow times of the year, as recommended by Dane (1978). For context, water depth at the culvert under the footbridge was 0.04 m on 3 March 2017.

Excavation of some of the sediment at the mouth of Spanish Bank Creek would increase the slope of the lower reaches, and would increase stream flow velocities, thereby mobilizing and washing more sediment out of Spanish Bank Creek into the estuary. In addition, removal of sediment from the mouth of Spanish Bank Creek would in turn mobilize some of the sediment that is blocking the two upstream culverts. Mobilization of finer sediments would result in deeper channels and bed materials that consist of larger particles. Mean water depth measured in Spanish Bank Creek on 21 October 2016 was

0.09 m. The dominant bed substrate in Spanish Bank Creek is sand, interspersed with some gravels. The coarse sands are likely to have diameters in the range of 0.5 to 2 mm (Wentworth, 1922). Mean water depth and substrate size could be improved towards more appropriate parameters for spawning salmonids (*Table 8*) by removal of sediments from the lower reaches of Spanish Bank Creek.

**Table 8**: Required water depth and substrate size for spawning chum, coho, and cutthroat salmonids (Bjornn and Reiser, 1991).

| Species | Water Depth (m) | Substrate Size (mm) |
|---|---|---|
| chum salmon | > 0.18 | 13 – 102 |
| coho salmon | > 0.18 | 13 – 102 |
| cutthroat trout | > 0.06 | 6 – 102 |

Besides improving spawning conditions for salmonids in Spanish Bank Creek by increasing water depth and decreasing fine sediments, removal of sediment will also positively affect the invertebrate communities that juvenile salmonids rely on as prey (Suttle *et al.*, 2004). Thus, survival and growth of salmonids at all life stages will be improved Spanish Bank Creek.

In consideration of the windows of lowest risk for chum, coho, and cutthroat salmonids, sediment removal for all three locations will be conducted in August of each year (Ministry of Environment, 2004). If needed, work can also be conducted in early September.

Phase three of restoration will be conducted annually, in a five-year framework to gradually decrease the depth of deposition within the lower reaches of Spanish Bank Creek. After five years, upslope restoration treatments should ameliorate the deleterious rates of sediment erosion and transport of sediment to the lower reaches of Spanish Bank Creek. As such, sediment removal from the lower reaches of Spanish Bank Creek might not be required after five years.

### 3.5 METRICS-OF-SUCCESS

Following restoration treatments, the following metrics-of-success will be assessed one-year post-restoration, three-years post-restoration, and five years post-restoration (*Table 9*).

**Table 9**: Metrics-of-success for the three phases of restoration treatments. Metrics-of-success will be assessed after one year, three years, and five years. For a map of the priority areas for severing climbing *Hedera* vines (*Figure 24*). Rates of live cutting survival range from < 30% survival to 100% survival based on a range of parameters (Goldsmith *et al.*, 2014).

| Phase | Treatment | Year 1 Metric | Year 3 Metric | Year 5 Metric |
|---|---|---|---|---|
| 1 | Sever climbing *Hedera* vines around the stems of invaded trees throughout the watershed of Spanish Bank Creek | Complete severance of climbing *Hedera* vines from 90% of all invaded trees in priority 1 area | Complete severance of climbing *Hedera* vines from 100% of all invaded trees in priority 1 area | Complete severance of climbing *Hedera* vines at least once from 100% of all the invaded trees in all four priority areas |
| 1 | Sever climbing *Hedera* vines around the stems of invaded trees throughout the watershed of Spanish Bank Creek | Complete severance of climbing *Hedera* vines from 75% of all invaded trees in priority 2 area | Complete severance of climbing *Hedera* vines from 90% of all invaded trees in priority 2 area | Complete severance of climbing *Hedera* vines at least once from 100% of all the invaded trees in all four priority areas |
| 1 | Sever climbing *Hedera* vines around the stems of invaded trees throughout the watershed of Spanish Bank Creek | Complete severance of climbing *Hedera* vines from 50% of all invaded trees in priority 3 area | Complete severance of climbing *Hedera* vines from 75% of all invaded trees in priority 3 area | Complete severance of climbing *Hedera* vines at least once from 100% of all the invaded trees in all four priority areas |
| 1 | Sever climbing *Hedera* vines around the stems of invaded trees throughout the watershed of Spanish Bank Creek | Complete severance of climbing *Hedera* vines from 25% of all invaded trees in priority 4 area | Complete severance of climbing *Hedera* vines from 50% of all invaded trees in priority 4 area | Complete severance of climbing *Hedera* vines at least once from 100% of all the invaded trees in all four priority areas |
| 2 | Install brush layers | 80% survival of all live cuttings | 75% survival of all live cuttings | 70% survival of all live cuttings |

| | | | | |
|---|---|---|---|---|
| 2 | Install live gully breaks | 75% survival of all live cuttings | 70% survival of all live cuttings | 65% survival of all live cuttings |
| 2 | Install live stakes | 80% survival of all live cuttings | 75% survival of all live cuttings | 70% survival of all live cuttings |
| 3 | Removal of sediment at pre-cast concrete headwall | Outfall of wood stave culver > 0.45 m year-round at pre-cast concrete headwall | Outfall of wood stave culver > 0.5 m year-round at pre-cast concrete headwall | Outfall of wood stave culver > 0.55 m year-round at pre-cast concrete headwall |
| 3 | Removal of sediment from culvert under footbridge | > 0.3 m from substrate to inside top edge of the north end of the footbridge culver year-round | > 0.35 m from substrate to inside top edge of the north end of the footbridge culver year-round | > 0.4 m from substrate to inside top edge of the north end of the footbridge culver year-round |
| 3 | Removal of sediment from the mouth of Spanish Bank Creek | > 1.5% grade in lower reaches of Spanish Bank Creek | > 1.75% grade in lower reaches of Spanish Bank Creek | > 2% grade in lower reaches of Spanish Bank Creek |

If phase one of restoration treatment does not meet the metrics-of-success for a given assessment year, then increased restoration effort will be applied in the iteration of treatment. If phase two of restoration does not meet the metrics-of-success for a given assessment year, then a second or third iteration of installation of live cuttings will be completed to meet the metric-of-success. If phase three of restoration does not meet the metrics-of-success for a given assessment year, then a greater volume of sediment will be removed in the following treatment.

## 3.6 MONITORING

If restoration efforts are successful in mitigating ecological stressors and establishing an ecological trajectory towards a forest with self-sustaining biological processes, then the vegetation assemblages throughout the watershed will shift over time. As a result, ecological function and structure will change. The following monitoring techniques are designed to measure these changes annually over a five-year monitoring period. A budget for monitoring is located in *Appendix F.*

*3.6.1 Variable-radius Circular Plots*

In accordance with reduction of *Hedera* cover from trees throughout the watershed of Spanish Bank Creek, as well as the use of soil bioengineering techniques to mitigate runoff, there will be a change in the vegetation assemblages in the watershed over time. To quantify these changes, variable-radius circular plots will be used. Variable-radius circular plots enable quantification of percent cover of vegetation at herb, shrub, and tree layers. A single survey at a point of interest consists of three concentric, nested circles (*Figure 27*). The largest circle is used to survey vegetation at the tree layer (> 10 m height), and has a radius of 11.28 m, which equals a survey area of 400 $m^2$. The medium-sized circle is used to survey vegetation at the shrub layer (< 10 m height, excluding herbaceous species), and has a radius of 2.82 m, which equals a survey area of 25 $m^2$. The smallest circle is used to survey vegetation at the herb layer (all herbaceous species, regardless of height), and has a radius of 1.26 m, which equals a survey area of 5 $m^2$. Cover mid-points will be used to mitigate bias in assessing percent cover of each species. Results of the vegetation plots will yield percent cover of each species as a function of area. Assuming that the transects and the locations of the vegetation plots along each of the transects are a representative sampling design, inferences about the composition of vegetation for the entire watershed can be made, and changes can be measured over time.

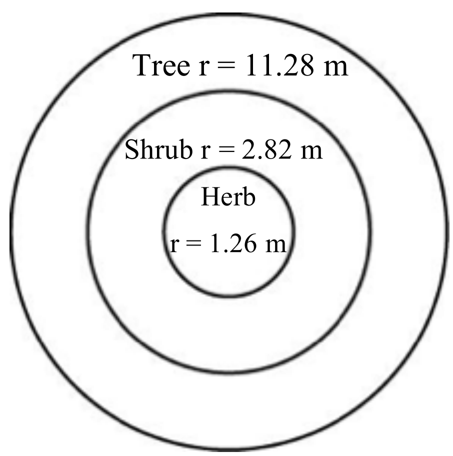


**Figure 27**: Variable-radius circular plots will be used to quantify vegetation composition at the tree, shrub, and herb layer throughout the watershed of Spanish Bank Creek. These surveys measure percent cover, as well as presence/not detected for vegetation species.

A total of 12 variable-radius circular plots will be used to quantify changes in vegetation composition over time. Each of these plots will be conducted at a random distance along each of the 12 transects that I used to assess vegetation throughout the watershed of Spanish Bank Creek (*Figure 28*). At each of the 12 variable-radius vegetation plots, surveyors will also record percent of trees that have had climbing *Hedera* vines severed around the tree stems. From this data, inferences can be made about the percent of trees that have been treated in each of the four priority areas of *Hedera* vine treatment (*Figure 24*; *3.5 Metrics-of-Success*). Variable-radius circular plots should be conducted once every year in the spring or summer, when vegetation is budding. This will facilitate accurate species identification.

**Figure 28**: Variable-radius circular plots will be used to assess vegetation composition at a random location along each of the twelve transects, as represented by the red lines (QGIS Development Team, 2009).

### *3.6.2 Soil Bioengineering Surveys*

Soil bioengineering surveys will be conducted to assess the efficacy of the soil bioengineering techniques in impeding routes of runoff into Spanish Bank Creek. The surveys will consist of a surveyor walking through the watershed of Spanish Bank Creek and recording the species, soil bioengineering technique used, and survival of each live cutting. Results of this survey will generate a rate of survival for each species and soil bioengineering technique used over time. Surveys should be conducted once every year in the spring and summer, when vegetation is budding. This will facilitate accurate assessment of survivorship from year to year.

*3.6.3 Fish Habitat Assessment Procedure*

A FHAP Level 1 will be conducted at the lower reaches of Spanish Bank Creek (north of NW Marine Drive). These reaches are characterized by rapid rates of sediment deposition that has altered instream conditions such that opportunities for salmonid spawning are limited, and aquatic productivity is hindered. Restoration treatments used will ameliorate these instream conditions. To quantify these changes, an FHAP Level 1 will be conducted. This FHAP Level 1 should be conducted annually, during summer low flows.

*3.6.4 Culvert Metrics*

To assess changes to the benthic conditions of the lower reaches of Spanish Bank Creek, surveys will be conducted to measure the height of culvert openings at the pre-cast concrete headwall and the north end of the culvert that spans under the footbridge. These surveys should be conducted on a monthly basis for the five-year monitoring period. Results of these surveys will indicate whether the lower reaches of Spanish Bank Creek are aggrading or eroding post-restoration. In conjunction with these culvert metrics, wetted width, wetted depth, and stream velocity should be measured in the lower reaches of Spanish Bank Creek. These results will facilitate analysis of how the sediment accumulation-flow velocity dynamic changes as a function of time and weather events for the five-year monitoring period.

*3.6.5 Sediment Accumulators*

After the five-year monitoring period, the last survey to be conducted will be sediment accumulation. This survey will be conducted by imitating the methods that I used to establish a baseline sediment accumulation rate in Spanish Bank Creek (*2.3.4 Sediment Transport*). Results of this survey will indicate whether the restoration treatments are successful in reducing sediment inputs into Spanish Bank Creek.

## 3.7 CLIMATE CHANGE CONSIDERATIONS

Generally, climate change projections for Vancouver BC indicate two main trends. The first is warmer year-round temperatures, and the second is increased annual precipitation (Metro Vancouver, 2016). These changes are projected to significantly affect ecological function and structure. Ecosystems are typically defined as specific biotic communities as an expression of local topography, soils, and regional climate (Green and Klinka, 1994). On a global scale, climate change effects will essentially reorganize abiotic ecosystem dynamics such that there will be a consequent reorganization of biotic communities. The following sections will briefly discuss how climate change will affect the ecology of the watershed of Spanish Bank Creek.

### *3.7.1 Warmer Temperatures*

Temperatures in Greater Vancouver are projected to increase 2.4 °C in winter, 3.7 °C in summer, and 2.9 °C annually by the 2050s (Metro Vancouver, 2016). Within the forest of the watershed of Spanish Bank Creek, the primary vegetation shift will be a shift from coastal western hemlock forests towards a composition that is more typical of coastal Douglas-fir ecosystems (Hebda, 1997). Groundwater inputs into Spanish Bank Creek typically buffer the stream from warm temperatures (*Figure 14*). Thus, groundwater inputs will likely continue to mitigate temperature extremes associated with climate change. Mean temperature measured in Spanish Bank Creek between 2007 and 2008 was 9.0 °C, with summer temperatures never recorded above 13 °C. Assuming a proportional increase in water temperature compared to ambient air temperature, summer-high stream temperature would increase to 16.6 °C from the warmest stream temperature recorded in the summer of 2008. A stream temperature of 16.6 °C would still be far below the 26 °C upper temperature limit of lethality to salmonids, and would be above the preferred range for chum and coho salmon by only 2.6 °C (Bjornn and Reiser, 1991). Therefore, Spanish Bank Creek is an ideal location for restoration for salmonids because climate change impacts are unlikely to shift abiotic conditions such that salmonids are unable to survive due to unfavourable water temperatures.

*3.7.2 Increased Precipitation*

Precipitation is projected to increase in the winter months, and decrease in the summer months, with a general increase in annual precipitation (Metro Vancouver, 2016). Within the watershed of Spanish Bank Creek, precipitation inputs are negatively affecting instream conditions for aquatic biota. Without restoration to ameliorate the current sediment dynamic throughout the watershed, increased precipitation associated with climate change will further exacerbate rates of hillslope erosion. Daily precipitation records at the UBC weather station indicate that from 1971 to 2001, mean annual precipitation was 1277.5 mm (Environment Canada, 2017c). From the same weather station, the mean annual precipitation from 1981 to 2010 was 2180.1 mm (Environment Canada, 2017b). This is an increase in annual precipitation by 902.6 mm. While this rate of precipitation increase over time is not likely to be representative of the actual rate of annual precipitation increase, it does indicate that precipitation can fluctuate significantly from year to year. The restoration treatments prescribed for the watershed of Spanish Bank Creek are designed to achieve the goal of restoring the forest to a resilient, self-replacing native composition. A forest with these characteristics will be more resilient to climate change impacts, especially increased annual precipitation, as a coniferous dominated forest is able to intercept more precipitation through leaf interception and stemflow compared to a deciduous dominated forest (Asadian, 2010). For Spanish Bank Creek, this will result in reduced rates of erosion and transport of upslope soils into the stream, a longer lag time between a precipitation event and peak flow in the stream, decreased stream discharge, and an associated longer hydraulic retention time and greater base flow (*Figure 6*).

Spanish Bank Creek receives input from three culvert outfalls that drain residential areas, and also flows through two culverts north of NW Marine Drive before arriving at Burrard Inlet. A major concern is the ability of drainage infrastructure to cope with increased stream velocities and discharge associated with increased annual precipitation. An increase in precipitation inputs greater than pipes and culverts were designed for may cause significant erosion at the mouth of outfalls (Kerr Wood Leidal Associates Ltd, 2008). Where pipes and culverts are undersized, flooding may occur as stream flow becomes backed up (Metro Vancouver, 2016). These are considerations that will be monitored closely during monthly surveys of culvert metrics (*3.6.4 Culvert Metrics*). Understanding and mitigating climate change impacts will be essential for effective management of Spanish Bank Creek and the surrounding watershed.

## 3.8 CONCLUSIONS

The results of my research indicate that an increase in canopy closure is correlated with a decrease in precipitation throughfall. Precipitation throughfall is thought to be the primary hydrologic input into the watershed of Spanish Bank Creek. This precipitation interacts with the forest vegetation, thereby producing a mosaic of variable rates of erosion throughout the watershed. Nearly a century of forest disturbance has resulted in significant erosion, with rates of instream sediment accumulation measured at 13.9 t per day over the 46-day study period. I have suggested that restoration of the forest to a resilient, self-replacing native composition will mitigate the deleterious effects of invasive species. In addition, restoration will establish an ecological trajectory towards a coniferous forest composition that typically consists of greater canopy closure than deciduous-dominated forest stands. Consequently, Spanish Bank Creek will experience diminished rates of sediment input. This will positively affect aquatic productivity by increasing nutrient cycling, primary productivity, decomposition, and translocation of materials (Wallace and Webster, 1996).

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## APPENDICES

APPENDIX A

Musqueam Traditional Territory – Musqueam Declaration (1976)

APPENDIX B

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APPENDIX C

Plants, Animals, and Ecosystems of Importance.

Derived from BC Conservation Data Centre. (2017). BC Species and Ecosystems Explorer.

| Scientific Name | English Name | COSEWIC | BC List | SARA |
|---|---|---|---|---|
| **DICOTS** | | | | |
| *Anagallis minima* | chaffweed | | Blue | |
| *Bidens amplissima* | Vancouver Island beggarticks | SC (Nov 2001) | Blue | 1-SC (Jun 2003) |
| *Claytonia washingtoniana* | Washington springbeauty | | Red | |
| *Elatine rubella* | three-flowered waterwort | | Blue | |
| *Helenium autumnale* var. *grandiflorum* | mountain sneezeweed | | Blue | |
| *Hypericum scouleri* ssp. *nortoniae* | western St. John's-wort | | Blue | |
| *Lindernia dubia* var. *anagallidea* | false-pimpernel | | Blue | |
| *Lupinus rivularis* | streambank lupine | E (Nov 2002) | Red | 1-E (Jan 2005) |
| *Navarretia intertexta* | needle-leaved navarretia | | Red | |
| *Rubus nivalis* | snow bramble | | Blue | |
| *Rupertia physodes* | California-tea | | Blue | |
| *Sidalcea hendersonii* | Henderson's checker-mallow | | Blue | |
| *Verbena hastata* var. *scabra* | blue vervain | | Blue | |
| **MONOCOTS** | | | | |
| *Carex feta* | green-sheathed sedge | | Blue | |
| *Carex interrupta* | green-fruited sedge | | Blue | |
| *Eleocharis parvula* | small spike-rush | | Blue | |
| *Eleocharis rostellata* | beaked spike-rush | | Blue | |
| *Glyceria leptostachya* | slender-spiked mannagrass | | Blue | |
| *Juncus oxymeris* | pointed rush | | Blue | |
| *Lilaea scilloides* | flowering quillwort | | Blue | |
| **QUILLWORTS** | | | | |
| *Isoetes nuttallii* | Nuttall's quillwort | | Blue | |

| Scientific Name | English Name | COSEWIC | BC List | SARA |
|---|---|---|---|---|
| **AMPHIBIANS** | | | | |
| *Anaxyrus boreas* | Western Toad | SC (Nov 2012) | Blue | 1-SC (Jan 2005) |
| *Ascaphus truei* | Coastal Tailed Frog | SC (Nov 2011) | Blue | 1-SC (Jun 2003) |
| *Rana aurora* | Northern Red-legged Frog | SC (May 2015) | Blue | 1-SC (Jan 2005) |
| *Rana pretiosa* | Oregon Spotted Frog | E (May 2011) | Red | 1-E (Jun 2003) |
| **BIRDS** | | | | |
| *Antigone canadensis* | Sandhill Crane | NAR (May 1979) | Yellow | |
| *Ardea herodias fannini* | Great Blue Heron, *fannini* subspecies | SC (Mar 2008) | Blue | 1-SC (Feb 2010) |
| *Asio flammeus* | Short-eared Owl | SC (Mar 2008) | Blue | 1-SC (Jul 2012) |
| *Botaurus lentiginosus* | American Bittern | | Blue | |
| *Brachyramphus marmoratus* | Marbled Murrelet | T (May 2012) | Blue | 1-T (Jun 2003) |
| *Buteo lagopus* | Rough-legged Hawk | NAR (May 1995) | Blue | |
| *Butorides virescens* | Green Heron | | Blue | |
| *Chordeiles minor* | Common Nighthawk | T (Apr 2007) | Yellow | 1-T (Feb 2010) |
| *Coccothraustes vespertinus* | Evening Grosbeak | SC (Nov 2016) | Yellow | |
| *Contopus cooperi* | Olive-sided Flycatcher | T (Nov 2007) | Blue | 1-T (Feb 2010) |
| *Cypseloides niger* | Black Swift | E (May 2015) | Blue | |
| *Falco peregrinus anatum* | Peregrine Falcon, *anatum* subspecies | SC (Apr 2007) | Red | 1-SC (Jun 2012) |
| *Hirundo rustica* | Barn Swallow | T (May 2011) | Blue | |
| *Hydroprogne caspia* | Caspian Tern | NAR (May 1999) | Blue | |
| *Megascops kennicottii kennicottii* | Western Screech-Owl, *kennicottii* subspecies | T (May 2012) | Blue | 1-SC (Jan 2005) |
| *Nycticorax nycticorax* | Black-crowned Night-heron | | Red | |
| *Patagioenas fasciata* | Band-tailed Pigeon | SC (Nov 2008) | Blue | 1-SC (Feb 2011) |
| *Phalacrocorax auritus* | Double-crested Cormorant | NAR (May 1978) | Blue | |
| *Progne subis* | Purple Martin | | Blue | |
| *Strix occidentalis* | Spotted Owl | E (Mar 2008) | Red | 1-E (Jun 2003) |
| *Tyto alba* | Barn Owl | T (Nov 2010) | Red | 1-SC (Jun 2003) |
| **BIVALVES** | | | | |
| *Sphaerium patella* | Rocky Mountain Fingernailclam | | Red | |
| **GASTROPODS** | | | | |
| *Allogona townsendiana* | Oregon Forestsnail | E (Apr 2013) | Red | 1-E (Jan 2005) |
| *Carychium occidentale* | Western Thorn | | Blue | |
| *Cryptomastix devia* | Puget Oregonian | XT (Apr 2013) | Red | 1-XX (Jan 2005) |

| Scientific Name | English Name | COSEWIC | BC List | SARA |
|---|---|---|---|---|
| **INSECTS** | | | | |
| *Argia emma* | Emma's Dancer | | Blue | |
| *Callophrys eryphon sheltonensis* | Western Pine Elfin, *sheltonensis* subspecies | | Blue | |
| *Callophrys johnsoni* | Johnson's Hairstreak | | Red | |
| *Danaus plexippus* | Monarch | E (Nov 2016) | Blue | 1-SC (Jun 2003) |
| *Epargyreus clarus* | Silver-spotted Skipper | | Blue | |
| *Euphyes vestris* | Dun Skipper | T (Apr 2013) | Red | 1-T (Jun 2003) |
| *Octogomphus specularis* | Grappletail | | Red | |
| *Ophiogomphus occidentis* | Sinuous Snaketail | | Blue | |
| *Pachydiplax longipennis* | Blue Dasher | | Blue | |
| *Plebejus saepiolus insulanus* | Greenish Blue, *insulanus* subspecies | E (May 2012) | Red | 1-E (Jun 2003) |
| *Speyeria zerene bremnerii* | Zerene Fritillary, *bremnerii* subspecies | | Red | |
| *Sympetrum vicinum* | Autumn Meadowhawk | | Blue | |
| *Tanypteryx hageni* | Black Petaltail | | Blue | |
| **MAMMALS** | | | | |
| *Aplodontia rufa* | Mountain Beaver | SC (May 2012) | Yellow | 1-SC (Jun 2003) |
| *Corynorhinus townsendii* | Townsend's Big-eared Bat | | Blue | |
| *Gulo gulo luscus* | Wolverine, *luscus* subspecies | SC (May 2014) | Blue | |
| *Lepus americanus washingtonii* | Snowshoe Hare, *washingtonii* subspecies | | Red | |
| *Mustela frenata altifrontalis* | Long-tailed weasel, *altifrontalis* subspecies | | Red | |
| *Myodes gapperi occidentalis* | Southern Red-backed Vole, *occidentalis* subspecies | | Red | |
| *Myotis keenii* | Keen's Myotis | DD (Nov 2003) | Blue | 3 (Mar 2005) |
| *Oreamnos americanus* | Mountain Goat | | Blue | |
| *Sorex bendirii* | Pacific Water Shrew | E (Apr 2016) | Red | 1-E (Jun 2003) |
| *Sorex rohweri* | Olympic Shrew | | Red | |
| *Sorex trowbridgii* | Trowbridge's Shrew | | Blue | |
| *Ursus arctos* | Grizzly Bear | SC (May 2002) | Blue | |
| **RAY-FINNED FISHES** | | | | |
| *Acipenser transmontanus* | White Sturgeon | E (Nov 2003) | No Status | 1-E (Aug 2006) |
| *Acipenser transmontanus* pop. 4 | White Sturgeon (Lower Fraser River population) | T (Nov 2012) | Red | |
| **REPTILES** | | | | |
| *Charina bottae* | Northern Rubber Boa | SC (Apr 2016) | Yellow | 1-SC (Jan 2005) |
| **TURTLES** | | | | |
| *Actinemys marmorata* | Western Pond Turtle | XT (May 2012) | Red | 1-XX (Jan 2005) |
| *Chrysemys picta* | Painted Turtle | E/SC (Apr 2006) | No Status | 1-E/SC (Dec 2007) |
| *Chrysemys picta* pop. 1 | Painted Turtle - Pacific Coast Population | T (Nov 2016) | Red | 1-E (Dec 2007) |

| Scientific Name | English Name | BC List | Ecosystem Group |
|---|---|---|---|
| **ESTUARINE** | | | |
| *Distichlis spicata var. spicata* Herbaceous Vegetation | seashore saltgrass Herbaceous Vegetation | Red | Estuary Marsh (Em) |
| *Zostera marina* Herbaceous Vegetation | common eel-grass Herbaceous Vegetation | No Status | Estuary Tidal Flat (Et) |
| ***TERRESTRIAL*** | | | |
| *Leymus mollis* ssp. *mollis - Lathyrus japonicus* | dune wildrye - beach pea | Red | Beach: Beach Beachland (Bb) |
| *Picea sitchensis / Rubus spectabilis* Very Dry Maritime | Sitka spruce / salmonberry Very Dry Maritime | Red | Flood: Flood (Highbench);Terrestrial - Forest: Mixed - moist/wet |
| *Populus trichocarpa - Alnus rubra / Rubus spectabilis* | black cottonwood - red alder / salmonberry | Blue | Flood: Flood Midbench (Fm);Terrestrial - Forest: Broadleaf - moist/wet |
| *Populus trichocarpa / Salix sitchensis* | black cottonwood / Sitka willow | Blue | Flood: Flood Midbench (Fm);Terrestrial - Forest: Broadleaf - moist/wet |
| *Pseudotsuga menziesii - Pinus contorta / Racomitrium canescens* | Douglas-fir - lodgepole pine / grey rock-moss | Red | Forest: Coniferous - dry |
| *Pseudotsuga menziesii / Polystichum munitum* | Douglas-fir / sword fern | Blue | Forest: Coniferous - dry |
| *Pseudotsuga menziesii - Tsuga heterophylla / Gaultheria shallon* Dry Maritime | Douglas-fir - western hemlock / salal Dry Maritime | Blue | Forest: Coniferous - dry |
| *Thuja plicata / Polystichum munitum* Very Dry Maritime | western redcedar / sword fern Very Dry Maritime | Blue | Forest: Coniferous - mesic |
| *Tsuga heterophylla - Pseudotsuga menziesii / Eurhynchium oreganum* | western hemlock - Douglas-fir / Oregon beaked-moss | Red | Forest: Coniferous - mesic |
| *Thuja plicata / Lonicera involucrata* | western redcedar / black twinberry | Red | Forest: Coniferous - moist/wet |
| *Thuja plicata / Rubus spectabilis* | western redcedar / salmonberry | Red | Forest: Coniferous - moist/wet |
| *Thuja plicata / Tiarella trifoliata* Very Dry Maritime | western redcedar / three-leaved foamflower Very Dry Maritime | Blue | Forest: Coniferous - moist/wet |
| *Tsuga heterophylla - Thuja plicata / Blechnum spicant* | western hemlock - western redcedar / deer fern | Red | Forest: Coniferous - moist/wet |
| *Thuja plicata / Carex obnupta* | western redcedar / slough sedge | Blue | Forest: Coniferous - moist/wet;Wetland - Mineral: Wetland Swamp (Ws) |
| *Thuja plicata - Picea sitchensis / Lysichiton americanus* | western redcedar - Sitka spruce / skunk cabbage | Blue | Forest: Coniferous - moist/wet;Wetland - Mineral: Wetland Swamp (Ws) |
| *Thuja plicata / Polystichum munitum - Lysichiton americanus* | western redcedar / sword fern - skunk cabbage | Blue | Forest: Coniferous - moist/wet;Wetland - Mineral: Wetland Swamp (Ws) |
| *Selaginella wallacei / Cladina spp.* | Wallace's selaginella / reindeer lichens | Blue | Grassland: Grassland (Gg);Terrestrial - Rock: Rock Outcrop (Ro) |
| ***WETLAND*** | | | |
| *Carex sitchensis - Oenanthe sarmentosa* | Sitka sedge - Pacific water-parsley | Blue | Mineral: Wetland Marsh (Wm) |
| *Schoenoplectus acutus* Deep Marsh | hard-stemmed bulrush Deep Marsh | Blue | Mineral: Wetland Marsh (Wm) |
| *Typha latifolia* Marsh | common cattail Marsh | Blue | Mineral: Wetland Marsh (Wm) |
| *Brasenia schreberi - Utricularia* spp. | water shield - bladderworts | No Status | Mineral: Wetland Shallow Water (Ww) |
| *Spiraea douglasii / Carex sitchensis* | hardhack / Sitka sedge | Yellow | Mineral: Wetland Swamp (Ws) |
| *Pinus contorta / Sphagnum* spp. *Very Dry Maritime* | lodgepole pine / peat-mosses Very Dry Maritime | Blue | Peatland: Wetland Bog (Wb) |
| *Rhododendron groenlandicum / Kalmia microphylla / Sphagnum* spp. | Labrador-tea / western bog-laurel / peat-mosses | Blue | Peatland: Wetland Bog (Wb) |
| *Carex lasiocarpa - Rhynchospora alba* | slender sedge - white beak-rush | Red | Peatland: Wetland Fen (Wf) |
| *Myrica gale / Carex sitchensis* | sweet gale / Sitka sedge | Red | Peatland: Wetland Fen (Wf) |

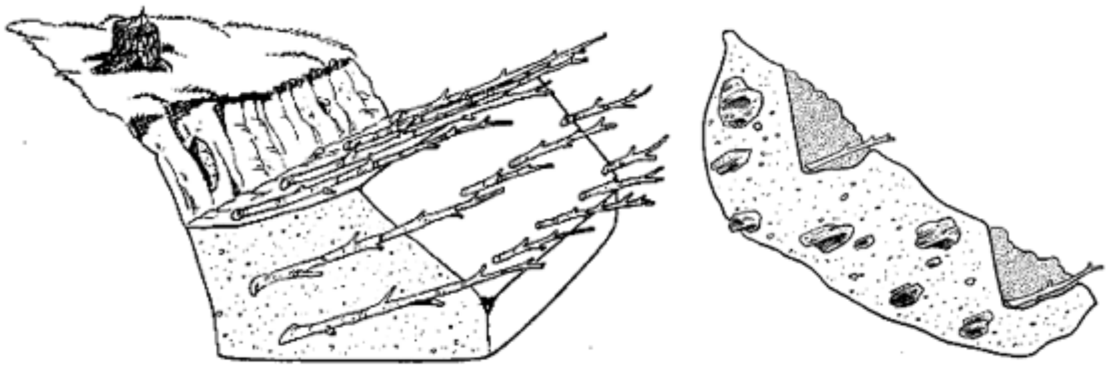
APPENDIX D

Restoration Treatment Budget (5-year plan)

| Phase | Description | Years | Quantity | Rate | Cost |
|---|---|---|---|---|---|
| 1: Sever climbing *Hedera*… | Labour | 5 | 244 hours per year | $ 18.00 per hour | $ 21,960.00 |
| 1: Sever climbing *Hedera*… | Materials (e.g., Personal protective equipment, loppers, pruning clippers, saws) | 1 – one-time purchase | 5 crew members | $ 60.00 each | $ 300.00 |
| 2: Soil bioengineering … | Labour (Installation of all three bioengineering structure types) | 1 | 400 hours | $ 18.00 per hour | $ 7,200.00 |
| 2: Soil bioengineering … | Materials (i.e., 2500 live cuttings) | 1 | 2500 | $ 1.05 per cutting | $ 2,625.00 |
| 3: Remove sediment… | Labour | 5 | 8 hours per year | $ 18.00 per hour | $ 720.00 |
| 3: Remove sediment… | Materials (e.g., shovel, chest waders) | 1 – one-time purchase | 1 | $ 120.00 | $ 120.00 |
| | | | | | **$ 32,925.00** |

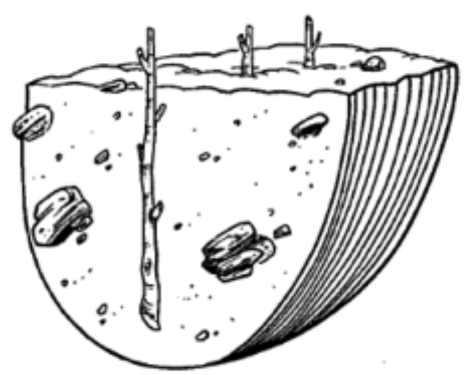
APPENDIX E

Brush Layer Installation Design (Polster, 2014).



Live Gully Break Installation Design (Polster, 2014).

Live Staking Installation Design (Polster, 2014).



APPENDIX F

Monitoring Budget

| Description | Years | Hours per Year | Rate | Cost |
|---|---|---|---|---|
| Variable-radius circular plots | 6 (baseline + 5) | 24 | $ 18.00 per hour | $ 2,592.00 |
| Soil bioengineering surveys | 5 | 32 | $ 18.00 per hour | $ 2,880.00 |
| FHAP Level 1 | 6 (baseline + 5) | 8 | $ 18.00 per hour | $ 864.00 |
| Culvert metrics | 6 (baseline + 5) | 24 | $ 18.00 per hour | $ 2,592.00 |
| Sediment accumulators | 1 | 24 | $ 18.00 per hour | $ 432.00 |
| | | | | **$ 9,360.00** |