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Salmonid Habitat Restoration on the Chocolay River, Michigan

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SALMONID HABITAT RESTORATION ON THE CHOCOLAY RIVER, MICHIGAN

by

Ross J. Crawford

A thesis submitted to the Graduate College
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SALMONID HABITAT RESTORATION ON THE CHOCOLAY RIVER, MICHIGAN

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This project seeks to improve salmonid habitat quality by improving riparian vegetation on the adjacent banks (from toe to terrace) on the Chocolay River in Michigan's Upper Peninsula. Quantities of large woody debris (LWD) were also analyzed to determine the heterogeneity of stream habitats, or channel roughness. Percentages of rock, gravel, sand, and silt were analyzed to determine spawning habitat quality. As the proportions of fines (<2mm) increases, in this case sand and silt, the survivability of salmonid embryos greatly decreases. ANOVA tests identified a significant relationship between proximity to major erosion sites, which were also inventoried, and percentages of fines in spawning sites. Implications are that for those erosion sites located close to salmonid spawning sites, restoration strategies should be initiated. Recommendations for twelve different biotechnical designs and LWD structures were made at each erosion site based on geotechnical properties of the site. This allows for priorities in restoration to be established.

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Ross J. Crawford

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CHAPTER 1

INTRODUCTION

To start, the following research will operate under the hypothesis that varied stream habitat restoration techniques will have a substantial impact on salmonid spawning habitat quality, specifically situated along a high gradient, gravel-bed stream that transitions to a low gradient, alluvial stream in Michigan's Upper Peninsula. Restoration techniques will involve both erosion site restoration and salmonid spawning habitat restoration. Not only can habitat heterogeneity be achieved by planting a high variety of herbaceous, shrub, and tree species in the riparian area, but also by using various biotechnical erosion control structures, and by proper placement of large woody debris (LWD). As salmonids increase in abundance, they become highly beneficial for several reasons: they increase recreation and sport fishing, they enrich riparian areas through salmon derived nutrients, they increase terrestrial and aquatic biodiversity, and they maintain their status as an integral part of the food web, and in some cases, can be considered a keystone species. Salmonids often serve as a proxy for healthy ecosystems (Harper & Ferguson 1995). When a project site is surveyed 5, 10, or 25 years post-project and an upward trend in salmonid stock quantity and quality is observed, the result is highly appealing. When the salmonids have benefited, typically the whole stream and riparian area have too.

Riparian areas are unique environments that, despite covering a relatively small percentage of the Earth's total landmass, represent some of the richest biodiversity, and must be managed carefully (Goebel et al. 2003). The vegetation located within riparian zones has a direct effect on many fluvial processes, including but not limited to: bankside erosion, meander migration rates, channel width, channel roughness, substrate composition, and deposition during inundation occurrences (Merritt & Cooper 2000). The distribution of riparian vegetation is affected by two main fluvial processes, namely flood processes and the characteristics of landforms that are shaped by floods (Bendix & Hupp 2000). To effectively study fluvial geomorphology and adjacent riparian areas, it is essential to isolate these key factors that have greater influence on the processes within these complex, interconnected systems.

To fully understand riparian areas, it is first important to provide a clear definition. Verry et al. (2004) joins many pervious definitions by explaining the intricacies of the multidimensional phenomena of riparian environments. Riparian areas are three-dimensional spaces of interaction that include terrestrial and aquatic ecosystems that extend down into the groundwater, up above the canopy, outward across the floodplain, up the near-slopes that drain to the water, laterally into the terrestrial ecosystem, and along the water course at a variable length (Verry et al. 2004). Riparian areas could also be thought of as four-dimensional because of course they vary temporally as well. For example, the geotechnical properties of a particular riverbank and biophysical properties of a particular species of vegetation will be able to more greatly resist erosion rates during fluvial processes that are predominant during a particular time period.

A healthy stream is typically accompanied by a healthy riparian corridor. Proper management of these areas is crucial in the preservation and conservation of the adjacent terrestrial and aquatic ecosystems (Rhode et al. 2006). Salmonid fish species, in particular, prefer a healthy cold-water stream as habitat (Battin et al. 2007). In-stream and riverbank vegetation are therefore critical components of Salmonid habitat. Pools, runs, and riffles are all important habitats for Salmonid species, which are all influenced by riparian vegetation with particular importance during different life-stages (Harper & Ferguson 1995). The spatial distribution of these habitats, with the addition of large woody debris (LWD), alters flow velocities throughout the channel (Gurnell et al. 2002).

Substrate composition is directly correlated to flow velocity because substrate is dependent on the stream's ability to move sediment of a certain size (Eaton et al. 2012). This results in a pattern of finer sediments being deposited around LWD and riverbank vegetation where flow velocities are slow, and coarser sediments being deposited in runs and riffles where velocities are fast. Salmonid species are found mainly in cold-water streams. Riparian vegetation keeps water temperatures cool by shading, increasing flow velocities, and narrowing the channel. Shading is a major determinant of cool water temperatures, especially in headwater locations and smaller streams, where a majority of the stream channel is not under the direct heating of the sun's rays (Chen et al. 1998). Narrow channels, with a relatively small volume of water, experience greater temperature fluctuations throughout the day when compared with wide channels, with a relatively large volume of water (Oglesby et al. 1972). Increased flow velocities occur because riverbank vegetation confines flows to a narrow channel. The amount of heating is decreased because there is less travel time that the flow has to go to get to base level, and there is less surface area to be heated by the sun's rays (Chen et al. 1998). When considering these influences, riparian vegetation is important in order to maintain habitat heterogeneity, and meeting the habitat demands of a biodiverse collection of cold-water fish species.

The intermediate disturbance hypothesis states that highest species richness occurs where an intermediate amount of disturbances occur, such as flooding and scouring, when compared to areas without disturbance (Hagan et al. 2006). Disturbance and physiological stress are the underlying mechanisms by which plants adapt to their environment by constantly imposing selection pressures (Lambert et al. 2010). For example, floods often occur during periods when the vegetation is without leaves, further reducing friction resistance, and hence, reducing potential damage (Naiman & Decamps 1997). The various plants that have this adaptation, or similar adaptations to disturbance, may be able to more effectively persist in a given riparian plant community until reproductive age. Reproductive strategies of some plants are contingent with fluvial disturbance, such as *Populus* and Salix, which time seed dispersal during the seasonal retreat of floodwaters to ensure moist seedbeds for successful germination and plant colonization (Naiman & Decamps 1997). Primary succession resulting from seed dispersal is one way that plants colonize riparian areas. As an alternative, many successional patterns in riparian areas begin with plant fragments, propagules, or biomass remaining from previous communities. In addition to direct hydrological disturbances shaping riparian plant communities, small-scale variations in topography, soils, and groundwater as a result of lateral migration of river channels increase habitat heterogeneity and species richness (Nilsson & Svedmark 2002).

Unfortunately, these biodiversity hotspots can be more susceptible to the invasion of exotic species. Vegetation removal, caused by human or natural disturbance, may facilitate invasion by eliminating a barrier to seedling establishment (Rachich & Reader 1999). Invasive plants are also prolific seed dispersers in many cases, and considering that these plants are often avoided by native animals, they have a distinct competitive advantage when compared to native plants (Lambert et al. 2010). Rivers and streams guide animal movement, and sufficiently wide riparian corridors can encompass a gradient of communities that will facilitate movement of many species, some of them exotic (Hilty et al. 2006).

The research objectives of this study can be broken down into three main categories: (i) to study the spatial relationship between erosion sites and the habitat quality of salmonid spawning sites, (ii) to explain the intricacies between riparian vegetation and river channel morphology of a Northern Michigan stream, and (iii) to produce a habitat restoration plan by providing detailed remediation techniques at each salmonid spawning habitat and erosion site. To accomplish these objectives, three main inventory forms were used to record data, which can be referred to in Appendix B: (i) spawning inventory, (ii) erosion inventory, and (iii) BEHI (bank erosion hazard index).

The following sections will provide more in-depth insight into how restoration of salmonid habitat to increase spawning habitat quality can be achieved, using the Chocolay River as a case study. Background information of the proposed research, including the study locations and history and context will follow. Next, the literature review will provide information on how this study fits into and contributes to the existing literature. The methods of analysis section will explain the methodological approaches that were employed in this study. The results and discussion section will state explicitly the hypothesis and will describe the implications that the results can have on watershed management objects, using the Chocolay River, Marquette County, Michigan as a case study. Finally, the conclusion is a habitat restoration plan that can be used to initiate restoration activities on the study reach of the Chocolay River.

CHAPTER 2

BACKGROUND

Study Area

The mainstream Chocolay River traverses 21.7 miles in Marquette County, Michigan 5 miles southeast of the city of Marquette (Figure 1) (Premo 1999). It drains a surface area of approximately 160 square miles beginning at the confluence of the East and West branches (46.377° N, 87.270° W) and flows toward Lake Superior (46.501° N, 87.353° W) (Premo 1999). The main tributaries include Silver Creek, Big Creek, Cherry Creek, and Cedar Creek; all of which have a steep profile and are influenced by cool, consistent ground water flows (Premo 1999). There are 16 lakes connected to the Chocolay River system.

The Chocolay River watershed has a high diversity of soils. Wallace, Alcona, and Ocqueoc soils are associated with the sandy to loamy soils that are most commonly found in the watershed. Skanee, Munising, and Gay soils are fine sandy loam in texture and are the next most common. Vegetation in the watershed is comprised primarily of northern hardwood and conifer species. Common species include sugar maple (*Acer saccharum*), yellow birch (*Betula alleghaniensis*), white cedar (*Thuja occidentalis*), balsam fir (*Abies balsamea*), red pine (*Pinus resinosa*), white pine (*Pinus strobus*), and quaking aspen (*Populus tremuloides*). Animal species that have been known to use the Chocolay River's fluvial corridor include bald eagle (*Haliaeetus leucocephalus)*, American woodcock (*Scolopax minor)*, wood duck (*Aix sponsa)*, fox squirrel (*Sciurus niger)*, black bear (*Ursus americanus*), North American river otter (*Lontra canadensis*), American mink (*Neovison vison)*, and ruffed grouse (*Bonasa umbellus*) amongst many others. Sediment, chemical pollution, beaver dams, and non-native invasive species are the most common threats to the terrestrial and aquatic ecosystems of the Chocolay River watershed (Premo 1999).

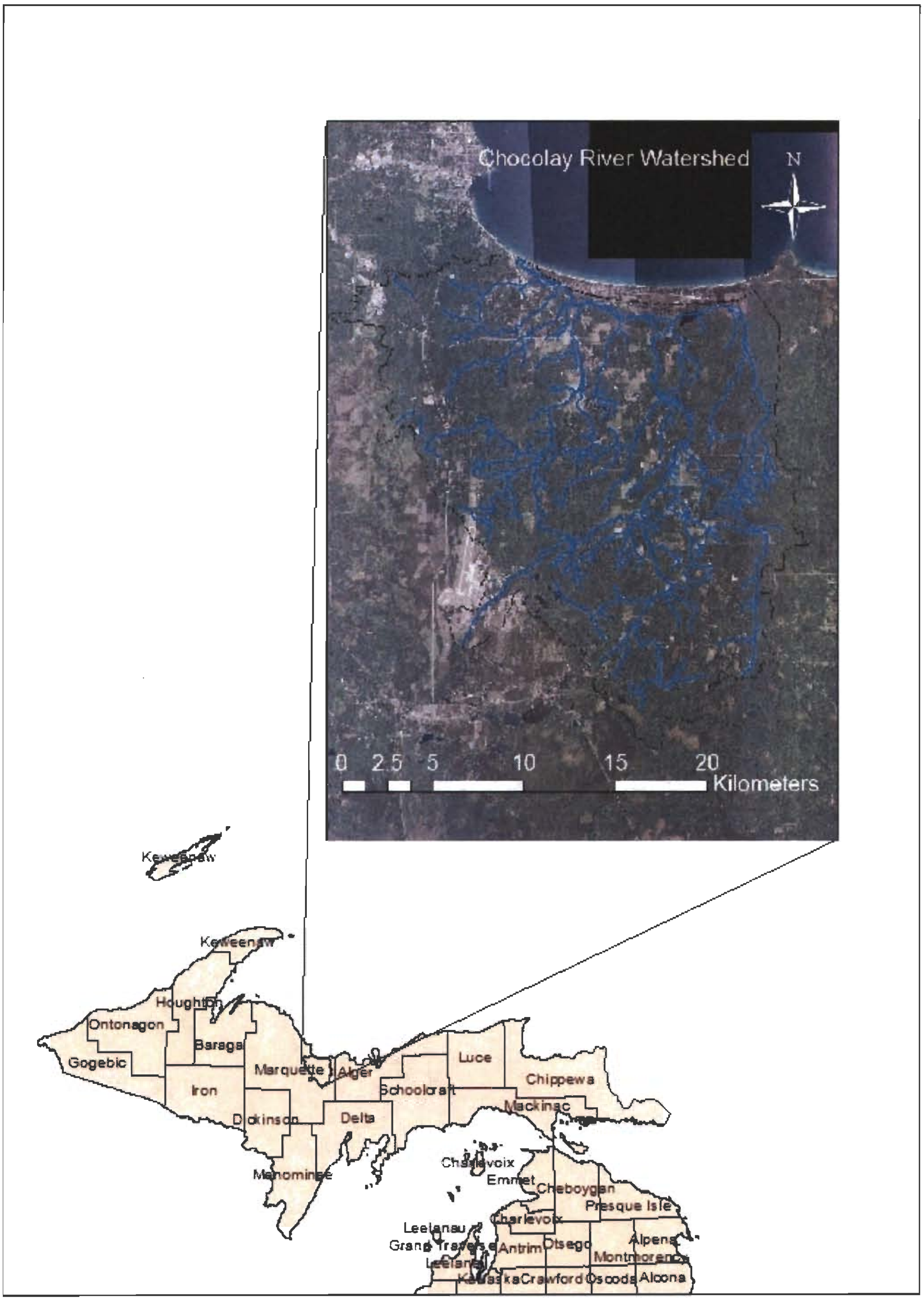

Figure 1: Chocolay River Watershed. Data acquired from the USDA/NRCS Geospatial Data Gateway

In the middle reach of the Chocolay River, there is a large problem with erosion of fine sediments, an issue that requires attention if salmonid populations are to be effectively managed. Despite this, it is sometimes difficult to analyze the bed material for fine particulate matter, such as clays, which are in no short supply within the Chocolay River watershed (Premo 1999). When the bed material is analyzed for sizes, it is usually found that all sizes down to a certain limit, such as clay or silt, are well represented, and that sizes smaller than that limit are found only in very insignificant amounts (Oglesby et al. 1972). This only reinforces findings that in most streams these fine sediments sizes constitute a large, often predominant part of the sediment load (Oglesby et al. 1972). In the case of the Chocolay River, riverbanks exhibit a relatively high amount of clay erosion. This occurs often because clays are highly susceptible to being periodically washed out of the gravel bed by medium to high flows (Oglesby et al. 1972). As high proportions of clays are transported in a stream's suspended load, an issue of decreasing light availability negatively affects both primary production (Mineau et al. 2011) and salmonid foraging (Oglesby et al. 1972).

Riverbank Erosion

The difficulty of including vegetation in any analysis of riverbank erosion lies in the modifications to bank hydrology, flow hydraulics, and bank geotechnical properties that the plants themselves introduce. Difficulty of quantifying riverbank erosion also lies in the assumption that the above factors are likely to change drastically over a small area. As catchment area increases, new bank-erosion mechanisms come into play as the channel becomes larger (Abernethy & Rutherfurd 1998).

This study employs an approach to studying the site-specific effect that vegetation and LWD has on erosion in a specific reach of the Chocolay River in Michigan, southeast of the city of Marquette. Along this river, there are distinctive sections where public access to state and federal land is possible, increasing the potential for the implementation of habitat restoration strategies. Plentiful public access can also pose many problems because, for example, alterations of hydrodynamics and sediment deposition imposed from bridges and roads located at a close proximity to the bank can result in changes in channel morphology many miles away (Trombulak & Frissell 1999). Road crossing can also act as physical barriers to the movement of fish, possibly because confined flows increase flow velocities to a speed that is too fast, or because barriers such as culverts may invoke a behavioral response in fish that prevent movement (Trombulak & Frissell 1999). Social factors may be of a concern if land-owners do not want to participate in restoration activities (Shields et al. 2003).

River Restoration

In the United States, restoration projects cost a billion dollars or more each year (Katz et al. 2007). These projects vary greatly in purpose and include: barrier removal, sediment reduction, restore stream complexity, diversion screens, nutrient enrichment, restore instream flow, restore riparian function, water quality improvement, and upland management (Katz et al. 2007). It is important to note that of these project types, the cheapest (sediment reduction, riparian improvements, and upland management) were found to be the most common (Katz et al. 2007). Specifically, improvement of vegetative cover is one of the most easily manipulated components of a drainage basin or river channel (Harper & Ferguson 1995). The proposed restoration of the Chocolay River is therefore highly practical when dealing with a limited budget because it offers planning solutions that are relatively easy to initiate.

In this study, the restoration objective will be to obtain an ecosystem, in this case both aquatic and terrestrial, with the same level of heterogeneity inherent in an undisturbed system.

This means that we cannot manage erosion in its entirety, but must strive for an equilibrium of erosion and deposition that would have been present prior to human impacts (Kondolf & Micheli 1995). In human disturbed riverscapes, effectively controlling invasive species has a positive influence on managing erosion and ecosystem heterogeneity, because they are all part of an interconnected system (Allan 2004). Sometimes planners have to concentrate all of their restoration efforts in certain areas to overcompensate because of the degradation occurring in sections of the watershed that are under private ownership where restoration is not achievable (Kondolf & Micheli 1995). Furthermore, much of the degradation that is seen in a given body of water is not from current poor land-use practices (Allan 2004). This degradation stems from what is termed "legacy effects" and are the consequence of disturbances that continue to influence environmental conditions long after their initial appearance (Allan 2004). This would seem to have a substantial influence on a watershed in Michigan's Upper Peninsula, for instance, because of the devastating logging operations that occurred there during the late 19th/early 20th centuries.

Today, the Chocolay River would appear to be substantially more natural than it did when its banks were logged. Because of these legacy effects, we can only imagine the state of the river's original condition. Emphasis always should be placed on the conservation of rivers prior to their degradation because of the time and costs associated with full-scale ecosystem recovery (Palmer et al. 2005). There may be only a select number of vegetation species that are available to be planted at a particular site, but in flooded areas, each individual influences seed and fruit recruitment in its own way (Corenblit et al. 2009). It is generally acknowledged that natural systems have greater species diversity, structural features, and spatial heterogeneity than planted stands (Harrington 1999). Once restoration establishes vegetation along the stream channel, species diversity will increase through time, especially if species rare along the fluvial corridor are encouraged. All in all, the more riparian species present along a fluvial corridor, the more species could potentially benefit from restoration efforts (Rohde et al. 2006).

CHAPTER 3

REVIEW OF LITERATURE

Introduction

The presence or absence of riparian vegetation greatly determines the rate of streamside erosion. Migration rates and bank erodibility rates for a wet meadow, where vegetation is concentrated, versus a dry meadow reach, where vegetation is sparse, of the South Fork of the Kern River at Monache Meadow, California indicated the presence of increased migration rates along the dry meadow reach (Martin & Church 2000). Within vegetated areas, characteristics of vegetation that influence erosion rates include vegetation density, species assemblage, root depth, root strength, and soil matic suction[1]. The addition of roots to riverbanks improves stability even under the worst-case hydrological conditions and the benefit is apparent over a range of bank geometries, varying with tree position (Abernethy & Rutherfurd 2000). Vegetation alters bank hydrology and flow hydraulics, but these factors also vary with tree position (Abernethy & Rutherfurd 2000).

There is empirical evidence that suggests that the complex interrelationships that occur between riparian vegetation and fluvial processes cannot be generalized across catchments (Abernethy & Rutherfurd 1998). Instead, catchment-specific analysis must be considered, where vegetation assemblages are unique. Even more, where rivers vary greatly in their geomorphology or vegetation assemblage, site-specific analysis must be considered. For example, a fourth-order alluvial stream in British Columbia went from a width of 30 m to 150 m after logging bankside vegetation, and it braided (Schumm 2005). Therefore, where riparian vegetation produces stark

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[1] Soil matic suction is a sedimentological bank cohesion condition that states that with increasing pore water pressures that occur in moist or wet soil, the cohesion of sub-surface materials (i.e. roots) is dramatically increased

differences in a stream's morphology along its transverse, generalizing vegetation's impact on stream geomorphological change across an entire catchment is not recommended.

The distribution of riparian vegetation is directly correlated with specific fluvial landforms and processes which vary greatly across catchments. Generally, although this is not always the case, vegetation patterns suggest that species distributions in the humid east are largely controlled by frequency, duration, and intensity of floods (Hupp & Osterkamp 1996). Most riparian plants germinate in alluvium that is deposited during floods, floods may destroy pre-existing vegetation, and the occurrence of floods subsequent to germination may determine whether seedlings survive to maturity (Bendix & Hupp 2000). It is these disturbance regimes that influence the actual distribution of riparian vegetation. Using GIS analysis of historical photographs, hydrologic and sediment records, and stream channel measurements comparing two similar alluvial rivers in northwestern Colorado, Merrit & Cooper (2000) argue that channel geometry, meander rates and patterns, and the creation of fluvial landforms affect the distribution of riparian vegetation in both natural and human-modified systems.

When implementing a habitat restoration plan for a fluvial corridor and riverbank vegetation, it is important to balance the need to effectively manage erosion with a biodiverse collection of tree species that readily adapt to riverine environments. Several studies have indicated that flooded areas to be in a constant state of succession. In their article on riparian vegetation succession dynamics during floods along the river Tech, France, Corenblit et al. (2009) found seeds and fruits from 219 species to be distributed in deposited sediment across the floodplain. Seed recruitment was found to be higher in sites dominated by herbaceous vegetation than areas dominated by shrub or woody vegetation. This is an interesting finding, because geodesign of fluvial landscapes should incorporate both the biostabilization offered by roots from woody vegetation and the bioconstruction offered by herbaceous land-cover. This is an important aspect of all fluvial corridors, because spatial and temporal considerations of both types need to be considered before any watershed specific planning design can be implemented. Even with these considerations, landscape planners must consider the influences that upstream vegetation's seed dispersal mechanisms in a frequently flooded riparian area have on the current and future distributions of vegetation at a particular location.

Riparian area width varies greatly along a river's transverse, with no clear relationship to stream order. It has been suggested that small streams may actually need wider buffers than larger streams because small streams have less water and are consequently more sensitive to environmental change. In these headwater sections, annual disturbance resulting from peak spring flows can have a relatively higher impact on the stream channel and surrounding communities due to a higher ratio of flood water when compared to downstream sections (Hagan et al. 2006). Earlier management practices associated with riparian vegetation used a fixed-width buffer analysis based on stream order and/or channel width in the delineation of riparian areas (Holmes & Goebel 2011). Unfortunately, this time and cost saving technique has largely proven to be ineffective in the management of these ecologically sensitive areas. Instead, more recent emphasis has concentrated on the delineation of the functional extent of the riparian area to satisfy management objectives (Holmes & Goebel 2011). Holmes & Goebel (2011) compare a functionally delineated riparian area to a 50 foot and 300 foot buffer along streams of the Cuyahoga Valley National Park and the Cuyahoga River, Ohio, with results that indicate that fixed-width buffers inadequately delineate functional riparian areas. It is important to note that areas closer to the stream have highest riparian function, whereas areas farther from the stream are less likely to be within the functional riparian area.

Large woody debris (LWD) needs to be effectively managed as Salmonid habitat for several reasons. LWD alters flows below, around, or above (if it is submerged) the structure to add to channel complexity, or channel roughness. These flows will increase or decrease flow velocities, which consequently determine the bottom substrate characteristics. The structure itself is used as important habitat for several species either as cover to more successfully prey upon passing fish or invertebrates, or as cover to hide from predator species. Fish also like to position themselves downstream from a structure to minimize their physical exertion to stay in place. LWD is also an important natural erosion control because it shields the riverbank from the destructive forces of high velocity flows. An additional effect of LWD, particularly in smaller rivers, is that by increasing water retention and flow complexity, small to medium flood peaks are attenuated, and flood peak travel time is ultimately increased (Gurnell et al. 2002).

Distributions of Vegetation as Modified by Fluvial Processes

Riparian vegetation is affected by both floods and the characteristics of landforms that are shaped by floods (Bendix & Hupp 2000). It is therefore possible to predict occurrences of riparian vegetation by understanding the processes that affect their distributions over time. Analysis of the relationships between species distributions and fluvial landforms suggest that stream geometry, meander rates and patterns, and the creation of fluvial landforms must be considered in efforts to model riparian vegetation (Merritt & Cooper 2000).

Distributions Affected by Floods

Many studies have focused on distributions of riparian vegetation that has been affected by floods. Bendix & Hupp (2000) found that the distribution of riparian vegetation in bottomland floodplains is ultimately correlated to floods, namely via the differential destruction of vegetation, changes in substrate characteristics, and the transport of propagules[2]. Floods influence both the distribution of present vegetation and plant diversity as unevenly dispersed across the floodplain (Bendix & Hupp 2000). Goebel et al. (2003) studied the influence of frequent and infrequent flooding, as well as landform properties, on riparian plant community organization. Through the use of GIS and field sampling techniques, Goebel et al. (2003) found that in slightly entrenched stream valleys, such as the Little Carp River in Michigan's Upper Peninsula, changes in plant community composition are more likely associated with infrequent rather than frequent floods. Thus, plant community distributions can be correlated to the type and duration of flood events that are prominent in a particular catchment, or even within a specific reach within the catchment. A fourteen year study on the Platte River of Nebraska showed that migration of seedlings due to flooding and the erosion of the seed bank, are direct results of fluvial processes, where seedling mortality and distributions of specific riparian vegetation age-classes can be researched (Johnson 2000). Floods are therefore expected to give both an increase and/or a decrease in specific riparian vegetation populations. This is an excellent example of the intermediate disturbance hypothesis, which suggests that species diversity should be greatest where there are intermediate levels of disturbance (Bendix & Hupp 2000).

How Some Vegetation Assemblages Occur

The structure and composition of ground-flora and overstory vegetation are related to specific valley floor landforms, as well as the distance from and elevation above the bankfull stream channel (Goebel et al. 2003). Vegetation has different dispersal mechanisms depending on species, so fluvial processes that favor the quick establishment of ground-flora, might be disadvantageous for overstory species. In the Little Carp River of Michigan's Upper Peninsula,

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[2] Propagules refers to seeds, fruits, or segments through which vegetation can reproduce from with type of dispersal mechanism dependent on the species

Goebel et al. (2003) found that patterns of ground-flora appear to be ordered along a complex environmental gradient running from the stream channel to the adjacent uplands. Shade-tolerate conifer species were found in high enough concentrations making establishment of conifers in second-growth settings without management intervention difficult (Goebel et al. 2003). Camporeale & Ridolfi (2006) developed a model that calculates the probability density function of the overall vegetation biomass, the associative effects of river hydrology, and the influence of the type of riparian vegetation, compared to field observations. This stochastic model can also produce output data of spatial and temporal distributions of riparian vegetation when compared with data collected from transect sampling methods.

Control of Vegetation on Fluvial Processes

Riverside sediments eroding into the stream channel are among the most significant pollutants that degrade water quality of rivers across the world (Pollen 2007). It is a natural process, but the rate of erosion, when not in equilibrium with deposition rates, can have devastating effects on a river and adjacent land (Mac Nally et al. 2008). When the processes of erosion and deposition are in disequilibrium, such as often occurs in conjunction with human impacts, both aquatic and riverside ecosystems suffer. Aquatic ecosystems in higher elevation watersheds, for example, are dependent on riparian zones to shade streams and moderate temperature, provide allocthonous detritus[3], and large woody debris (LWD) to streams, stabilize banks, and mediate water, sediment, and nutrient inputs into streams (Mac Nally et al. 2008). When erosion is not kept in equilibrium by vegetation, such as would happen with activities such as streamside logging, these moderating characteristics of higher elevation watersheds are lost, and biodiversity suffers (Mac Nally et al. 2008). Cascading effects become apparent across the riparian zone; fish that have evolved for a particular ecosystem can become excluded because of

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[3] Allocthonous detritus is particulate matter with terrestrial origin, which enters a water body

sediment pollution, invasive species fill the niche left by the void of cleared vegetation, and increased meandering endangers human infrastructure. When considering the above factors, the importance of implementing best management practices and riparian management objectives, which can be incorporated into a larger watershed-scale management, is readily apparent.

Various studies have focused on the role vegetation plays in altering riverbank erosion rates (Abernethy & Rutherfurd 1998; Abernethy & Rutherfurd 2000; Corenblit et al. 2009; Eaton 2006; Mickovski et al. 2009; Pizzuto et al. 2010; Pollen 2007; Van De Weil & Darby 2007). Many of these have dealt specifically with quantifying the influence plant root properties of various species have on streambank erosion by using models that incorporate a multiplicity of factors associated with specific vegetation types. Along riverbanks, once vegetation is established, root systems increase erosion resistance and the stability of fluvially deposited sediments (Bertoldi et al. 2011). Models that focus primarily on root properties, such as the one created by Pollen (2007), can be used to determine rates of erosion in their spatial context. Other models, such as those generated by Abernethy & Rutherfurd (2000) and Van De Weil & Darby (2007), focus on comparing two or three tree species' effect on erosion. These models incorporate both the geotechnical properties of the riverbank and biophysical properties of the vegetation to determine differential rates of erosion in their spatial and temporal context (Abernethy & Rutherfurd 2000).

Typically during restoration riparian vegetation is manipulated in order to alter erosion rates, bank hydrology, and flow hydrology (Abernethy & Rutherfurd 1998). Predominant bank erosion by the mechanisms of subaerial preparation, fluvial environment, and mass failure have been found by Abernethy and Rutherfurd (1998) to have differential effects throughout upper, mid, and lower basin reaches of the Latrobe River, Gippsland, Victoria, Australia. Vegetation was found to exert three main influences on erosion in this study: (i) the main influence of vegetation over subaerial preparation is by the transfer of bank sediment to the flow via wind-thrown trees, (ii) increased hydraulic resistance due to large woody debris (LWD) and standing vegetation within the channel exerts a strong influence over the erosivity of the flow, and (iii) the main role of vegetation in stabilizing banks against mass failure is increased bank-substrate strength due to the presence of roots (Abernethy & Rutherfurd 1998). These factors (in their spatial context) can be used for the development of best management practices and to aid riparian zone management and watershed-scale management as well.

In a similar study, Van De Wiel & Darby (2007) determined that three specific factors control bank stability: (i) the surcharge exerted by vegetative biomass, (ii) the additional shear strength derived from root reinforcement of the soil, and (iii) variations in bank pore water pressure induced by the influence of vegetation on infiltration, evaporation, and canopy interception. Many studies have produced bank strength models using all or some of the above factors, and others including the bank strength model developed by Eaton (2006) that incorporates the main components of frictional properties of the material and effective cohesion, and quantifies the effect of vegetation on riverbank stability. Other studies have dealt specifically with isolating root properties of vegetation and determining its influence on erosion (Canadell et al. 1996, Collison 2001, Martin & Church 2000, Mickovski et al. 2009, Pollen 2007, Rinaldi et al. 2008, Van de Wiel et al. 2007)

Root Reinforcement of Riverbanks

Studies along the Goodwin Creek and Long Creek sites in Mississippi by Pollen (2007) demonstrate that equations can determine root reinforcement rates based on variations in root density, species assemblage, and soil shear strength. Models of the physical properties of riparian root networks in relation to streambank stability, where root tensile strength and soil moisture are interrelated factors, are used to determine distributions of erosion (Pollen 2007). A related study by Abernethy and Rutherfurd (2000) compare two species, *Eucalyptus camaldulensis* and *Melaleuca ericifolia*, to model root reinforcement of riverbanks. Van De Weil & Darby (2007) incorporate three mature riparian vegetation species (birch, poplar, and willow) and their effect on net riverbank stability. Extensive strong root networks tend to improve bank stability while excessive vegetation weight is destabilizing (Van De Weil & Darby 2007). Maximum rooting depth of 253 species of vegetation were quantified by Canadell et al. (1996), making geodesign of riparian zones possible with integration of compatible species, of which a few are commonly present in the riparian zones of the upper Midwest states. Of the many species, root depth varies greatly, and is directly correlated to adaptations to the environment.

Grassy vs. Woody Vegetation

Grassy or woody vegetation may be more appropriate in managing erosion in particular geotechnical settings. For example, grassy vegetation may even be superior to woody vegetation in preventing erosion where banks are lower and less steep (Lyons et al. 2000). This is because herbaceous land cover has a dense collection of fine roots as opposed to the thicker roots provided by woody vegetation that reach to deeper depths. In a related study, Wynn et al. (2004) found that the root length density of herbaceous sites were higher than forested sites in the top 30 cm of the soil profile. Alternatively, forested sites had a much higher root length density below this depth (Wynn et al. 2004). Woody vegetation would then be expected to provide better erosion protection when banks are high (> 1 meter) and steep (> 45 degrees) (Lyons et al. 2000). When managing the vegetation on the banks of a river, however, it is important to note that it is much better to go from herbaceous land cover to woody land cover than the opposite. Seedlings can be planted with minimal impact of releasing sediment into the stream channel, but to remove a large tree could have devastating effects.

Large Woody Debris

An important aspect to consider when implementing LWD projects on a particular stream is whether wood recruitment rates are in equilibrium of what would be expected under natural, non-human modified environmental conditions. Today, stream restoration projects are often implemented without significant thought regarding the historical amount of wood recruitment that has occurred predating human influences (Warren et al. 2009). An often neglected aspect to consider, but nonetheless important, is that as much as 80% of salmon carcasses have been shown to be retained by woody debris within as little as 200 m of release sites. This is an important aspect given that salmonid derived nutrients play a crucial role in nutrient recycling in streams (Naiman & Décamps 1997). Warren et al. (2009) use a space-for-time analysis to quantify large wood loading to 28 streams in the northeast United States with a range of in-stream and riparian forest characteristics and find that the frequency and volume of LWD in streams is most closely associated with the age of the dominant canopy trees in the riparian forest. This would have a significant impact on LWD recruitment, as expected, if the banks of the river channel are forested or have land that is comprised of human land-uses. LWD has historically been removed for many reasons including: use for firewood, improve navigation, increase the hydraulic capacity of the channels, facilitate fish migration, or for aesthetic reasons (Díez et al. 2000).

In pristine Salmonid habitat along a cold water stream in the northeast United States, incorporating LWD strategies into any restoration plan is a necessity. LWD serves important functions including: pool formation, sediment and organic matter retention, and in creating fish and invertebrate habitat (Warren et al. 2009). These positive effects on the stream channel are readily apparent when LWD is removed. Díez et al. (2000) tested these effects by experimentally removing all wood from two first-order reaches of two neighboring tributaries in the Basque County in Spain. Results indicate that the removal of LWD increases water velocity, increases scouring of sediments, decreases channel stability, and decreases the number and size of pools. Furthermore, the removal of LWD significantly altered the stream morphology, and the amount and composition of sediments.

Because Salmonid species require sediment of a particular size for spawning, LWD is an essential component of a restoration project focusing on these fish. Considering habitat heterogeneity, LWD significantly alters flow regimes throughout the channel, which in turn alters the spatial and temporal deposition of sediment (Naiman & Decamps 1997). Instead of a mixed sediment composition type that would likely occur in the absence of LWD, the presence of LWD will create patches of fine sediment and "deflect" maximum velocity flows, creating patches of coarse sediment along riffles in the process. Finally, debris jams trap organic matter and increase contact time with nitrate rich water, creating hot spots of N retention in forested streams (Vidon et al. 2010).

LWD present is also contingent on stream size. Kraft et al. (2011) attempted to quantify the spatial extent and pattern of in-stream wood distribution, and apply a binned neighbor-k approach in evaluating the distribution of wood habitat in 17 northeast North American streams. Results indicated that there is increased wood distribution organization at an intermediate stream size (up to 10 meter bankfull width) (Kraft et al. 2011). LWD in small streams and upper reaches is most likely to have originated from the surrounding landscape rather than by transport and accumulation, which is significant in larger streams and lower reaches.

Despite the evidence that suggests that the transportation of large wood, which is defined as at least one meter and length and ten centimeters in diameter, is higher in larger streams and lower reaches, small wood still plays an important role upstream (Millington & Sear 2007). Millington and Sear (2007) stimulate small wood in three study reaches within a low-order stream in the New Forest, UK to provide a detailed representation of the influence of restoration on small-wood transport and the relative importance of different trapping sites. Results indicate that wood jams are the most effective structures for trapping small wood and that, as expected, small wood travels further than long pieces. This suggests that LWD structures are dependent on the confounding interaction among stream size (affecting upstream transport) and the surrounding vegetation age (influencing wood size).

Webster et al. (2008) investigated coarse woody debris size-structure, decay class composition, and distribution of riparian communities in a catchment of the Lake Superior watershed on the Keweenaw Peninsula, Michigan. They found that down dead wood accumulation is nonlinearly distributed along transects perpendicular to the stream, with a peak in abundance 30-50 m away from the wetted channel. Fallen wood closer to the stream channel obviously has a higher probability of stream transport and being incorporated as LWD within the channel, as well as encountering enhanced decomposition rates due to moist conditions (Webster et al. 2008). Considering that vegetation 30-50 m away from the stream channel may still experience periodic disturbance, it makes sense that abundances are greatest at this distance. Fallen vegetation on the forest floor may persist for a century or more due to restrictive transport by standing vegetation, outward channel migration, or insufficient flood velocities to transport the down wood where it is located on the forest floor (Webster et al. 2008).

LWD also causes seasonal changes in a species preference to use it as habitat. Nagayama et al. (2012) examine the effects of the configuration of LWD on the use of habitats by fish in autumn and winter. As expected, fish habitat use of wood structures differed between warm and cool seasons because fish generally become lackadaisical during cooler months. This study observed that during both seasons, in-stream LWD, particularly log jams with longer size and higher complexity, provide habitats for various fish species. As discussed previously, LWD structures improve stream channel heterogeneity by providing deeper habitat, finer sediment, and more diverse flow conditions, all of which are advantageous characteristics of fish habitat. Thus, for a migrating and non-migrating salmonid species, LWD's importance as habitat is crucial.

The habitat suitability of LWD is usually contingent on fish behavior, with LWD preferences of an individual dependent on fish species and fish size. Relationships between salmonid assemblages and large wood jams differ between different geomorphological settings, as shown by Morris et al. (2012) in a study on the habitat preferences of brook trout (*Salcelinus fontimalis*) in the Little Carp River, a small tributary to Lake Superior in old-growth conifer hardwood forest in northern Michigan. Brook trout increase in abundance and have a greater size distribution in pools with large wood jams compared to pools without, with large wood jams with more pieces providing the most ample habitat (Morris et al. 2012).

Salmonid Nutrient Recycling in Streams

There exists a positive feedback mechanism between salmonid nutrient recycling and riparian vegetation growth (Helfield & Naiman 2001). Post spawning salmonid carcasses release particulate and dissolved organic matter within the stream, enhancing stream bacterial and algal growth, that is, if they escape terrestrial predators and scavengers (Owens et al. 2005). Furthermore, these nutrients, especially nitrogen (N) and phosphorous (P), facilitate enhanced growth rates of riparian vegetation (Vidon et al. 2010). Results from Helfield and Naiman (2001) indicate that trees and shrubs near spawning streams derive 22-24% of their foliar N from spawning salmon. As growth rates increase due to this subsidy, the quality of instream habitat is increased through shading, sediment and nutrient filtration, and production of large woody debris (LWD) (Helfield & Naiman 2001). In conclusion, in a natural system, decomposing salmon resulting in the mass release of salmonid derived nutrients ensures healthy habitat for future generations.

Mass spawning migrations of salmonids influence rivers both directly, by altering streambed and bank morphology and annual volumes of bedload transported material through redd construction[4], and indirectly, by influencing the supply of nutrients to the riparian zone through carcass decomposition (DeVries 2012). The supply of nutrients that salmonid species import into stream ecosystems can significantly alter tree growth rates, which may influence the in-channel dynamics of LWD and bank stability (DeVries 2012). Some recent research has focused on the impact that salmonid species can have on riparian vegetation growth rates by studying tree-ring cores of trees adjacent to the river channel (Drake & Naiman 2007). Incorporating this method into their research, Drake and Naiman (2007) were able to reconstruct the abundance of stream spawning salmon over 150-350 years in five mid-order rivers in the Pacific Northwest, with years of rapid growth indicating large salmon populations and years of slow growth indicating small salmon populations. Although tree growth is only likely to respond to salmon derived nutrients if the trees are nutrient limited, chronology data suggests that abundant salmon, nevertheless, increase riparian vegetation growth rates, than in the absence of salmon (Drake & Naiman 2007). Increased growth rates of vegetation coincides with an increased supply of LWD to the stream channel, which can influence floodplain formation and

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[4] Redd-a hollow in sand or gravel on a river bed, excavated as a spawning place for salmon, trout, or other fish

channel planform, development and maintenance of channel splits, bathymetry, channel width, local channel slope and grade control, distributions of sediment grain sizes, and processing of episodic large sediment inputs (DeVries 2012).

Salmonids create biogeochemical hotspots, which are areas or patches that show disproportionately high reaction rates relative to the surrounding area (Vidon et al. 2010), in the aquatic and riparian environments during spawning events, which is one more driver that can increase biodiversity in these already biodiverse ecosystems (McIntyre et al. 2008). There exists four primary mechanisms by which salmonid derived nutrients are transported to the riparian zone: (i) deposition of carcasses, (ii) transference of dissolved nutrients through the hyphoric[5] zone to groundwater and roots, (iii) terrestrial and avian predators, and (iv) freezing and ice formation (DeVries 2012). Spawning migrations often result in long-distance transport of nutrients which may become more concentrated in suitable spawning localities (McIntyre et al. 2008). Trees may retain salmonid derived nutrients in the ecosystem for 30 years or more (DeVries 2012).

Sitka spruce (*Picea sitchensis*) and western hemlock (*Tsuga heterophylla*) are two riparian species that have been shown to have accelerated growth rates due to salmonid derived nutrients (Helfield & Naiman 2001). Performing isotopic analysis on nitrogen ratios from riparian vegetation foliage can indicate which plant individuals have had growth rates influenced by marine enrichment, which is exemplified by Helfield and Naiman (2001), whose research indicates that vegetation near spawning streams derive ~22-24% of their foliar N from spawning salmon.

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[5] Hyphoric zone refers to a region beneath and alongside a stream bed, where mixing of shallow groundwater and surface water occurs, along with their nutrients

Besides N, phosphorous (P) is another product of salmonid derived nutrients that are delivered to riparian communities (McIntyre et al. 2008). To assess the role of fish derived nutrients in creating habitat spatial variation, McIntyre et al. (2008) compared fish community characteristics (species richness, density, individual mass, community biomass) and aggregate excretion (N, P, N:P) between riffles and runs in Rio Las Marias, a species-rich tropical stream located in Venezuela. Habitat preferences of fish, especially during spawning, create hotspots of nutrient recycling in streams. Size structure is an important determinant, as demonstrated by McIntyre et al. (2008), which shows that riffles are characterized by dense populations of small fish, whereas runs have lower densities but larger species. This "patchy" distribution of fish and invertebrates in streams, due to habitat preferences, species interactions, and social behaviors, is what ultimately determines N and P loading rates in aquatic and adjacent terrestrial ecosystems (McIntyre et al. 2008).

In addition, salmonid derived nutrients are likely to transferred to and retained more in certain landforms than others, and nutrients available to plants may already previously be more readily available in some fluvial settings than others. Therefore, any additions of salmonid derived nutrients could be deemed as surplus (Mouw & Dixson 2008). Mouw and Dixson (2008) study the influence that different fluvial landforms have on tree growth and understory species richness in a tributary of Turnagain Arm of Cook Inlet, Alaska and find that trees in floodplains and alluvial fans grow up to three times the growth rate supported upon bedrock-controlled landforms. The higher growth rates observed in depositional landforms compared to bedrock-controlled landforms could be due to a greater capacity of groundwater retention and conveyance than bedrock substratum, in addition to the transport of nutrients in groundwater (Mouw & Dixson 2008).

Salmonid derived nutrients have the potential to increase habitat heterogeneity by increasing riparian vegetation growth rates (DeVries 2012). These riparian plants strongly affect the ecological character of streams, especially through subsidies such as leaves, wood, nutrients, and invertebrates, which affect stream food webs and aquatic ecosystem processes (Harper & Ferguson 1995). These subsidies can have a net positive impact on fish species and providing suitable habitat that is essential for the different life stages of salmonids (Drake & Naiman 2007). This is a perfect example of a positive feedback mechanism between salmon and the riparian forests.

Nevertheless, a study by Wilzbach et al. (2005) points out that primary production in streams is often reduced by excessive nutrients and limited incipient solar radiation. Deemed as a somewhat controversial measure, Wilzbach et al. (2005) find that canopy opening consistently enhances salmonid biomass, density, and growth. Canopy opening increases primary production, which is debatably the most important trophic pathway for increasing the availability of aquatic macroinvertebrates preferred by salmonids during spring and fall (Wilzbach et al. 2005). Caution should be made before attempting to implement this controversial measure, because increased stream water temperatures could make salmonid habitat unsuitable, especially if stream temperatures are currently near an inhospitable temperature threshold, or are expected to be in light of future climate change (Wilzbach et al. 2005).

Redd Construction and Influence of Fine Sediment Deposition

Too much sediment in a stream can obviously have several negative consequences. The following three examples demonstrate how sediment can negatively affect riverine ecosystems: (i) sedimentation on floodplains affecting habitats and land use, (ii) sedimentation on river channels causing changes in river morphology and behavior, and (iii) sedimentation of salmonid spawning gravel and altering other sensitive habitats, which reduces or changes biodiversity (Owens et al. 2005). Of these three, this study focuses primarily on the third, but it must be emphasized that all influences are intimately connected. That is, sedimentation that changes river morphology will affect salmonid habitat of all life stages, and floodplain sedimentation affecting habitats and land use will subsequently influence riparian vegetation assemblage, which in turn affects stream morphology and salmonid habitat.

Salmonids spawn by digging in selected gravel and small cobble substrates to bury fertilized eggs in a redd, or egg nest. Excavated material is flushed downstream during redd construction, with finer grain sizes transported farther downstream than coarser grain sizes, resulting in partial sorting of the substrate (DeVries 2012). Once redds are created, they contain gravels of enhanced permeability and have a distinct morphology that induces down-welling of surface water, which increases oxygen availability (Grieg et al. 2007). Suitable substrate increases embryo survivability in several ways: (i) protection from predators, (ii) shelter from currents, (iii) habitat for invertebrates, and (iv) increases the availability of heterogeneous habitat (Kemp et al. 2011).

In a freshwater ecology laboratory in Quebec, Franssen et al. (2012) study potential factors that may influence embryo survivability in an artificial environment, and find that emergence spans a highly variable time period ranging from 66 days to 142 days after egg fertilization. Interestingly, embryos that encounter stressful environmental conditions (e.g. limited oxygen supply or excess nutrients) may emerge early, but underdevelopment often causes decreased fitness (Franssen et al. 2012). Silt and sand deposition in the pores occupied by salmonid eggs prohibits oxygen consumption, nullifying the positive affect of increased flow velocity and oxygen flux through trough the gravel bed (Franssen et al. 2012). Given that both males and females die within a few days to two weeks post-spawning (O'Toole et al. 2006), protection of the redd is expected to be short lived, developing embryos are left vulnerable, and deposition of fine sediment can significantly decrease the probability of salmonid emergence. Conversely, salmonids sometimes may select substrates previously used for spawning, being that it requires less energy, and may flush fine sediment that may have accumulated since the redd's original construction, increasing survivability of eggs previously deposited in the process (DeVries 2012).

Agricultural practices are often associated with excessive fine sediment[6] deposition in streams, which often is accompanied with enhanced levels of sediment bound nutrients, pesticides, and herbicides (Greig et al. 2007). Soulsby et al. (2001) study spawning habitat utilized by Atlantic salmon (*Salmon salar*) and sea trout (*Salmo trutta*) in a highly canalized lowland agricultural tributary of the River Don in Aberdeenshire, Scotland, and the results are startling. Egg mortalities can be as high as 86% due to fine sediment infiltration, reduced permeability of spawning gravels, and reduced oxygen supply to ova (Soulsby et al. 2001). Given that the probability of salmonid survival is substantially low in early developmental life stages (Kemp et al. 2011), a 14% hatch rate is unlikely to maintain a population, especially given the multiplicity of stressors that agricultural streams can have on all life stages of salmonids. A model that predicts salmonid embryo survivability rates in the presence of percent fine material less than or equal to one millimeter created by Kemp et al. (2011) suggests that an upward limit of 90-95% survivability occurs irrespective of the level of fines, and <5% occurs in conditions of relatively high sediment greater than thirty percent by mass.

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[6] Fine sediment size of less than or equal to two millimeters is quoted in the literature to negatively affect salmonid spawning habitat

Survivability rates can vary greatly between rivers, or specific sections of river, as exemplified by Greig et al. (2007), whose research indicates that maximum survival rates were anywhere from 8.7%-100% at sites occupying eight different rivers located in the United Kingdom. Again, fine sediment deposition was the main factor in determining embryo survivability, with an addition of 0.3 g and 0.5 g of clay reducing oxygen consumption by 41%, and 96% respectively (Greig et al. 2007). These reduced consumption rates are likely to cause dramatic increases in mortalities, because the clay particles create a zone of low oxygen supply around the eggs and can physically block the pore canals in the outer layer of the egg's membrane, thereby restricting the transport of oxygen (Greig et al. 2007). Simply stated, mortalities occur once oxygen concentrations drop below a critical threshold or when oxygen supply rates are insufficient to support metabolic demands (Greig et al. 2007). Additionally, spawning substrate suitability is dependent on the size of the female fish and the species of concern, factors that determine egg diameter (Kemp et al. 2011). *Salmo trutta* remains fairly flexible in their particle size preferences, which range from 7 to 128 mm, given that their egg diameter varies between 3.2-5.9 mm (Kemp et al. 2011).

Oxygen supply is the best determinant of egg to emergence survival (Greig et al. 2005). The settling and infiltration of fine sediment into gravel interstices disrupts inter-gravel water flow and reduces oxygen levels, which are vital to benthic invertebrates (Owens et al. 2005) and especially crucial for developing salmonid embryos (Greig et al. 2007). Decreased oxygen concentrations can also be the result of the decomposition of organic matter or by oxygen consumption of the salmonid eggs themselves (Sternecker et al. 2013). 15% fines are typical of those quoted in the literature as likely to reduce the survival of embryos due to reduced oxygen availability (Soulsby et al. 2001). Fine sediment deposition causes entombment and asphyxiation of developing salmonid embryos, the key mechanisms in salmonid egg to emergence survival (Franssen et al. 2012). Also, at least a minimum interstitial flow[7] velocity is required to ensure adequate oxygen transport to the egg membrane (Franssen et al. 2012).

Sand is transported both in suspension and in contact with the bed as migrating bedforms, with rates depending on stream power (Brown 1999), which would have a significant negative impact if high sand densities are located directly upstream from a newly constructed redd and an influx of stream power causes sand migration downstream. These factors have been shown to produce starkly different embryo survivability rates, as Sternecker et al. (2013) demonstrates in a study on brown trout (*Salmo trutta*) egg hatching rates, which vary greatly between hatchery and natural conditions in the stream bed, as well as between different streams and different sediment depths. A significant decrease in hatching rate can be expected at lower substrate depths, unless accumulated fine sediment in the surface of the interstitial zone is accompanied by oxygenated upwelling groundwater at deeper depths, making conditions at deeper substratum more favorable (Sternecker et al. 2013). It shouldn't come as a surprise that salmonid populations have been shown to display preferences for spawning in zones of groundwater upwelling, which are often located at zones of high topographic relief (Greig et al. 2007).

Animal Impacts to River Corridors

Herds of large herbivores can cause significant impacts to riparian vegetation, such as may occur wherever a large group of white-tailed deer (*Odocoileus virginianus*) crosses a stream, which causes impacts associated with erosion (Forman 1995). Some species may even move variable distances along the corridor, causing significant effects on the vegetation, soil, and water (Forman 1995). White-tailed deer are likely to cause the largest impacts to stand

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[7] Interstitial flow refers to fluid flow around an interstitial cell: a cell attached to extracellular matrix in three dimensions. In this case, the developing embryo is attached to an extracellular matrix comprised of various sediment sizes in the stream substrate, with flow influenced by both depth and volume of sediment pore space.

composition and development through browsing wherever favorable habitat exists in many Northwest states (Ruzicka et al. 2010). Ruzicka et al. (2010) studied the tree species composition, herbaceous vegetation, and deer browsing patterns in the Cache River watershed in southern Illinois following lowland hardwood forest restoration, and found that deer browsing influences forest stand composition and density as a function of distance from the nearest forest edge. The vegetative species that exist along the forest edge, such as swamp Spanish oak (*Quercus palustris*), are likely to be favored by white-tailed deer for browsing, and thus are more likely to influence overall vegetation composition (Ruzicka et al. 2010).

Understory communities are impacted through differential browsing of vegetation by white-tailed deer, which decreases the frequency of sexual reproduction and fecundity of preferred forage species (Kraft et al. 2004). In a study by Kraft et al. (2004), the composition and structure of vegetation following browsing by white-tailed deer in three thinned and two unthinned forest dominated by sugar maple (*Acer saccharum* Marsh.) in Michigan's Upper Peninsula indicated that plant morphology, frequency of flowering, and frequency of fruiting were the most sensitive indicators of deer browsing activities. The recruitment of younger vegetation size classes may significantly decrease in this case (Kraft et al. 2004). Initial planting of larger plants should be done in riparian vegetation restoration schemes, so as to reduce the potential of damaging deer browsing (Kraft et al. 2004).

Considering that riparian vegetation is highly variable in composition spanning across different spatial and temporal scales, for example from shrub growth along the riverbanks to species adapted to hydric soils on the terrace to upland vegetation further out, these corridors are highly favorable for many species including white-tailed deer (Forman 1995). Different groups of animals occupy the different layers of vegetation (i.e. because of differences in distance to water, shade, and food production), and this causes a multitude of effects on the different vegetative species spanning across this corridor (Patten 1998).

Interestingly, Hickford and Schiel (2010) studied source and sink population dynamics of the common Galaxias (*Galaxias maculatus*), a fish common in the southern hemisphere, in 14 rivers in New Zealand and found that the exclusion of livestock resulted in quick regeneration of riparian vegetation, and a tenfold increase in egg laying by fish and a threefold increase in survival. Rivers or sections of rivers with extreme impacts from livestock or native fauna can therefore be considered sinks because local fish species cannot produce a sustainable population (Hickford and Schiel 2010).

Riparian Areas as Habitat

Riparian vegetation is an important habitat component for both aquatic and terrestrial species. For example, specific tree species provide bankside cover to the North American river otter (*Lontra canadensis*), which is an essential element of their habitat to be used as a holt[8] (Harper & Ferguson 1995). Animals also provide a positive feedback mechanism in enriching riparian vegetation species richness, because mammalian herbivores can play an influential role in plant succession, and salmonids can impact plant growth and forest structure by fertilization (Mouw & Dixson 2008). Differential habitat is essential, especially when maintaining two populations of competing animals, such as the North American river otter and the American mink. Without varied habitat and adequate terrestrial prey populations (such as rabbits and voles), the population of the American mink would be expected to suffer in the presence of otters, given the aquatic foraging skills of the North American river otter (Bonesi & Macdonald 2004). Fallen dead trees, with increased proportions attributed to fluvial disturbance events,

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[8] A otter's den is referred to as a holt. In the U.K., otters prefer the streamside roots of mature ash and sycamore trees to be used as holts (Harper & Ferguson 1995).

provides important habitat for amphibians, small mammals, plants, and fungi (Webster et al. 2008). Within stream channels, LWD provides habitat for many species of aquatic invertebrates, fish, and critical rearing areas for juvenile fish (Webster et al. 2008).

Riparian vegetation is essential for nature's most influential hydrological engineer, the North American beaver (*Castor Canadensis*). The work of beavers has been deemed as somewhat controversial. As a benefit, beavers increase habitat heterogeneity through the construction of dams, which in turn increases invertebrate biomass up to fivefold and changes riparian vegetation species assemblage. Mature deciduous trees are cleared in the process of dam construction, allowing for increased shrubby growth and decreased competition for coniferous trees. As flow velocities decrease, the retention of sediment and organic matter increases (Harper & Ferguson 1995). The result is a decreased suspended load of fine particulate matter downstream of beaver dams. Although this factor may be beneficial to salmonid species with regards to decreased rates of sedimentation in spawning redds, the migration of salmonids is sometimes impeded by large beaver dams. It is therefore important that populations of the North American beaver be monitored in natural systems so that potential impacts are kept in equilibrium; a factor that has proven to be extremely detrimental where the population has gotten out of hand, evident in some European streams where it is non-native (Harper & Ferguson 1995).

Flow characteristics and patterns influence the colonization of plants, as long as the plant is able to withstand the force exerted by the flow over varying timescales (Harper & Ferguson 1995). For example, plants may colonize in alluvium deposited during a small flood at a short distance away from the stream channel. This hypothetical plant may be able to withstand flow conditions for a variable time period after the flood occurrence, but if larger floods are common, the plant may not be able to survive until reproductive age. Thus, consideration of high flows is essential when designing river rehabilitation or restoration projects that focus on increasing vegetative cover (Harper & Ferguson 1995). Alternatively, many species can resprout after breakage or burial of either the stem or roots from floods, or after being partially eaten, and introductions of these resilient species in riparian environments should be strongly considered (Nilsson & Svedmark 2002). Once these plants establish themselves, longer and denser roots increase bank stability, and decrease erosion (Abernethy & Rutherfurd 1997). Periodic flooding often holds successional change in check, therefore, keeping a consistent species assemblage of certain riparian communities through time (Bendix & Hupp 2000).

Invasive Species

Non-native invasive plants can be detrimental to ecosystems worldwide because they are generally homogenizing species that outcompete natives for nutrients and resources. Many invasive plants have "weedy" life history characteristics that adapt them for rapid dispersal and invasion of early successional communities, especially if there is a great deal of similarity between the introduced species' native and present environments (Hilty et al. 2006). Human land-uses adjacent to a stream are usually significant sources of invasive species dispersal, especially from roads or urban areas. For example, roads provide dispersal of exotics via three mechanisms: (i) providing habitat by altering conditions, (ii) making invasion more likely by stressing or removing native species, and (iii) allowing easier movement by wild or human vectors (Trombulak & Frissell 1999). Native fauna actively select native plants to browse upon, being familiar with them, which leads to higher survivability of invasive plants due to decreased competition (Hilty et al. 2006). A heterogeneous riparian vegetation community is essential in providing stream complexity (will be discussed more in-depth in the literature review). Homogenizing species such as purple loosestrife (*Lythrum salicaria*) and phragmites

(*Phragmites australis*) can have devastating impacts on maintaining an equilibrium of channel morphological change through time, which subsequently impacts riparian fauna, especially salmonid species (Schumm 2005). For example, purple loosestrife is a herbaceous plant that doesn't have long roots compared to some riparian species, which would have a negative impact if banks are high and they exceed the depth of roots, resulting in undercutting that eventually causes bank failure (Schumm 2005).

Other invasive species, such as phragmites and purple loosestrife, have been degrading wetland habitats across Michigan, including riparian areas (Morrison 2002; Lambert et al. 2010). For example, purple loosestrife displaces native plants, provides poor animal habitat, alters hydrology, and alters nutrient cycling (Morrison 2002). Phragmites quickly transforms native low- or mixed-statured communities into tall grass monocultures wherever it is established, greatly affecting nutrient cycling and sedimentation rates in the process (Lambert et al. 2010).

Invasive plants can have a remarked impact on nutrient cycling in terrestrial and aquatic systems. Mineau et al. (2011) hypothesize that Russian olive (*Elaeagnus angustifolia*) has the potential to subsidize stream ecosystems by nitrogen fixation, with infestations of greater density being the most detrimental. This is because primary productivity is limited in terrestrial and aquatic systems when nitrogen inputs are increased, which can negatively affect food webs. The impact is magnified further when organic inputs to streams (i.e. leaves, wood, nutrients, and invertebrates) are substantially different than native riparian vegetation, causing a further decrease in primary productivity. Russian olive's cousin, autumn olive (*Elaeagnus umbellate*), another nitrogen fixing species, has been vigorously invading riparian communities across Michigan, and should be prioritized as a main threat to these systems in this state (Mineau et al. 2011).

Because this study focuses on both restoration and preservation of the interface between aquatic and terrestrial systems, early detection of invasive species before they spread and become increasingly difficult to eradicate is an important issue (Lambert et al. 2010). Monitoring efforts on the Chocolay River would be somewhat difficult, however, because of access difficulties for much of the mainstream, besides the last few miles of the river before it empties into Lake Superior. Furthermore, it is expected that Phragmites and purple loosestrife would have a lower probability of incidence along the Chocolay River, because they are often associated with human disturbances in wetlands, which there are relatively few in this area (Lambert et al. 2010).

Rachich and Reader (1999) study the influence that disturbance and herbivores have on purple loosestrife distributions, by comparing vegetated and non-vegetated plots, and enclosed and non-enclosed plots, along Cox's Creek, northwest of Guelph, Ontario, Canada. In this study, only plots where vegetation was removed did purple loosestrife become established, with herbivores having minimal impact in seedling establishment. Along the Chocolay River, for instance, natural disturbances are usually moderate, with spring snowmelts providing the most damage. Purple loosestrife are prolific seed dispersers in the summer months, establishing a viable seed-bank along the fluvial corridor, and eventually spring emergence coinciding with spring disturbances (Morrison 2002).

Chemical Pollution

Rivers can be expected to have increased proportions of contaminants when compared to upland ecosystems (Malmqvist & Rundle 2002; O'Toole et al. 2006; Vidon et al. 2010). This can be explained by the transport of nutrients or chemicals to the stream channel by either natural or human causes (Vidon et al. 2010). Additions of both organic and inorganic nutrients stimulate the growth of bacteria, which increases the rate of conversion of organic carbon to inorganic carbon, resulting in an overall increase in the number of algae (Oglesby et al. 1972). One such human cause is the construction of roads, which are often responsible for high levels of dissolved nitrogen in the stream, and an increase of sediment, often accommodated by a phosphorus subsidy (Trombulak & Frissell 1999). In addition to harmful pollutants, an influx of nutrients delivered by road crossings causes increased eutrophication in the stream, as well as increased sediment, which has myriad consequences including a decrease in primary production (Trombulak & Frissell 1999). Natural processes cause a multitude of chemical substances to enter rivers from atmospheric inputs, decomposition of organic matter, and the weathering or rocks (Malmqvist & Rundle 2002). Riparian zones can therefore be considered as biogeochemical hot spots, as Vidon et al. (2010) demonstrate, due to disproportionately higher reaction rates relative to the surrounding area. Debris dams, in particular, have increased retention rates of organic material, and thus, are often considered hot spots of NO_3 retention in forested streams (Vidon et al. 2010).

This is an important factor, considering that N is often the nutrient limiting primary productivity in terrestrial and aquatic systems, because increased algal growth limits the transmission of insipient solar radiation (Mineau et al. 2011). Furthermore, temperature increases can be expected when greater N inputs create more turbid conditions. Conversely, the organic matter that accumulates at flow obstructions often supports richer invertebrate communities and may become vegetated (Harper & Ferguson 1995), suggesting a positive feedback mechanism that may increase habitat heterogeneity, and eventually lead to an increase in species richness. Nevertheless, overloading of N in rivers can negatively impact water quality due to decreased oxygen (Mineau et al. 2011). In fact, fewer than 10% of rivers can be classified as pristine in terms of their nitrate status, which is a product of N, as defined by the World Health Organization (Malmqvist & Rundle 2002).

Acid rain is also a problem, especially in the northern latitudes of developed countries, because it physically alters the pH of surface water (Malmqvist & Rundle 2002). Coniferous forests exacerbate both acidification and aluminum leaching, leading to a magnification of pH change in northern latitude streams where acid rain is also an issue (Harper & Ferguson 1995). Sulfate may be the predominant anion[9] in surface waters affected by acid rain, however, riparian soils and vegetation naturally reduce concentrations in sub-surface water due to uptake and microbial mediated reduction processes in anaerobic conditions (Liegel et al. 1991).

Other pollutants, such as pesticides and mercury, are often present in excess amounts in streams, and must be considered when assessing water quality (Vidon et al. 2010). Calcium, magnesium, potassium, sodium, and chlorine are also often present well in excess of biological demands within rivers (Harper & Ferguson 1995). Fine-grained sediment loads transported by many rivers are showing evidence of unhealthy concentrations of contaminants and nutrients, which can be deposited wherever slow flow velocities occur (Owens et al. 2005). The importance of riparian zones in fostering the removal of chemicals and excess nutrients is essential in maintaining healthy stream communities (Vidon et al. 2010). Transpiration may be quite high in riparian forests, increasing the mass flow of nutrient solutes toward root systems, often facilitated by nutrient uptake of flood-tolerant species under low-oxygen conditions (Naiman & Decamps 1997). Nutrients are then accumulated short-term in non-woody biomass and long-term in woody biomass of riparian vegetation (Naiman & Décamps 1997).

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[9] An anion (-) is an ion with more electrons than protons, giving it a net negative charge. These ions bind to cations (+), which have a net positive charge, such as sodium (Na+).

Contaminated aquatic ecosystems have been shown to contribute to increased proportions of pollutants in salmonids, as O'Toole et al. (2006) demonstrate. Polychlorinated biphenyls (PCBs) and organochlorines (OCs) accumulate in high concentrations in the tissues of fish in contaminated aquatic ecosystems, and may be released into river ecosystems in eggs, and through breakdown of lipid-rich tissues during carcass decay following spawning (O'Toole et al. 2006). Salmonids quickly accumulate these pollutants in their early life-stages, due to increased concentrations following carcass decay, with further additions likely being the result of atmospheric deposition of pollutants (O'Toole et al. 2006). These pollutants can then make their way onto land as salmonids are preyed upon, ingested, and fecal matter carries the contaminated contents some distance away from the stream channel (Nilsson & Svedmark 2002).

Management of Salmonid Habitat

The final aspect to consider in this bottom-up approach, is to consider how the above influences in-stream Salmonid habitat. A heterogeneous mixture of grassy vs. woody vegetation along the riverbanks in the right locations will also increase habitat heterogeneity in the river itself (Lyons et al. 2000). In the presence of grassy vegetation, one would expect a much higher proportion of undercut banks. It is important to provide localized conditions where undercut banks have the potential to occur because they are great habitat for juvenile salmonid fish and microinvertebrates. Knowing the habitat demands of all life stages of the intended management concern is essential to ensure that a sustainable population persists into the future (Harper & Ferguson 1995).

Woody vegetation is an important control of erosion, which ensures that the river channel itself is a "rough" channel; meaning that habitat heterogeneity is present in the form of pools, runs, and riffles interspaced throughout the channel. Proper management of woody vegetation is essential because erosion of riverbank sediments influences the stream bottom substrate composition, which is an important aspect considering Salmonid species require adequate spawning gravel of 16-150 mm (Hendry et al. 2003). In narrow streams, dense overstory vegetation may decrease water temperatures by increased shading, which should be a significant consideration in light of future climate change (Battin et al. 2007).

Another important aspect to consider is how particular land-use patterns influence salmonid abundance. As we have seen, riverbank characteristics influence the stream channel in numerous ways; stream geometry, substrate composition, and flow complexity all are determined by the adjacent riverbank. In a study on salmonid species abundance in the Snohomish River watershed in Washington, George et al. (2002) found that there are correlations between salmonid abundance and land use patterns/landscape characteristics. As expected, wetland occurrence, local geology, stream gradient, and land use were significantly correlated with abundance of adult coho salmon (George et al. 2002). Results indicated that coho salmon densities in forest-dominated areas were 1.5-3.5 times that of populations located in rural, urban, and agricultural areas (George et al. 2002). A snowball effect of salmonid population decrease occurs in conjunction with the amount of degraded habitat, water temperature increase, and increase in contaminants in these areas. Watersheds that have high levels of agriculture and urban land-uses generally carry more contaminants (Yong & Chen 2002).

Some salmonid species can be expected to respond differently to implemented restoration strategies from others. In their study, Jensen et al. (2009) create predictive relationships between percent fine sediment and egg-to-fry survival of Chinook, coho, and chum salmon, and steelhead trout. Their analysis indicates that coho salmon populations decrease most rapidly when fine sediment is deposited in spawning gravels and chum salmon the least rapidly. A threshold of 25-

30% fine gravel less than 0.85 millimeters in diameter is correlated to a significant decrease in salmon fry survival (Jensen et al. 2009).

Habitat Restoration for Future Trends

Restoration strategies of riparian vegetation also need to incorporate future trends in a dynamic system; meander patterns and climate change. The former is crucial because the proposed habitat restoration needs to be relatively long-term. As we have seen, climate change creates conditions that species across a wide spectrum need to adapt to, altering ecosystems in the process. For example, if climate change is likely to negatively influence the groundwater input across a riparian area, several species might not be able to survive (Pulwarty & Redmond 1997). The same holds true of temperature increase and damaging effects that may occur from direct solar radiation (Chen et al. 1998). New plantings of riparian vegetation should include species that can adapt to future projected climates. There are far too many sites that are in need of habitat restoration to constantly revisit and improve upon the same sites; they must be semi-permanent solutions to the unique issues that are present to a particular area. The later, river meandering, is a process of how the river moves longitudinally in conjunction with the spatial and temporal distributions of erosion and deposition rates. Many vegetation species in a particular riparian area prefer to be located a certain distance away from the stream channel, and these processes often determine if they live or die.

Climate Change

Climate change is expected to have a large negative effect on species intolerant of high temperatures, such as many salmonid species (Battin et al. 2007). Foreseen changes in temperature are likely to impact water conditions at a watershed scale, thus leaving salmonid species with nowhere to go. Of greatest concern are the pristine low-order reaches of a stream that are naturally more sensitive to change. Because these areas are often associated with a narrow channel and fast flowing conditions, they are accompanied with coarser sediments and become ideal locations for spawning. In their study, Battin et al. (2007) found that climate change is likely to have a greater influence on pristine low-order reaches, but these areas often have a lower potential for restoration that downstream localities. Focusing restoration on these locations, together with climate change, is likely to cause a spatial shift in salmonid abundance (Battin et al. 2007). Being able to forecast the future climate and its impact on salmonid species is important in order to focus restoration efforts in particular areas (Pulwarty & Redmond 1997). Ruesch et al. (2012) predicted climate-induced changes in summer thermal habitat for juvenile Chinook salmon, rainbow trout, and bull trout in the John Day River basin, northwestern United States. This study finds that trends in climate change are expected to drastically impact salmonid habitat by the year 2100, with habitat declines for Chinook salmon, rainbow trout, and bull trout estimated at 69-95%, 51-87%, and 86-100% respectively. It is noteworthy that these projections are made at the current rate of climate change and do not consider vegetation's influence on providing suitable salmonid habitat through shading and altering flow complexity through time. Battin et al. (2007) approach the task of projecting the effect of future climate change on salmonid habitat somewhat differently by using a series of models of climate, land cover, hydrology, and salmonid population dynamics.

To effectively be able to model for future climate change, it is first important to model the spatial and temporal distributions of stream temperature. Chen et al. (1998) developed a model to predict surface water temperatures in the Upper Grande Ronde watershed in northeast Oregon. They combine two main factors in their model; (i) solar radiation factors, including diurnal, seasonal, and longitudinal variations and (ii) shade factors from riparian vegetation density, height, and composition. When validating this model, stream temperatures are accurate to 2.6-3.0 degrees Celsius. Using this model, stream temperatures can be simulated for different hydroclimatic conditions and hypothetical restoration scenarios of riparian vegetation (Chen et al. 1998). In a similar study, Tague et al. (2007) modeled groundwater inputs as the main control of stream temperature within the McKenzie River basin in western Oregon. Results indicate that streams which are sourced from deeper groundwater reservoirs versus shallow subsurface flow systems have distinct summer temperature regimes (Tague et al. 2007). These two methods of modeling stream temperature are nonetheless seen as an improvement over using just air temperature as the main factor.

River Meandering

Modeling river migration is important in order to determine the location of natural and human areas that are in danger of stream erosion. A meander rate model can be generated by combining flow and bed topography sub-models with a geotechnical bank erosion sub-model (Darby et al. 2002). To test for the significance of the model, rates of erosion and/or deposition on both sides of a particular river bend were observed and compared by Darby et al. (2002) to the model over a five and a half year period.

Constantine et al. (2009) calculate meander rates based on state government bank erosion studies and geology maps, historical aerial photography, and field observations on the Sacramento River in northern California and found that in a large incised stream, riparian vegetation is expected to have less influence on curbing erosion rates, and mass failure and/or fluvial shear will have a larger impact. It is important to note that bank height is eight to ten meters and predominate depth is two to four meters, hence greatly incised, which would make the biostabilization offered by roots difficult. In these cases, quick growing vegetation with long rooting depths will have the greatest chance to lower erosion rates. By modeling meandering, an idea develops of where the stream channel will be located at a particular time in the future, this giving new plantings of vegetation that we want located next to the stream channel time to take root and become mature.

Several techniques have historically been used to model river meandering, with interpreting change through sequences of historical aerial photographs proving to be popular. This method involves taking aerial photographs taken at a similar spatial scale, georeferencing the images to a common coordinate system, and digitizing the stream's longitudinal profile. These longitudinal profiles produced from aerial photographs taken at different times will allow them to be compared, and for river meandering rates to be calculated. Micheli and Kirchner (2002) use remotely sensed photographs from 1955, 1976, and 1995 to quantify stream longitudinal profile and adjacent riparian vegetation types and integrate this data into a geographic information system. This process produced maps for a stretch of the South Fork of the Kern River at Monache Meadow, California to depict spatial and temporal patterns of increased migration, such as along higher riverbanks and the outside of bends (Micheli & Kirchner 2002).

Conclusion

Again, it is important for researchers to determine the spatial and temporal variability of erosion that occurs in catchment specific areas determined by a multiplicity of factors, especially vegetation type. Riparian vegetation management would be most effective when a clear, concise understanding of how much influence any given vegetation species might have on erosion rates in particular locations and times. To add to this complexity, habitat heterogeneity needs to be stressed as an alternative of just planting one single species that might have a much higher influence on controlling erosion in any particular site. Herbaceous vegetation needs to be stressed when appropriate to add to habitat heterogeneity due to both deposition of propagules on the riverbank and undercut banks for fish cover. Finally, the presence of LWD will serve two functions; to shield the riverbank from erosion and provide habitat for Salmonid species. To effectively accomplish this task of implementing a successful habitat restoration plan focusing around Salmonid fish species management, methods of analysis from various research perspectives should be extrapolated to study a particular catchment, or section of river.

In restoration of a habitat as sensitive to environmental change as riparian areas, landscape planners need to understand how successful past restoration strategies have been in the long-term. This is an important aspect to consider in order to be as efficient as possible with a limited budget, despite restoration projects costing a billion dollars or more each year in the United States alone (Katz et al. 2007). This figure only reinforces our understanding that riparian areas are diverse ecosystems that need to be restored for biodiversity, economics, and overall human well-being. Ecologically successful river restoration gives us hope in light of drastically changing conditions of riparian ecosystems, because restoration creates conditions (hydrological, geomorphological, and ecological) that allow the river to be a resilient self-sustainable system, one that has the capacity for recovery from rapid change and stress (Palmer et al. 2005). These favorable conditions take time to develop, because often what we see are “legacy effects” that continue to influence environmental conditions long after the initial appearance of the disturbance (Allan 2004). Eventually, the end result of restoration should be an ecosystem with the same level of heterogeneity inherent in an undisturbed system, and in the case of salmonid habitat restoration, the heterogeneity of riparian vegetation, river flows, and in-stream habitat (Harrington 1999). Through proper management of LWD and riparian vegetation, and looking at the past and future implications of habitat restoration, salmonid habitat can successfully be restored to pristine conditions, despite luminous climate change.

CHAPTER 4

METHODS

Field research was conducted on the Chocolay River during the months of June, July, and August in the year 2013. The researcher waded and/or kayaked the main river branch on suitable days, resulting in 10 full field days distributed over the summer. Suitable days were those in which the river did not exhibit high flows. The study reach was selected because it represents a transition from a high gradient gravel bed river to a sand bed alluvial river, which contains the first suitable spawning sites that anadromous salmonids come across as they migrate upstream. Salmonid spawning sites were selected based on continuous runs of spawning gravel that was observed by the researcher. Erosion sites were selected based on observations of exposed sediment, road/stream crossings, and developed areas, which are areas that are impacted by human infrastructure or manicured lawns, for example.

Three stream quality inventory forms were developed to study the spatial relationships between erosion sites and the habitat quality of salmonid spawning sites. The salmonid spawning site inventory form was completed at salmonid spawning locations. Both the erosion inventory form and the Bank Erosion Hazard Index form (BEHI) were completed at erosion locations. Magnitude of erosion measured in erosion spatial extent and BEHI, stream distance (m) of a spawning site to the closest upstream erosion site, and percentage of fines (<2mm) at the central position of the spawning site. Spawning site characteristics such as depth (cm), flow velocity (cm/sec), and bankfull width (m), that were likely influenced by the nearest upstream erosion site, were noted.

In order to explain the intricacies between riparian vegetation and river channel morphology of a Northern Michigan stream, riparian vegetation type at erosion sites and adjacent to spawning sites, in addition to the BEHI form, were used to qualitatively explain how these features may be able to influence channel morphology. Channel morphology was determined by taking depth, flow velocity, bankfull width, bank slope (degrees), and bank height (m) at both erosion and spawning sites. Based on the characteristics of the riparian vegetation, inferences are made as to how this makeup impacts some of the specific characteristics of the proximate river channel.

To produce a habitat restoration plan by providing detailed remediation techniques at each salmonid spawning habitat and erosion site, objectives one and two were synthesized as a baseline to choose restoration techniques, and to assign priorities for restoration. High severity erosion sites that are located a short distance upstream from high quality spawning sites were given a high restoration priority, for example.

By understanding the dynamic relationship between adjacent riparian vegetation and river morphology, the fluvial researcher can make inferences as to which riparian vegetation compositions most benefit salmonid spawning habitat quality. Restoration techniques in this study, however, did not just include revegetation techniques of the adjacent banks for habitat restoration, because vegetation can take a long time to grow. As such, recommendations for more immediate techniques for erosion site restoration such as the installation of LWD and biotechnical structures (Appendix A) are provided. Based on severity of the erosion (dimensions and BEHI) and geotechnical characteristics of the restoration site (slope, bank height, soil composition, adjacent depth, and adjacent flow velocity), recommendations are made for the particular biotechnical structures that would most benefit a particular erosion site. Spawning site restoration, on the other hand, is largely focused on revegetation and installation of LWD. Effective revegetation strategies directly benefit habitat conditions that are favorable to salmonids, such as increased stream roughness, partial sorting of substrates, and stream shading (Abernethy & Rutherfurd 1998; Abernethy & Rutherfurd 2000; Corenblit et al. 2009; Eaton 2006; Mickovski et al. 2009; Pizzuto et al. 2010; Pollen 2007; Van De Weil & Darby 2007). Based on these factors, a restoration plan on the 37 salmonid spawning sites and 26 erosion sites found along the 5572 m long study reach in the next two sections were made.

Material

Various instrumental and technical tools were needed for the field research conducted on the Chocolay River during the months of June, July, and August in the year 2013. To collect necessary data, the following tools and methods were used (Table 1):

Table 1

Equipment and Uses on the Chocolay River Field Data Collection

Equipment	Use
Sediment Corer	Collect substrate samples
Ziploc bags	Collect substrate samples
Marker	Record substrate ID
GPS	Collect GPS coordinates
100 ft. (30.4) tape measure	Measure depth, bankfull width, bank height, size of area, velocity
Inclinometer	Measure bank slope
Float bobber	Measure flow velocity
Stopwatch	Measure flow velocity
Sediment sorter	Record proportion by mass of each substrate size class
Pencil	Record information
Scoop	Collect substrate from sediment sorter
Assorted beakers	Measure substrate
Waders	Collect in-stream data, cross flow obstructions
Kayak	Reach field sites, make observations

Spawning Sites

Spawning sites were those defined to have a continuous run of larger particle sizes greater than 2 mm. The end of a spawning site was signaled where the run of spawning gravel transitioned to finer particle sizes. Measurements were taken from the center of each run of spawning gravel and written into a salmonid spawning site inventory form. GPS coordinates were taken from a standard Garmin eTrex to an accuracy of ~3 m. Standard attributes were recorded including: date, time, pictures, and notes. Adjacent to the spawning site, the presence or absence of invasive species, noticeable eroded banks, and LWD was recorded. At the central location of the spawning gravel, the data recorded included: depth (cm), water temperature (°C), and flow velocity (cm/sec). Flow velocity recordings were made via a tape-measure, stopwatch, and floating bobber. Three flow velocity measurements were taken and averaged to ensure greater validity to the recordings. Other measurements included: bankfull width (m), bank height (m), and bank slope (deg.). An inclinometer was used to measure bank slope. Size of spawning run recorded the maximum width and length of the spawning run. All height and length measurements were made with a 30.4 m tape-measure.

A sediment core sample was taken from the central position of each spawning run. Approximately 200 mL of substrate was taken from each site via a sediment corer, and taken back to the lab for analysis. A sediment sorter was used on each substrate sample to get measurements of four different substrate size classes. These size classes, from small particle sizes to large, were as follows: silt (63-250 μm), sand (250 μm-2 mm), fine gravel (2-4 mm), and gravel (>4 mm). Each size class comprised a quantitative measure of the spawning gravel quality and measured in mL separately. Beakers from 5 mL to 100 mL were used in order to get the quantitative proportion of each size class in mass. Larger proportions of sand and silt sized particles (<2 mm) greatly decrease embryo survivability and discourage successful spawning of salmonids.

Erosion Sites

Just as the spawning sites on the Chocolay River were evaluated, several attributes were recorded for each noticeable erosion site. These sites were observed to have either an absence of vegetation, meaning that exposed sediment was evident along the riverbank, or whether there was extreme undercutting of the bank. It is important to note that small point bars were excluded from this analysis because these sites exhibited greater rates of deposition rather than erosion. Management concerns were divided into three main categories: (i) exposed sediment, (ii) developed areas, and (iii) road crossings. Exposed sediment may be either natural or anthropogenic, while the other two are always anthropogenic. A developed area, for example, may have manicured lawns on the riverbank instead of exposed sediment.

Several basic attributes were recorded for erosion sites in this study including: date, time, GPS coordinates, and notes. At least three pictures were taken for each site. Larger erosion sites required more pictures. Instead of taking measurements in the middle of the stream, locations of maximum velocity flow measurements were the main determinant of all other stream measurements in the stream erosion inventory. This is because of the short distance between the position of the thalweg and the cutbank, which is where the most significant erosion sites occur. These rates were more likely to exert hydraulic influences on riverbank erosion than a point in the center of the stream, and were therefore included in this analysis. At observed maximum velocity, flow velocity and depth were recorded. Adjacent to this reading, bankfull width was recorded. On the side of the stream where the actual erosion occurred, slope and bank height were recorded.

On the riverbank itself, recordings included bankfull height, bank slope, and size of erosion area. Height was measured with a 30.4 m length tape measure, while slope was measured by an inclinometer. Area was later calculated by multiplying the length and width of the erosion site. If exposed sediment was evident at a site, this attribute would be checked off on the inventory form (note: proportions of vegetative cover were discussed more on the BEHI form). The presence/absence of LWD and invasive species was recorded as well. Dominant understory and overstory vegetation was recorded since vegetation type, not just presence/absence of vegetation, is a main determinant of riverbank erosion rates. Severity of each site was determined qualitatively (low/medium/severe), which may be of use in prioritization of habitat restoration on these sites.

Using ArcGIS 10.1, the distance to each erosion site was recorded by using the measure tool. A rectified 2008 orthographic image from the USGS was used as the backdrop to make these recordings, since distance had to be measured along the sinuous character of the stream instead of Euclidian distance. If multiple erosion sites occurred between two spawning sites, this data would then be recorded into the Excel spreadsheet. This would be of importance, because multiple erosion sites are likely to exert a larger impact upon a spawning site than just one. In addition to multiple erosion sites, erosion sites that were closer to or adjacent to the spawning location were considered to exert a greater influence than their counterparts. A public land survey shapefile from the Michigan Center for Geographic Information provided information regarding land ownership. As with any habitat restoration plan, private ownership may be a huge road-block to restoration if land-owners are unwilling to allow the plan to take place.

Site specific analysis of each erosion site concluded with determining which one of twelve biotechnical streambank stabilization techniques is most appropriate at each particular erosion site, as outlined by Li and Eddleman (2002) and shown in Appendix A. These techniques include: (i) live stakes, (ii) live fascines, (iii) brush layering, (iv) branchpacking, (v) vegetated geogrids, (vi) live cribwall, (vii) joint planting, (viii) brushmattress, (ix) tree revetment, (x) root wad, (xi) dormant post-plantings, and (xii) coconut fiber rolls. Each technique varies greatly in cost and time, which is likely to restrict which technique is feasible in a particular river restoration project. Furthermore, each technique is more appropriate in particular biogeotechnical settings than others. For example, live fascines may be most appropriate on the bank zone (above the splash zone which is frequently inundated by normal flow fluctuations), and are most effective on slopes less than 33% (Li & Eddleman 2002).

BEHI Index

Riverbank erosion potential was determined using Rosgen's Bank Erosion Hazard Index (BEHI) at every inventoried riverbank erosion site along the study reach (Rosgen 2001). This index assigns point values to several aspects of bank condition along a particular erosion site of varying spatial scales. On the erosion inventory form, a unique identifier was assigned to each site coinciding with its assigned BEHI form. Four variables were measured at each site: (i) root depth, (ii) root density, (iii) surface protection, and (iv) bank angle (deg.). Root depth is the ratio of the average depth of roots to bank height in the eroded area, expressed as a percent. Where roots were exposed to the surface, this metric was fairly easy to quantify. Root density is the ratio of root mass to eroded area, expressed as a percent. While this rate is sometimes sinuous with root depth, it would be much different if a high proportion of roots branch from the main root laterally. Surface protection is the percentage of the riverbank protected from any structural object. For example, downed wood, grass, rocks, bushes, etc. all contribute to surface protection. Bank angle is the average slope of the riverbank. This rate was most effectively measured by an inclinometer positioned at the top of the bank and measured to the water surface. Each of the four BEHI variables was divided into six numerical categories, allowing for slight human error in the measurements. Each measurement was given an arbitrary BEHI score and summed to get the total score, or erosion potential, for each site (Table 2). Sites that scored low on the BEHI index and received a score of less than 7.25, meaning that erosion is relatively minor. High scores received a score of 42.51-50 and coincided with severe potential erosion. These rates give a quantitative measure of the erosion of each site, so that restoration activities can be prioritized further.

Table 2

Rosgen's Modified BEHI Index Scores for Four Bank Erosion Variables

BEHI Category	Root Depth Values	Root Depth Scores	Root Density (%)	Root Density Scores	Surface Protection (Avg. %)	Surface Protection Scores	Bank Angle (degrees)	Bank Angle Scores	Total Score, by Category
Very low	90-100	**1.45**	80-100	**1.45**	80-100	**1.45**	0-20	**1.45**	**≤ 5.8**
Low	50-89	**2.95**	55-79	**2.95**	55-79	**2.95**	21-60	**2.95**	**5.8 – 11.8**
Moderate	30-49	**4.95**	30-54	**4.95**	30-54	**4.95**	61-80	**4.95**	**11.9 – 19.8**
High	15-29	**6.95**	15-29	**6.95**	15-29	**6.95**	81-90	**6.95**	**19.9 – 27.8**
Very high	5-14	**8.5**	5-14	**8.5**	10-14	**8.5**	91-119	**8.5**	**27.9 – 34.0**
Extreme	< 5	**10**	< 5	**10**	< 10	**10**	> 119	**10**	**34.1 - 40**

Statistical Analysis

ANOVA, or analysis of variance, statistical tests were conducted on the data from this research. ANOVA allows the fluvial researcher to make inferences on whether sediment size class distribution is in dynamic equilibrium with flow characteristics, such as bankfull width, stream gradient, and flow velocity. Furthermore, these statistical tests will be able to provide a better understanding that if these sediment size classes are not in dynamic equilibrium with the stream channel, human impacts or excess erosion from an upstream source are likely the cause. In this study, ANOVA were used to test for the following: the relationship between percentage of fines <2 mm (factor) and the distance to erosion, BEHI of the upstream erosion, stream gradient, flow velocity, depth, and bankfull width (independent variables). These variables will prove to have a statistically significant relationship if the level of significance is <0.05. It is the goal of this research to not control erosion in its entirety, because erosion is a natural and necessary phenomenon, but to restore rates to dynamic equilibrium. Essentially, ANOVA will aid in this process of determining which spawning sites have anthropogenic rates of sediment deposition, and those which are exhibiting excess rates of fine sediment deposition.

ANOVA was used to test erosion sites for statistical significance (sig. <0.05) to determine the relationship between BEHI (factor) and root depth, root density, surface protection, and bank angle (independent variables). The variables that prove to have the highest statistical significance are most likely to contribute to a higher BEHI score along this particular study reach on the Chocolay River. Essentially, the most statistically significant variables will be the most prevalent, which will help to determine restoration activities accordingly.

Linear regression tests were also conducted on the salmonid spawning habitat data to test for similarities between percent fines (dependent variable) and flow velocity, stream gradient, and depth (independent variables). As with ANOVA, these tests will allow this research to make inferences on spawning habitat quality in particular geotechnical settings. Again, a level of significance <0.05 will prove to be statistically significant on this data. High variability and low levels of significance may be due to anthropogenic influences, and therefore serve as spawning sites that are highly impacted by adjacent or upstream erosion sites.

CHAPTER 5

RESULTS AND DISCUSSION

Spawning Sites

In total, 37 spawning sites were inventoried on the Chocolay River during the summer of 2013. These sites had a higher proportion of gravel and rock sized substrates. Coarse sand or fine gravel sizes were also present in higher proportions than those locations comprised primarily of sand sized substrates. Spawning sites were those defined to have a continuous run of larger particle sizes. Where the run of spawning gravel transitioned to finer particle sizes signaled the end of a spawning site.

The furthest most upstream spawning site inventoried is located 66.4 m downstream from a major erosion site (BEHI 32.95). This spawning site is characterized by a moderate to fast flow of 74.07 cm/sec, an average depth of 25.39 cm, and an average bankfull width of 13.41 m. There is no LWD present but there are a few instream boulders to exert their fluvial influence (Figure 6). The adjacent banks are characterized by a vegetation composition dominated by maple (overstory) and grass/sedge (understory) growing on steep banks (90°) that are .74 m high. Percentage of fines is elevated at 31.4%.

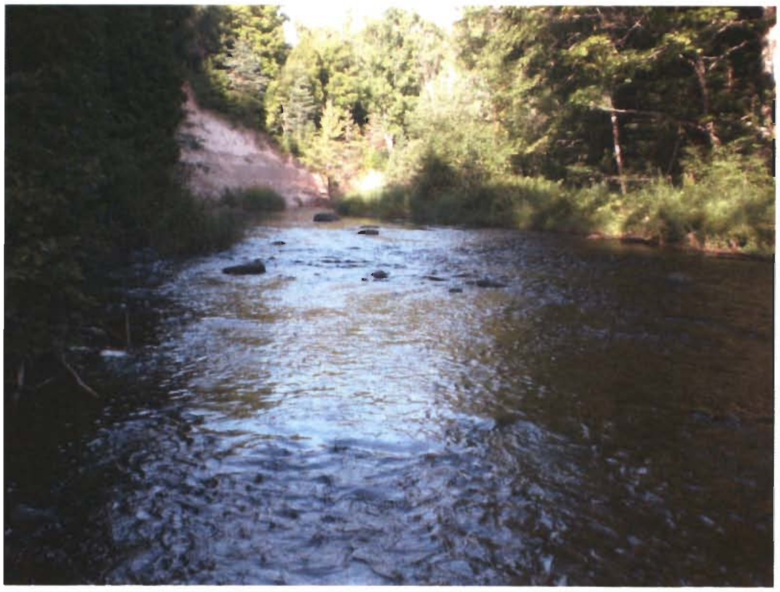


Figure 2: Salmonid Spawning Site One

The second salmonid spawning site is located 176.3 m downstream from the same erosion site (BEHI 32.95) as the previous spawning site. This spawning site is characterized by a moderate to fast flow of 74.07 cm/sec, an average depth of 27.95 cm, and an average bankfull width of 13.41 m. There is LWD present along this spawning site that measures 64 m long, as well as plentiful large rocks and boulders. The adjacent banks are characterized by a vegetation composition dominated by spruce and grass/sedge growing on relatively steep banks (74°) that are 2.36 m high. Percentage of fines is slightly higher than the upstream spawning site at 31.8%.

Figure 3: Salmonid Spawning Site Two

The third salmonid spawning site is located 20 m downstream from a major erosion site (BEHI 30.4). This spawning site is characterized by a flow velocity of 76.2 cm/sec, an average depth of 33 cm, and an average bankfull width of 13.1 m. There is no LWD along this large spawning site that measures 129.5 m of continuous spawning gravel, but there are plentiful flow obstructions in the form of large rocks and boulders. The adjacent banks are characterized by a vegetation composition dominated by spruce/maple and grass/ferns growing on vertical banks (90°) that are 1.8 m high. Percentage of fines is at 27.6%.

Figure 4: Salmonid Spawning Site Three

The fourth salmonid spawning site is located 11.4 m downstream from medium to high severity erosion site (BEHI 21.35). This spawning site is characterized by a flow velocity of 56.1 cm/sec, an average depth of 17.8 cm, and a bankfull width of 20.1 m. As can be seen from Figure 7, LWD is present in this 61 m long section of spawning gravel, even though it offers negligible bank protection. The adjacent banks are characterized by a vegetation composition dominated by spruce/maple and grass growing on vertical banks (90°) that are 3.1 m high. Percentage of fines is identical to the site immediately upstream at 27.6%.

Figure 5: Salmonid Spawning Site Four

The fifth salmonid spawning site is located 70.8 m downstream from the highest severity erosion site in this study (BEHI: 35.45). This spawning site is characterized by a flow velocity of 135.9 cm/sec, an average depth of 22.9 cm, and a bankfull width of 18.3 m. LWD is present along this 53.9 m section of spawning gravel, which, together with a relatively low depth and a narrow bankfull width, produces the rapid flow velocities present along this reach. These factors are the main reasons why this site is only one of three that has percentages of fines below 15% at 14.25%. Adjacent banks have a moderate slope of 35° that are 1.9 m high. Vegetation composition is dominated by old-growth maple with an understory of ostrich and bracken ferns.

Figure 6: Salmonid Spawning Site Five

The sixth salmonid habitat site is located 62.2 m downstream from a moderate severity erosion site (BEHI: 21.8). This spawning site is characterized by a flow velocity of 37.5 cm/sec, an average depth of 50.8 cm, and a bankfull width of 15.2 m. LWD is present along the east bank of this 18.6 m section of spawning habitat, although pieces are relatively small in length and diameter. The adjacent banks are characterized by a dominant overstory and understory of spruce/maple and grass species respectively. These banks are both moderate to high in height (2.6 m) and slope (74°). Percentages of fines are elevated at 32.3%, which may be due to the lack of stream roughness at this location. Lack of stream roughness can be attributed to many factors, but can easily be narrowed down to the lack of fluvial influence the LWD are exerting at this particular spawning location. LWD that doesn't just lay tangent to the banks, but also protrudes into the flow at an angle, would create a better sorting of substrates at this location and subsequently more heterogeneity of stream habitat. This LWD would need to be either larger in size (to prevent stream transport) or be anchored to the stream-bottom with a metal stake.

Figure 7: Salmonid Spawning Site Six

The seventh salmonid spawning habitat site is located 34 m downstream from a major erosion site (BEHI: 28.85). This spawning site is characterized by a flow velocity of 62.5 cm/sec, an average depth of 12.7 cm, and a bankfull width of 21.9 m. Some LWD is present along this 22.3 m section of spawning habitat that is fairly evenly dispersed along the stream cross-section and at a consistent depth (riffle section). An instream island has formed toward the eastern bank, which is comprised primarily of a vegetation composition of tall grass/sedge species. This island may have formed due to the shallow depth of this riffle and the close proximity to the upstream erosion site. The adjacent banks are 1.7 m high with a vertical slope. Fortunately, tall grass/sedge species interspaced with spruce offer adequate bank protection along this spawning section. Percentage of fines is at 16.1%, which provides a moderate salmonid spawning habitat quality.

Figure 8: Salmonid Spawning Site Seven

The eighth salmonid spawning site is located 34.2 m downstream from a low to medium severity erosion site (BEHI: 12.85), which is the only noticeable erosion immediately upstream from nine separate spawning sites for a distance of up to 448.5 m along the stream. This particular site is characterized by a flow velocity of 34.4 cm/sec, an average depth of 17.8 cm, and a bankfull width of 17.4 m. Spruce, grass, and ferns predominate on steep banks (82°) that are 2.2 m high. The channel itself has no LWD present along the entire 38.1 m length of continuous spawning habitat, which is a mystery considering that much of the channel is less than 10 cm deep at this location and a few small islands have started to form because of this shallow depth. There is no more than 1 m^2 of deposits creating these islands, which insists that they would have low potential to trap LWD, especially considering that they are also shallow in height, meaning that LWD transported during high flow events would simply go unimpeded. As discussed previously, spawning times often coincide with periods of seasonally high flows, meaning that the riffles at this location, which are already well oxygenated, will be highly suitable for redd construction. Percentages of fines is at 22.2% at the time of study, but due to the low depth, an increase in flow will have a noticeable effect on transporting some of these fines downstream.

Figure 9: Salmonid Spawning Site Eight

The ninth salmonid spawning site is located 68.3 m downstream from the same erosion site as site eight. This salmonid spawning site is characterized by a flow velocity of 68.6 cm/sec, an average depth of 30.4 cm, and a bankfull width of 17.4 m. One large piece of LWD is directed into the flow at a ~30° angle along the middle of this 24.7 m section of spawning habitat. Adjacent banks are dominated by a vegetation composition of spruce and ferns growing on steep (85°) banks up to 2.2 m high. Everything about this riffle seems nice, but the percentage of fines, which is elevated to 26.3%.

Figure 10: Salmonid Spawning Site Nine

The tenth salmonid spawning site is located 95.9 m downstream from the same erosion site as the previous two spawning sites. This spawning site is characterized by a flow velocity of 82.3 cm/sec, an average depth of 58.4 cm, and a bankfull width of 13.4 m. A narrower channel at this location has created the higher depths and still maintained a favorable flow velocity for salmonid habitat. Very little LWD is present along this 27.1 m section of spawning habitat. Cover is mostly in the form of grass/sedge and tree branches overhanging from the adjacent banks. Spruce/maple and grass/sedge comprise a majority of the vegetation growing on banks with a slope of 78° which reach 2.2 m high. Percentages of fines are elevated at 25.3% at this spawning location.

Figure 11: Salmonid Spawning Site Ten

The eleventh salmonid spawning site is located 171.3 m downstream from the same erosion site as the previous four spawning sites. This spawning site is characterized by a flow velocity of 33.2 cm/sec, an average depth of 50.8 cm, and a bankfull width of 17.4 m. Depth is comparable to the previous site, but because of the wider channel, flow velocity is well below average. Spruce and grass dominate the overstory and understory riparian species respectively, both growing on 64° banks 2.2 m high. Percentages of fines are elevated at 29.9%, which can easily be seen from Figure 14.

Figure 12: Salmonid Spawning Site Eleven

The twelfth salmonid spawning site is located 212 m downstream from the same erosion site as the previous five sites. This spawning site is characterized by a flow velocity of 82 cm/sec, an average depth of 33 cm, and a bankfull width of 18 m. LWD is present on the downstream side of this 28 m long spawning site where there are greater depths, although much of the instream cover comes from large rocks/boulders protruding from the surface in the shallow riffle section. Many of these obstructions are placed in the middle of the channel where they encounter maximum velocity flows. These features serve as important cover for feeding and as refuge from quick flows in the mid channel. The LWD on the downstream side is located on the outside of a bend, which creates a deep hole where maximum velocity flows are encountered. Cedar/spruce and grass predominate on the 52° banks that are 1.4 m high. Considering the above attributes, it would be expected that spawning habitat quality would be high at this site. Unfortunately, percentages of fines are elevated at 29.7%.

Figure 13: Salmonid Spawning Site Twelve

The thirteenth salmonid spawning site is located 226 m downstream from the same erosion site as the previous six sites. This spawning site is characterized by a flow velocity of 61.6 cm/sec, an average depth of 33 cm, and a bankfull width of 14.6 m. These conditions are fairly typical of spawning sites in the middle of the study reach. Stream heterogeneity is good in this 20.4 m section of spawning habitat. The upstream section's fast flows cascade over shallow gravel and around large rocks/boulders. Downstream, LWD located on both sides of the river add a bit of sinuosity through this stretch. Predominant vegetation is comprised of spruce and grass species growing on vertical banks that are 1.4 m high. Percentage of fines is elevated at 29.2%, although upstream percentages from this middle sampling point where flow velocity is higher could have been substantially lower.

Figure 14: Salmonid Spawning Site Thirteen

The fourteenth salmonid spawning site is located 267.7 m downstream from the same erosion site as the previous seven sites. This spawning site is characterized by a flow velocity of 36.9 cm/sec, an average depth of 17.8 cm, and a bankfull width of 12.8 m. Some LWD is located along this middle of this 27.1 m section of spawning habitat, but it has little or no effect on altering hydrology. A dominant overstory of spruce/maple and understory of small alders grow on gentle sloping banks (25°) that are 1.3 m high. This site has the highest percentage of fines observed yet at 35.3%, although many larger rocks were too large in diameter to be sampled. Nonetheless, deposition of fines is expected to be high wherever large rocks and no rocks of small to intermediate size are found, because of the high volume of pore spaces in these circumstances.

Figure 15: Salmonid Spawning Site Fourteen

The fifteenth salmonid spawning site is located 369 m downstream from the same erosion site as the previous eight sites. This spawning site is characterized by a flow velocity of 65.2 cm/sec, an average depth of of 30.4, and a bankfull width of 15.6 m. LWD is not present along this 54.9 m long section of spawning habitat, although cover exists in the form of large rocks and one large boulder in the middle of the channel. The adjacent banks grow steeply (78°) to 1.7 m and are dominated by a overstory vegetation composition of spruce/maple. Overhanging alders provide streamside cover on the east bank, while the west bank is mostly comprised of grass/sedge species. The addition of large rocks and boulders makes this a difficult section to traverse by kayak. Flow complexity created by these flow obstructions has created conditions for moderate quality spawning habitat with percentages of fines at 20.8%. The upstream portion of this section has a majority of boulders and streamside cover. Downstream, especially along the west bank, a lack of bankside overstory vegetation, LWD, or large rocks has created homogeneous habitat conditions.

Figure 16: Salmonid Spawning Site Fifteen

The sixteenth salmonid spawning site is located 448.5 m downstream from the same erosion site as the previous nine sites. This spawning site is characterized by a flow velocity of 62.5 cm/sec, an average depth of 28 cm, and a bankfull width of 14 m. No LWD is present along the entire 71 m length of spawning habitat at this location. This site forms nearly a continuous stretch of spawning gravel with the previous site, but was decided to be inventoried separately because of a small section with a higher proportion of fines separating the two spawning sites. Channel form is nearly identical to the upstream site. Dominant vegetation changes to spruce and grass/sedge species growing on vertical banks that are 2 m high. Percentages of fines are moderate at 19.1%, which is best of all of the previous nine spawning sites located downstream from the last erosion site.

Figure 17: Salmonid Spawning Site Sixteen

The seventeenth salmonid spawning site is located 89.8 m downstream from a moderate severity erosion site (BEHI: 14.3). This spawning site is characterized by a flow velocity of 90.8 cm/sec, an average depth of 15.2 cm, and a bankfull width of 15.2 m. Like the spawning site immediately upstream, this site is devoid of LWD along its entire 63.7 m course. This is likely due to the shallow depths and swift current throughout most of the river channel here. White cedar and ostrich ferns/bracken ferns predominate on steep banks (79°) that are 2.2 m high. Percentages of fines are at 17.9%, which is very near the 15% threshold for high quality salmonid spawning habitat.

Figure 18: Salmonid Spawning Site Seventeen

The eighteenth salmonid spawning site is located 176 m downstream from the same erosion site as the previous spawning site. This spawning site is characterized by a flow velocity of 92.4 cm/sec, an average depth of 30.4 cm, and a bankfull width of 13.7 m. This 59.7 m long section of spawning habitat is also devoid of LWD, although cover exists in the form of overhanging trees, which are plentiful along the east bank. Instream variability is low throughout this site, but at the bend immediately downstream from this section is both deep and provides plentiful cover for large fish. The adjacent banks have a moderate slope (43°) that reach a height of 2.7 m. Dominant overstory and understory is spruce and grass/alder respectively, with alder providing much of the vegetation overhanging the stream channel. Percentages of fines is elevated at 26.2%, which may occur because of the slight increase in depth at this site compared with the spawning site immediately upstream, which is nearly a continuous site with this one.

Figure 19: Salmonid Spawning Site Eighteen

The nineteenth salmonid spawning site is located 16.3 m downstream from a moderate to severe erosion site (BEHI: 23.8). This spawning site is characterized by a flow velocity of 48.2 cm/sec, an average depth of 40.2 cm, and a bankfull width of 13.4 m. Depth varies most throughout this 15.5 m long site, with greatest depth occurring along the cluster of LWD located along the north/east bank. Along the opposite bank, flow velocity and depth is very minimal, which encourages the deposition of fines. This partial sorting of fines has proven to be very successful at this location, however, with percentages of fines the best out of every site inventoried at 7.2%. The erosion at the site immediately upstream may be unlikely to negatively impact the high quality spawning habitat along the middle section of the channel because much of the fines originating from this site are likely to deposit in the deeper section along the north/east bank, where the thalweg also occurs. Steep banks (80°) grow to a height of 2.4 m and are dominated by spruce and alder. LWD is located along the entire length of spawning habitat. This may be because of the steep decrease in flow velocity and an increase in depth compared to sites fifteen-eighteen, which may have transported LWD from these sections to this point.

Figure 20: Salmonid Spawning Site Nineteen

The twentieth salmonid spawning site is located 18.1 m downstream from the same erosion site as the previous site. This spawning site is characterized by a flow velocity of 39.9 cm/sec, an average depth of 64.3 cm, and a bankfull width of 11.9 m. Plentiful LWD is present along the outside bend (South/West bank) along this 14.3 m section of spawning gravel. Large rocks are numerous, but all are positioned in the deep section of the channel, and therefore do not reach the surface of the river. Eroded banks with a steep angle (100°) are located on the downstream edge of this section of spawning habitat. Percentage of fines is elevated at 30.8%, low quality, but due to the slow stream velocity and depth that is not ideal, can be expected.

Figure 21: Salmonid Spawning Site Twenty

The twenty-first salmonid spawning site is located 51.2 m downstream from a moderate severity erosion site (BEHI: 15.85). This spawning site is characterized by a flow velocity of 46.3 cm/sec, an average depth of 50.8 cm, and a bankfull width of 14.6 m. LWD creates a large pool on the upstream side of this 20.7 m long section of spawning habitat, and results in high sinuosity and stream heterogeneity throughout the middle section. White pine/spruce and ostrich/bracken ferns dominate the overstory and understory respectively. Surface protection is high due to the strong roots from trees, resulting in high stability of 2.8 m banks with a 47° slope. Percentage of fines is slightly improved from the upstream site at 24.4%.

Figure 22: Salmonid Spawning Site Twenty-one

The twenty-second salmonid spawning site is located 19.8 m downstream from a moderate severity erosion site (BEHI: 21.8). This spawning site is characterized by a flow velocity of 71.9 cm/sec, an average depth of 38.1 cm, and a bankfull width of 13.7 m. LWD is present along this 10.4 m section of spawning gravel, although it is made up entirely of only one spruce tree perpendicular and extended halfway into the channel. The adjacent banks are comprised of white cedar and grass/sedge species, and are 2.4 m high with a slope of 34°. Despite the relatively gentle slope, erosion occurs here. On the opposite banks (South/east side), european thistle is present in manageable numbers. Despite the quick flow velocity, percentage of fines is elevated at 31.6%

Figure 23: Salmonid Spawning Site Twenty-two

The twenty-third salmonid spawning site is located 43.4 m downstream from a moderate severity erosion site (BEHI: 15.8). This spawning site is characterized by a flow velocity of 38.4 cm/sec, an average depth of 76.2 cm, and a bankfull width of 11.3 m. LWD is not present along this short 8.5 m long section of spawning gravel, although it is located a short distance upstream from a major log jam. Ash and alder grow on the 1.6 m high banks with a slope of 58°. This site has the greatest depth and the greatest percentage of silt material (4.1%) of all spawning sites inventoried, resulting in a total percentage of fines elevated at 34.1%.

Figure 24: Salmonid Spawning Site Twenty-three

The twenty-fourth salmonid spawning site is located 70.1 m downstream from the same erosion site as the previous site. This site is characterized by a flow velocity of 34.4 cm/sec, an average depth of 71.1 cm, and a bankfull width of 10.1 m. LWD is present adjacent to this 16.2 m long section of spawning gravel, as well as immediately upstream in the form of the major log jam, as stated previously. Birch/spruce and grass/sedge species comprise the dominant overstory and understory vegetation compositions respectively. 1.9 m high banks have a steep slope of 85°. The spawning gravel itself is concentrated on the west side of the stream where most of the LWD is positioned. Despite this, percentage of fines is considered bad at 41.7%.

Figure 25: Salmonid Spawning Site Twenty-four

The twenty-fifth salmonid spawning site is located 165.6 m downstream from the same erosion site as the previous two sites. Note that this section of spawning gravel runs through an area of houses located along both banks. Some residents manicure their lawns right up to the riverbank. Use of fertilizer and/or pesticides is unknown. This site is characterized by a flow velocity of 40.2 cm/sec, an average depth of 48.2 cm, and a bankfull width of 13.4 m. LWD is absent along this 9.1 m long section of spawning gravel. Cedar, alder, and grass species comprise the tree, shrub, and herbaceous layers of the vegetation growing along the banks. Banks are 1.8 m high with a slope of 80°. The residents along the west bank, who appear to be full-time, have made a rock structure in the river adjacent to their property, which appears to play a role in the partial sorting of sediment at this site. Percentage of fines is elevated at 32.8%.

Figure 26: Salmonid Spawning Site Twenty-five

The twenty-sixth salmonid spawning site is located 234 m downstream from the same erosion site as the previous site three sites. This spawning site is characterized by a flow velocity of 49.4 cm/sec, an average depth of 33 cm, and a bankfull width of 17.4 m. This 45.7 m long section of spawning gravel has some LWD present, but most seems to be removed due to the adjacent housing developments. Spruce/cedar and grass make up the dominant overstory and understory respectively. The adjacent banks are 2.4 m high with a slope of 70°, which is likely to cause some access difficulties and exaggerated erosion. Percentage fines are elevated at 37.3%.

Figure 27: Salmonid Spawning Site Twenty-six

The twenty-seventh salmonid spawning site is located adjacent (0 m) to low severity erosion site (BEHI: 14.3). This spawning site is characterized by a flow velocity of 49.4 cm/sec, an average depth of 48.2 cm, and a bankfull width of 19.5 m. There are no LWD structures throughout this 10.7 m long stretch of spawning gravel. The vegetation composition of the adjacent banks is mostly comprised of white cedar and grass species growing on 1.4 m high banks with a slope of 55°. Percentage of fines is at 20.1%.

Figure 28: Salmonid Spawning Site Twenty-seven

The twenty-eighth salmonid spawning site is located 149.2 m downstream from the same erosion site as the previous site. This spawning site is characterized by a flow velocity of 19.5 cm/sec, an average depth of 40.6 cm, and a bankfull width of 16.2 m. There is no LWD along this 20.1 m long section of spawning gravel, whether or not it has been physically removed is unknown. Along the eastern bank is probably the most extreme case of physical alteration of the streambank due to mowing and landscaping. As beautiful as this may be, percentage of fines is at 26.1%. The opposite, and more natural banks, are 2.1 m high with a slope of 65°. Cedar, alder, and grass make up the predominant tree, shrub, and herbaceous layers at this location. Some rocks at this location were actually too large to be sampled, and therefore, the results could have been slightly skewed.

Figure 29: Salmonid Spawning Site Twenty-eight

The twenty-ninth salmonid spawning site is located 23.6 m downstreram from two low to moderate severity erosion sites (BEHI: 14.3 and 17.8). These two erosion sites are adjacent to one another at the upstream bridge crossing at Greengarden Road. This spawning site is characterized by a flow velocity of 117.3 cm/sec, an average depth of 38.1 cm, and a bankfull width of 31.5 m. There is no LWD present along this 11.6 m stretch of spawning gravel, the first below the bridge. Immediately downstream from the bridge confined flow and a series of cascading rapids create a deep pool that some locals use for bridge jumping. Most of the LWD in the vicinity of the bridge is located upstream where flow is much slower and depths are much greater. The very fast flow present at this spawning riffle (117.3 cm/sec) would be enough to displace all but the largest pieces of wood. The adjacent banks are devoid of tree and shrub vegetation, but are comprised entirely of tall grass/sedge species. Bank height is low at 0.9 m with a slope of 70°. Considering that the bank height is so low, the depth of grass and sedge roots would prove adequate in providing bank stabilization. Furthermore, fisherman would appreciate the ease of access through this vegetation since access upstream at the deep pool is not safely recommended. Despite the quick flow velocity and low depth, percentage of fines is elevated at 28.6%. Close proximity to the bridge erosion and human access, which is low and only moderate during steelhead season, are likely the two variables most accountable for this figure. This site could be an important spawning site for steelhead for those individuals who do not want to ascend the steep rapids underneath the bridge, or those who are finicky enough of the bridge itself to not want to pass.

Figure 30: Salmonid Spawning Site Twenty-nine

The thirtieth salmonid spawning site is located 34.7 m downstream from a moderate severity erosion site (BEHI: 23.8). This spawning site is characterized by a flow velocity of 66.8 cm/sec, an average depth of 48.2 cm, and a bankfull width of 13.7 m. Depth is most variable along this 52.8 m long section, with a collection of LWD and a downstream riverbend, creating high stream heterogeneity. On the upstream side of this site, a LWD structure is extended perpendicular into the flow from the east bank, and spans almost the entire width of the channel. The same is true with another LWD structure located on the downstream side of this site and along the opposite bank. These pieces are not the largest, but their influence in stream hydrodynamics is only positive. It will be interesting to see if these structures still exist in this location after the anticipated large spring snowmelt of 2014, and the resultant spring floods. White cedar shades much of the stream here and appears to have been the source of some of this LWD. The adjacent banks are 1.8 m high with a slope of 70°. Due to the high heterogeneity of stream habitat, substrate compositions vary greatly along this section. At the thalweg at the center of this section, percentage of fines is at 22.7%. There is no issue with erosion at this site, but effective management of the upstream erosion sites would likely decrease the percentage of fines to below 15%. If some LWD is removed, more can be introduced at this quality spawning site.

Figure 31: Salmonid Spawning Site Thirty

The thirty-first salmonid spawning site is located 47.6 m downstream from the same erosion site as the previous site. This spawning site is characterized by a flow velocity of 28.7 cm/sec, an average depth of 53.3 cm, and a bankfull width of 14.3 m. Unlike the previous site, this site has low heterogeneity, which accounts for the consistent depth and slow flow velocities along the stream's transect at this location. There is one piece of submerged LWD along this 7 m section of spawning gravel. White cedar predominates along the east bank, which is high (2.4 m) with a slope of 70°. The opposite bank is much lower and is comprised entirely of grass/sedge species. Percentage of fines is at 25.7% at this site.

Figure 32: Salmonid Spawning Site Thirty-one

The thirty-second salmonid spawning site is located 87.9 m downstream from the same two erosion sites as the previous two sites. This spawning site is characterized by a flow velocity of 39.9 cm/sec, an average depth of 45.7 cm, and a bankfull width of 15.6 m. LWD is present along this 12.4 m long section of spawning gravel, as well as a disposed tire. Despite the apparent fluvial influence that the tire itself exerts on the stream, as the best quality spawning habitat is located around the tire, it should nonetheless be removed. More natural structures would serve a better purpose. White cedar, grass, and ostrich/bracken ferns are prevalent on the 1.7 m high vertical (90°) banks. Percentage of fines is at 26.6%.

Figure 33: Salmonid Spawning Site Thirty-two

The thirty-third salmonid spawning site is located adjacent (0 m) from a low severity erosion site (BEHI: 13.8). This spawning site is characterized by a flow velocity of 72.8 cm/sec, an average depth of 34.3 cm, and a bankfull width of 18.6 m. A nice LWD structure is located on the upstream side of this 17.4 m long section of spawning gravel, although it does not deter the erosion located a short distance downstream and adjacent to the spawning riffle. Where tree growth does occur, it is mostly white cedar. Herbaceous growth is mostly grass/sedge species which grows on 1.8 m high banks with a slope of 70°. The deep hole located on the downstream side along a river bend is partially responsible for the erosion. As the depth and the surface area of the pool increased, it has decreased the stability of the adjacent bank comprised of mostly herbaceous growth. Percentage of fines between this feature and the upstream LWD structure is elevated at 44.3%.

Figure 34: Salmonid Spawning Site Thirty-three

The thirty-fourth salmonid spawning site is located adjacent (0 m) from a moderate severity erosion site (BEHI: 21.35). This spawning site is characterized by a flow velocity of 33.2 cm/sec, an average depth of 50.8 cm, and a bankfull width of 12.8 m. LWD structures are present along both sides of this 4.3 m long stretch of spawning gravel, especially along the west bank. Both sides of the spawning gravel are very deep and cannot be navigable by waders. An overstory composition of spruce and an understory of grass species predominate on high (2.4 m) and steep (90°) banks. Percentage of fines is elevated at 30.8%, considerably better than the nearest upstream site, but still low quality.

Figure 35: Salmonid Spawning Site Thirty-four

Sites thirty-five through thirty-seven, as stated previously, have percentages of fines that are too high and will not be part of this analysis. From a sampling point of view, these sites appeared to be the highest quality spawning sites within their respective reach, due to visually observing coarse substrates. Nonetheless, all three sites had percentages of fines that would be entirely unsuitable for salmonids spawning site selection. Percentage of fines, starting upstream and working down, are 77%, 74.3%, and 80.4% respectively.

Erosion Sites

Erosion sites situated along the study reach of the Chocolay River are the main focus of restoration activities in this study. Also, the seven erosion sites that are located downstream from the last 'suitable' spawning sites are excluded from site specific restoration due to being outside of the goals of this study. A complete map of erosion sites and spawning sites is shown in figure 54 on page 112. As can be seen from Figure 54, the Chocolay River is highly sinuous in character, which is likely attributed to a change in base level during its history (i.e. Lake Superior water surface fluctuations) and deforestation activities during the late 1800s and early 1900s.

Two salmonid spawning sites (sites one and two) lay the shortest distance downstream from the first erosion site than the other sites. The BEHI metric calculated an erosion score of 32.95, which is high. The first erosion site is both high (terrace height of 20.73 m) and steep (68°). The soil composition is comprised largely of clays, therefore, only a few scrubby trees/bushes and a few invasive weeds grow here. This factor greatly limits the habitat restoration types that may be suitable for this location. Having the second highest BEHI of all sites inventoried, and located close to a large spawning site (length of 94.49 m), this site can be considered a priority for restoration.

Figure 36: Erosion Site One

One salmonid spawning site (site three) lays the shortest distance downstream from the second erosion site than the other sites. The BEHI metric calculated an erosion score of 30.4, which is high. As can be seen, the terrace height of the second erosion site is both high (17.1 m) and steep (68°). Surface protection is slightly higher than the previous erosion site at 15-29%, although much of the vegetation is comprised of small herbaceous plants, some of them exotic (european thistle), with low root depth (<5% of bank height).

Figure 37: Erosion Site Two

One salmonid spawning site (site four) lays the shortest distance downstream from the third erosion site than the other sites. The BEHI metric calculated an average erosion score of 21.35. Bank height, slope, and adjacent flow velocity of the third erosion site is the same as the fourth spawning site. What differs greatly at this site is the amount of exposed clays. Because of the close proximity to this erosion site, the percentage of fines at this spawning site is 27.6%, well above the 15% threshold. An increase in bankfull width and a subsequent decrease in flow velocity at this spawning site is likely to responsible for the elevated percentage of fines, irrespective of its juxtaposition further from the immediate upstream erosion site.

Figure 38: Erosion Site Three

One salmonid spawning site (site five) lays the shortest distance downstream from the fourth erosion site than the other sites. The BEHI metric calculated a high erosion score of 35.45. Considering that the percentage of fines at spawning habitat site five is nearly at the 15% threshold for 'preferred' salmonid spawning habitat, restoration of the fourth erosion site should be an utmost priority as of this writing. This erosion site covers an expansive area of 24.4 x 18.9 m exposed on nearly vertical banks (82°). Negligible scores for root depth (<5%), root density (<5%), and surface protection (10-14%) account for the high BEHI score at this site. Only a single log located at the toe of the bank and a few spruce trees located along the periphery of the erosion site offer minimal protection from erosion. Adjacent impacts to the stream channel at this location are stark with a near stationary flow of 12.2 cm/sec and a depth greater than 121.9 cm. This depth was the maximum measure that was allowed in the study reach because of safety concerns.

Figure 39: Erosion Site Four

One salmonid spawning site (site six) lays the shortest distance downstream from the fifth erosion site than the other sites. The BEHI metric calculated an average erosion score of 21.8. Due to the elevated percentage of fines at this spawning site, together with the geotechnical properties of the fifth erosion site, restoration of this site can also be implemented to ensure an increase in spawning habitat quality. This erosion site covers an area of 17.1 x 3.7 m exposed on nearly vertical banks (85°). Flow velocity (57.3 cm/sec compared to 37.5 cm/sec), depth (25.3 cm compared to 50.8 cm), and bankfull width (15.8 m compared to 15.2 m) are all comparable between the channel adjacent to the erosion site and the downstream spawning habitat site. This could mean that the sediment eroding from this site is able to travel further downstream without depositing in a deep hole or low velocity section adjacent to the erosion site. Surface protection of 55-79% is provided by a complex of LWD (which actually is quite large), brush, grass, and a few spruce and maple trees.

Figure 40: Erosion Site Five

One salmonid spawning site (site seven) lays the shortest distance downstream from the sixth erosion site than the other sites. The BEHI metric calculated an average to high erosion score of 28.85. Some effective restoration of the sixth erosion site can transform the seventh spawning site from an average quality spawning site to an excellent one. This erosion site covers a large area of 19.2 x 22.3 m on 65° slopes. Surface protection may be 15-29%, but the vegetation present in the form of weeds, some of them invasive, offers negligible bank protection overall. This is because these weeds have a low root depth (much less than 5%) growing on a 22.3 m high terrace. There is some LWD at the toe of the bank, and some brush located on the bank, but together, these two influences does little to prevent the failing clay on the bank from reaching the stream. Adjacent to the erosion site, the river channel has one of the most abrupt small to mid-scale changes in features evident along the study reach. Depth adjacent to this erosion site is well over the 121.9 cm depth that would have been considered safe to inventory.

Figure 41: Erosion Site Six

Nine salmonid spawning sites (site eight through sixteen) lay the shortest distance downstream from the seventh erosion site than the other sites. The BEHI metric calculated a low erosion score of 12.85. This closest spawning site has a percentage of fines below the average (but still above 15%), and due to the high surface area of this site, restoration of the immediate upstream erosion site should be initiated after higher priority sites are restored. This erosion site extends along the bank for 23.8 m and up the entire height of the 2.4 m vertical (90°) bank. Undercutting is resulting in bank failure, erosion of sandy loam soils, and a large amount of LWD recruitment. LWD of various sizes is present along the majority of this erosion site which is both angled into the stream channel and laying parallel to the bank. Over time, LWD at this location will restore this erosion site and improve adjacent stream conditions for salmonids.

Figure 42: Erosion Site Seven

Two salmonid spawning sites (seventeen and eighteen) lay the shortest distance downstream from the eighth erosion site than the other spawning sites. The BEHI metric calculated a low to moderate erosion score of 14.3. Spawning sites seventeen and eighteen have percentages of fines at 26.2% and 17.9% respectively, but due to the considerable distance between these sites and the erosion site, an erosion site of this magnitude is unlikely to have a great negative impact. The erosion site extends for 16.5 m along the east side of the channel and 2 m up the bank at 90°. Spruce and maple roots keep the majority of the bank cohesive. Once further erosion and undercutting of the bank occurs, however, these trees are likely to become LWD at this site.

Figure 43: Erosion Site Eight

Two salmonid spawning sites (nineteen and twenty) lay the shortest distance downstream from the ninth erosion site than the other spawning sites. The BEHI metric calculated a moderate to high erosion score of 23.8. Spawning sites nineteen and twenty have percentages of fines at 30.8% and 7.2% respectively. The vast difference in fines between these two sites is due to the presence of plentiful LWD along spawning site twenty, a much smaller quantity of LWD along spawning site nineteen, and the difference in depth between the two sites. Due to the high quality of the closest spawning site, restoration of this erosion site can be considered a priority. This erosion site is positioned along the east bank and extends along the channel for 16.8 m. Eroded banks are 2.4 m high with a slope of 90°. Ash trees comprise most of the vegetation on the banks, but unfortunately due to the emerald ash borer, these trees are now either dead or dying.

Figure 44: Erosion Site Nine

One salmonid spawning site (twenty-one) lays the shortest distance downstream from the tenth erosion site than the other erosion sites. The BEHI metric calculated an erosion score of 15.85. Percentage of fines at salmonid spawning site twenty-one is 24.4%. The erosion site extends for 13.4 m along the channel, 1.6 m high up the bank, and at a slope of 100°. Surface protection and root density were both at 55-79%, but due to the extreme angle of the bank, even the deep roots of spruce, ash, and alder couldn't keep this site from eroding. The adjacent channel has a flow velocity of 39.9 cm/sec, a depth of 63.4 cm, and a bankfull width of 11.9 m.

Figure 45: Erosion Site Ten

One salmonid spawning site (twenty-two) lays the shortest distance downstream from the eleventh erosion site that the other erosion sites. The BEHI metric calculated an erosion score of 21.8. Spawning site twenty-two has a percentage of fines at 31.6%, perhaps due its position a short distance of 19.8 m downstream from a moderate severity erosion site. This erosion site extends for 18.9 m along the channel, has a bank height of 2.1 m, and a slope of 80°. Root depth is only 15-29% due to the absence of overstory vegetation, with only grass species present, which are unable to provide deep enough roots for these high banks to remain stable. The adjacent channel has a flow velocity of 36.3 cm/sec, a depth of 91.4 cm, and a bankfull width of 10.7 m.

Figure 46: Erosion Site Eleven

Four salmonid spawning sites (twenty-three and twenty-six) lay the shortest distance downstream from the twelfth erosion site than the other erosion sites. The BEHI metric calculated an erosion score of 15.8. Spawning sites, starting upstream and working downstream, had percentages of fines elevated at 34.1%, 41.7%, 32.8% and 37.3% respectively. Distance from the erosion site at 43.4 m (twenty-three), 70.1 m (twenty-four), 165.6 m (twenty-five), and 234 m (twenty-six), is unlikely to cause the high proportions of fines observed at these four sites, especially since this erosion site is only moderate in severity. This erosion site extends for 15.8 m along the channel, up the bank for 2 m, and has a slope of 90°. The adjacent channel has a flow velocity of 31.7 cm/sec, a depth over 122 cm, and a bankfull width of 11 m. The steep banks has caused one recent tree to fall along the channel with the rootwad still intact. This has caused a small area of exposed sediment, with no vegetative cover, at this location.

Figure 47: Erosion Site Twelve

Two salmonid spawning sites (twenty-seven and twenty-eight) lay the shortest distance downstream for the thirteenth erosion site than the other erosion sites. The BEHI metric calculated an erosion score of 14.3. Percentages of fines is at 21% and 26.1% respectively. Spawning site twenty-seven lays adjacent to the erosion area, but spawning site twenty-eight is located around the next riverbend 149.2 m downstream. The erosion site extends for 39.6 m along the channel, 1.4 m up the bank, and at a slope of 55°. This erosion site would actually be nonexistent if the landowner didn't remove all vegetative growth bar the manicured lawns that are maintained all the way up until the stream edge. There is one apple tree located along this long stretch of property, but it is located high up on the terrace, and is unlikely to protect much against erosion.

Figure 48: Erosion Site Thirteen

There are no spawning sites that lay between erosion site fourteen and the next erosion site downstream. The BEHI metric calculated an erosion score of 23.35. The erosion site extends for 17.1 m along the channel, 1.1 m up the bank, and at a 90° slope. This erosion site is located on the cutbank side of the channel, with the physical alteration of the channel morphology is various. The adjacent channel has a flow velocity of 3.7 cm/sec, a depth of over 122 cm, and a bankfull width of 18 m. It is not safe to wade in the stream close to this erosion site. Depth and slow flow velocity is likely both an influence of the erosion site itself, and the bridge located immediately downstream. The bridge has confined flows and created a steep gradient at the bridge itself, therefore the channel immediately upstream had to adjust its gradient accordingly. The average gradient at this site is .0257 or a drop of 25.7 m/km, half of the average gradient of the study reach of .0533 or a drop of 53.3 m/km.

Figure 49: Erosion Site Fourteen

One salmonid spawning site (twenty-nine) lays the shortest distance from erosion sites fifteen and sixteen than the other erosion sites. The BEHI metric calculated an erosion score of 17.8 and 14.3 respectively. These two sites could be considered as one because their position is directly across the channel from one another at the Greengarden Bridge. The downstream spawning site has a percentage of fines of 28.6%. Considering that this spawning site has very quick flow velocities (117.3 cm/sec), the elevated proportions of fines exhibited here can be considered a result of the upstream bridge, and the erosion it causes.

Erosion site fifteen extends for 25.9 m along the channel, up the bank for 0.91 m, and at a slope of 25°. Erosion site sixteen extends for 12.2 m along the channel, up the bank for 0.91 m, and at a slope of 30°. Most of the flow under the bridge is forced near the west bank (erosion site sixteen), where riprap has been placed. The opposite bank (erosion site fifteen) is made up primarily of fine sediment deposits. These clay and silt materials contain a high proportion of water and can easily trap a boot of an unwary fisherman. Because of these differences, flow velocity (103.6 cm/sec to 27.7 cm/sec) varies greatly between both erosion sites. Depth remains fairly consistently deeper than 122 cm, except in the middle of the channel where a large rock and gravel buildup is present. Bankfull width is 13.7 m.

Figure 50: Erosion Sites Fifteen (Left) and Sixteen (Right)

Three salmonid spawning sites (thirty through thirty-two) lay the shortest distance downstream from the seventeenth erosion site than the other erosion sites. The BEHI metric calculated an erosion score of 23.8. Percentages of fines at this spawning site, starting upstream and working our way downstream, are 22.7%, 25.7%, and 26.6%, interesting considering that percentage of fines increases the further the spawning site is located from this particular erosion site. This erosion site extends for 15.2 m along the channel, 2.4 m up the bank, and at a slope of 80°. Only a few white cedars line the banks, with most of the vegetation comprised of ferns and grasses.

Figure 51: Erosion Site Seventeen

One salmonid spawning site (thirty-three) is located closer to erosion site eighteen than the other erosion sites. The BEHI metric calculated an erosion score of 13.8. Percentage of fines at this spawning site is elevated at 44.3%, which is located adjacent to the erosion. This erosion site extends along the channel for 18.3 m, up the bank for 1.8 m, and at a slope of 70°. The adjacent channel is characterized by a flow velocity of 72.8 cm/sec, a depth of 35.7 cm, and a bankfull width of 18.6 m.

Figure 52: Erosion Site Eighteen

One salmonid spawning site (thirty-four) lies closer downstream from erosion site nineteen than the other erosion site. The BEHI metric calculated an erosion score of 21.35. Percentage of fines at this spawning site is 30.8% which lays adjacent to the erosion. Around this riverbend flow encounters are large collection of LWD, which is impeding the flow. This has created a large amount of channel widening, deepening, confined flows, and deposition of fines along the cutbank. This erosion site extends of 24.4 m along the channel, 2.4 m up the bank, and at a slope of >90°. Characteristics of the adjacent channel include a flow velocity of 33.2 cm/sec, a depth of over 122 cm, and a bankfull width of 12.8 m. Note that these measurements were only taken in the confined flow along the east bank, and were not taken in the deep, silty section behind the large log jam.

Figure 53: Erosion Site Nineteen

The remaining seven erosion sites lay downstream from the last salmonid spawning site suitable for restoration given that the three spawning sites located downstream from erosion site twenty have percentages of fines elevated at 77%, 74.3%, and 80.4% respectively. It is highly unlikely that restoration will be able to restore these sites to a percentage of fines anywhere near the 15% threshold, and it would make little difference if restoration was attempted at both the upstream erosion sites and the spawning sites themselves. Because of this, restoration of these sites are not a priority, and could be restored after the rest of the sites, but only if project budget allows to do so. An average gradient below of only 2.4 m/km below erosion site twenty until spawning site thirty-seven below Magnum Road is very low and the primary reason for the low quality salmonid habitat throughout. There are a few log jams in this section that entirely block the channel and could be removed. These structures make passage by the river restorationist very difficult, and will most likely impede the upstream progress of salmonids to some extent too. Breaking apart these structures and redistributing the LWD along the banks would be beneficial in many ways. Furthermore, LWD in these low flow velocity/gradient areas will provide great habitat for microinvertebrates that require the predominantly sandy substrate as habitat.

Review of Sites

In total, 37 spawning sites and 26 erosion sites were inventoried during nine different days in July and August 2013 (Figure 2). These sites were inventoried over a reach of 5572 m and comprised an area of 10,151.8 m² of spawning gravel extending from lengths 4.3 to 129.5 m. For a complete view of spawning habitat, erosion site, and BEHI data consult Appendix C.

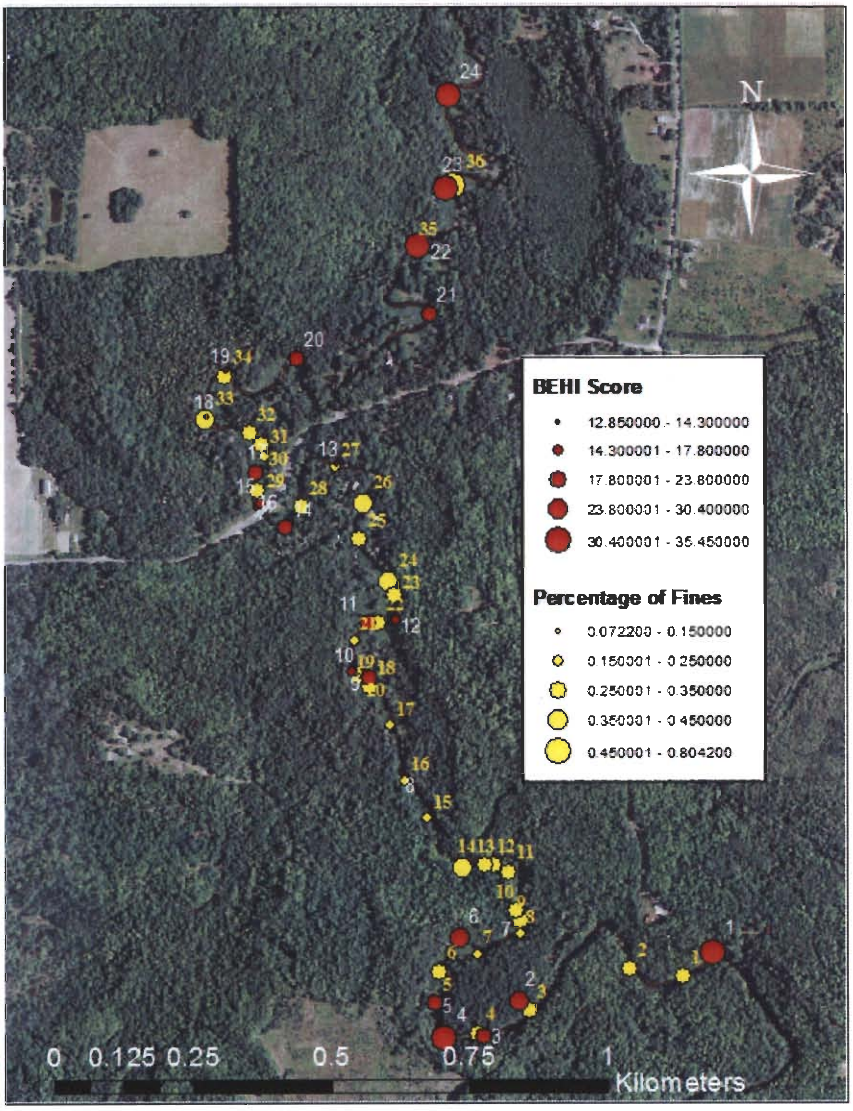


Figure 54: Chocolay River Map Displaying Erosion Sites (Red) in Graduated BEHI Score Magnitudes and Spawning Sites (Yellow) as a Function of the Percentage of Fines at Each Site

Statistical Analysis

As can be seen from table 3, percentage of fines has no significant relationship with stream gradient, BEHI, depth, flow velocity, or bankfull width (N=37, df=35). However, there is a significant relationship observed between distances downstream from an erosion site and the percentage of fines of the closest spawning habitat (sig. 0.05). This implies that salmonid spawning sites that are located close to an erosion site are more likely to exhibit enhanced percentages of fines.

As can be seen from the ANOVA table in Table 4, the relationship between BEHI score and surface protection (N=27, df=25) proved to be highly statistically significant (sig. 0.003). Note that these scores were derived from Table 2 (page 56). This means that surface protection, which is the percentage of surface area that is protected by vegetation, debris, man-made structures, etc., has the greatest bearing on BEHI score than the other three variables in the study reach. Through observation, eroded areas that have low surface protection are often the most noticeable, which may have played a small role in these results. Root density, which is the percentage of surface area of an erosion site that is covered by root biomass (disregarding the tiny spaces in between individual roots from a single plant), also has a statistically significant relationship with BEHI score. Root density and surface protection are often interrelated, which is no surprise here. This is because surface protection is often the root density percentage plus the surface area of the additional objects on the erosion site. Bank angle and root density had no statistical significance with BEHI score in this study.

Table 3

One-Way ANOVA Comparing Percentage of Fines with Stream Gradient, Distance to Erosion, BEHI Score, Depth, Flow Velocity, and Bankfull Width

		Sum of Squares	df	Mean Square	F	Sig.
Gradient	Between Groups	0.051	35	0.001	29.045	0.146
	Within Groups	0	1	0		
	Total	0.051	36			
Distance to Erosion (km)	Between Groups	0.563	35	0.016	245.87	**0.05**
	Within Groups	0	1	0		
	Total	0.563	36			
BEHI	Between Groups	2127.953	35	60.799	1.625	0.562
	Within Groups	37.411	1	37.411		
	Total	2165.365	36			
Depth (ft)	Between Groups	9.173	35	0.262	2.097	0.506
	Within Groups	0.125	1	0.125		
	Total	9.298	36			
Flow velocity (ft/sec)	Between Groups	25.034	35	0.715	3.284	0.415
	Within Groups	0.218	1	0.218		
	Total	25.252	36			
Backfull width (ft)	Between Groups	3130.689	35	89.448	0.338	0.906
	Within Groups	264.5	1	264.5		
	Total	3395.189	36			

Table 4

One-Way ANOVA Comparing BEHI with Bank Angle, Surface Protection, Root Depth, and Root Density

	Sum of Squares	df	Mean Square	F	Sig.	
Bank Angle Score	Between Groups	68.078	16	4.255	1.853	0.175
	Within Groups	20.667	9	2.296		
	Total	88.745	25			
Surface Protection Score	Between Groups	156.343	16	9.771	6.943	**0.003**
	Within Groups	12.667	9	1.407		
	Total	169.01	25			
Root Depth Score	Between Groups	211.385	16	13.212	2.452	0.087
	Within Groups	48.5	9	5.389		
	Total	259.885	25			
Root Density Score	Between Groups	163.128	16	10.196	5.795	**0.006**
	Within Groups	15.833	9	1.759		
	Total	178.962	25			

From table 5, we can see that there is no significant relationship between percent fines and flow velocity, stream gradient, or depth (sig. 0.224, 0.127, 0.211). Because streams are systems, it would be expected that a multiplicity of factors would work interchangeably to create the percentage of fines observed at a particular spawning site.

Table 5

Linear Regression Analysis Correlating Percent Fines (Dependent Variable) with Flow Velocity, Stream Gradient, and Depth

Model	Unstandardized Coefficients	Standardized Coefficients	t	Sig.		
	B	Std. Error	Beta			
1	(Constant)	0.331	0.104		3.178	0.003
	Flow velocity (ft/sec)	-0.036	0.029	-0.217	-1.24	0.224
	Gradient	-0.93	0.594	-0.249	-1.565	0.127
	Depth (ft)	0.062	0.049	0.225	1.274	0.211

Overall Patterns

Downstream from the coordinates 46.447°, -87.258° the Chocolay River transforms into a gravel-bed river with a steep average gradient (0.0533 or 53.3m/km) to an sand-bed alluvial river with a gentle average gradient (0.0036 or 3.6m/km). The result of this transformation in salmonid spawning habitat quality is stark. The three spawning locations sampled downstream from this point had percentage fines of 0.77, 0.7428, and 0.8042, and stream flow velocities of 78.9, 33.22, and 39.62 cm/sec respectively. These three spawning site locations would obviously have proportions of fines too high to manage to a more acceptable level in the scope of this study, and therefore were excluded from specific site management plans. To effectively manage this fishery, it is first essential that spawning salmonids are able to travel upstream from this location in order to seek out quality spawning habitat. Research on the Chocolay River was somewhat constricted to the section that was studied because of access difficulties downstream from Magnum Road (Figure 3). At a short distance downstream from this point, the river seemingly splits into multiple channels and becomes brush-choked and clogged with free-flowing debris. Further monitoring and research is required to determine success rates of salmonids traveling upstream from this area on the quest to find more suitable spawning habitat.

Figure 55: Aerial Photograph of the Chocolay River's Middle Reach, Which Splits into Multiple Channels through an Area of Extremely Low Relief

Interestingly, proximity of spawning sites to erosion sites and percentages of fine substrates (<2mm) proved to be statistically significant (sig. 0.05 at 95% confidence). This implies that spawning sites that are close to major erosion sites are more likely to be negatively influenced by the deposition of fines. In a planning aspect, restoration of these sites should be prioritized before other sites that are less negatively impacted. Distance to upstream sources of noticeable erosion ranged from 0m (adjacent) to 494 m with an average of 110 m. Only five of the 37 spawning sites had multiple erosion sites located between itself and the next upstream spawning site. These sites would nevertheless be expected to exhibit slightly higher rates of fine sediment deposition because of the impact from multiple erosion sites.

Even though the proportions of fines at many spawning sites is somewhat elevated compared to preferred levels, the construction of the salmonid redd itself flushes many of these fines downstream, which induces downwelling of oxygen rich surface water (Greig et al. 2007). Prior to this excavating action that spawning salmonids impose on the substrates themselves, percentages of fines ranged from 7.2% to 80.4 % and averaged 29.5% by volume. Given that proportions of fines elevated above 15% cause decreased rates of embryo survival (Soulsby et al. 2001), spawning habitat restoration on the Chocolay River could be beneficial in the long term sustainability of salmonid stocks. Only three sites of the 37 surveyed have proportions of fines below this 15% threshold. Each of these three sites had incidences of LWD along their courses of 7.92, 15.54, and 53.95 m long respectively. This may have played a significant impact on the spatial distribution of substrate in the channel at these locations given that 64.9% of spawning sites were proximate to LWD and a spawning site average length of 31.09 m, meaning that these three sites exhibit increased concentrations of LWD.

CHAPTER 6

CONCLUSION

Salmonid Spawning Site Habitat Restoration

The following sections will describe habitat restoration strategies that are recommended for salmonid spawning sites with the intention of increasing the quality of salmonid spawning habitat. Note that secondary improvements to habitat are sometimes the result, such as would occur if the strategic placement of LWD creates a heterogeneous habitat that is useful for different life stages of salmonids. Despite this, these structures are intended to provide a specific result to stream morphology and are discussed here. Many of these habitat improvement structures have designs that are outlined in Appendix A, however, LWD is the most common structural improvement of salmonid spawning sites and is not referenced there. Designs of LWD are contingent on varied site characteristics and the adjacent vegetation and are not as complex in character. The sites that do not have restoration strategies that should be initiated, currently have a low need for restoration, and are not included in this site by site analysis.

Spawning Habitat Site Nine

There are a lot of large rocks and boulders present at this site, so sampling error could have come into play considering that the sediment corer can only sample sediment less than the diameter of the corer itself, which may have come into play. Nevertheless, this is a large spawning site and a few more LWD structures anchored to the stream-bottom and deflected into the flow, would increase the spatial sorting of fines and lead to a decreased concentration in the interstitial spaces of the spawning substrate. The same erosion restoration strategy applies for this site as the one previous because there are no more erosion sites between these two spawning sites.

Spawning Habitat Site Ten

Channel roughness is very minimal here; it is neither a high quality riffle, deep enough to support cover for large fish, or has adequate refuge for newly hatched smolts. Introductions of LWD can increase all of these functions. LWD can either be introduced off-site or on-site. Here, we are starting to see more occurrences of Emerald Ash Borer feeding on ash trees in the riparian area. Instead of these ash trees falling naturally and facing the odds of falling away from the stream channel, these dead or dying trees can purposefully be hoisted into the stream channel, where they may provide a greater benefit. Most of these trees are taller than bankfull width, meaning that anchoring into the streambed isn't necessary. Introducing just two of these felled trees into the stream channel, because of their great size, should be able to achieve the desired level of stream heterogeneity at this spawning site. If these trees were removed close to the stream channel, then fast-growing moist soil tolerant plant species such as Norway spruce, white cedar, or black willow should be the replacement, with species type dependant on shade conditions.

Spawning Habitat Site Eleven

This site resembles the previous one in that LWD is both sparse and could be introduced as a restoration method along this 23.8 m section of spawning habitat. Stream roughness is very low in this straight reach, which can easily be explained by the lack of LWD and boulders. Similar introductions of LWD into the stream channel can be employed as in the previous site. LWD should be placed at an angle pointing downstream in the channel to increase flow and substrate complexity at this site.

Spawning Habitat Site Twelve

Even with rapids present throughout the riffle, spawning habitat quality is only moderate. On the upstream bend where this spawning stretch starts, there is a deep hole which would act as storage for fines transported downstream, and eventually to this spawning site. LWD placed directly downstream from this hole, where there is currently none, would serve to trap a greater proportion of these fines before depositing on the spawning gravel.

Spawning Habitat Site Thirteen

Coconut fiber rolls deployed at the toe of the vertical banks to prevent further undercutting could contribute to an increase in spawning habitat quality at this location. These rolls not only are efficient in controlling erosion, they also trap fluvially transported sediment and seeds.

Spawning Habitat Site Fourteen

European thistle was observed here, which if it is to be controlled, introductions of appropriate native seedlings would be recommended. Highbush cranberries offer a high ecological value as a food source to wildlife because of their persistence throughout autumn and into winter. Black willow is another recommended plant that has a high utility in restoring stream banks and providing cover to many animals, including bankside cover for fish. Stream roughness is very low in this section; the depth and glow velocity is essentially uniform throughout the spawning site. Like many of the previous sites, this site could greatly benefit from the introduction of LWD. Alternating sides of the stream channel with a crisscross pattern of LWD in this straight riffle section greatly lacking fish cover and suffering from low quality spawning habitat, could be a useful strategy. Spacing of LWD is contingent on wood size, but should include at least three structures on each side of the stream. Given that one piece is half way in the channel already, simply repositioning it would increase its effectiveness in adding depth, storing fines, and redirecting maximum velocity flows. If dead or dying trees are found in the vicinity, these can easily be hoisted to their desired location. Alternatively, LWD can be brought in from another location, which would prevent the removal of decaying riparian wood and minimize the negative impacts of redistributing nutrients. This technique can be extremely costly, however, such as one would expect if LWD needed to be brought in by helicopter, which is sometimes done.

Spawning Habitat Site Fifteen

Planting a few seedlings that will eventually have a large canopy, such as black maple, might be of use a few meters away from the stream channel (accounting for stream variability until time required for plant maturity). Protection of this bank can be achieved by installing two LWD pieces at this location, which will also increase spawning habitat quality. At the bend located immediately downstream and on the opposite bank, there are around a half dozen large standing ash trees that are fatalities of the emerald ash borer. Only one of these logs cut in half would be needed to achieve the task at this site.

Spawning Habitat Site Sixteen

Bizarrely, percentages of fines increased after traveling downstream from this erosion site (see sites eight through fourteen), but decreased for the last two sites (fifteen and sixteen) in this sequence. For vertical banks, grass species are not usually recommended given that undercutting is usually the result. However, since these banks are only 2 m high, which is exactly the average bank height in this study, root depth is near adequate for bank cohesion. To ensure the long-term stability of the banks, quick growing shrub species, like those discussed for the previous site, would be recommended. Also, because there is no LWD present here due to the lack of woody vegetation on the banks, the erosion site located immediately downstream (see habitat restoration site nineteen) with dead and decaying ash trees would be an easy and effective way to increase salmonid spawning habitat quality at this site. Three ash trees would need to be anchored along the west bank in the stream channel, where overhanging woody vegetation is absent, to help transform this long riffle section into one with more diverse habitat and increased spatial distributions of substrate, which both positively impact salmonids.

Spawning Habitat Site Seventeen

The same restoration strategies as the previous site also apply here: LWD installed on the west bank and strengthening bank stability by introducing a few seedlings of quick growing shrub species.

Spawning Habitat Site Eighteen

This is the last site upstream from the erosion site that has a large incidence of dead standing ash trees. These can be introduced into the stream channel here primarily along the west bank just like the previous three spawning sites. Quick growing shrub seedlings can be placed along this bank to further protect erosion and to provide food, nutrients, and shelter to both aquatic and terrestrial systems. Further from the bank, and with wider spacing, tall growing trees native to the area such as white pine, blue spruce, and white birch can be introduced to serve five important objectives for a healthy stream: (i) offer the mid- to long-term stability of streambanks, (ii) provide future inputs of LWD, (iii) influence nutrient cycling in the stream, (iv) cool stream temperatures through shading, and (v) provide habitat for terrestrial animals that affect the stream in some way. Yellow birch white pine, and black willow all provide a canopy that can serve all of these functions. The speed at which they grow is provided in the same order, with yellow birch growing the quickest, which would allow it to be planted closer to the streambank for more immediate effect.

Spawning Habitat Site Nineteen

The upstream erosion site has also appeared to have caused bank failure to the point of trees falling into the channel. Here, is an excellent example of how a rootwad provides an excellent piece for which other LWD pieces can join to, which can provide excellent habitat, especially at river bends.

Spawning Habitat Site Twenty

These banks average a height of 1.6 m, suggesting that coconut fiber rolls may not be the best restoration strategy throughout this section, but can be viable wherever heights do not exceed 1.0 m. The rest of this section can be restored by tree and rootwad revetment. Installing dormant post plantings or live fascines would not be feasible because this section is highly vegetated as is, especially considering that the high root density located at the plane of bank failure is the only variable keeping mass erosion of sediment from reaching the stream channel. Spruce/ash and alder comprise most of the tree and shrub life along the banks here. Located immediately upstream is a small feeder creek, which may play a role in regulating cool stream temperatures at the micro-scale, but was not observed by the reading in this study (16°C; measurement taken August fourth at 1:32pm).

Spawning Habitat Site Twenty-three

The log jam located downstream has many pieces, both large and small, which is largely responsible for these numbers, in addition to restricting fish passage. This log jam will need to be broken up and have LWD positioned elsewhere. This will have a positive effect on this spawning site and the spawning site located immediately downstream from the log jam, as well as a few other sites.

Salmonid Spawning Site Twenty-four

Removal of the log jam is the first step in the restoration of this site. Stabilizing the steep banks on the west bank with some of the LWD retrieved from the log jam could be an effective and cost-efficient strategy.

Salmonid Spawning Site Twenty-five

The developed area on the west bank has caused a small erosion site, which has appeared due to the combination of steep banks, human access, and removal of vegetation. LWD from the upstream log jam can be used at this site to protect the bank from further excessive erosion. These logs can be anchored into the substrate. The landowners can be contacted so that they may be educated in the importance of stream restoration at this location, and learn about how this can possibly benefit their lives. If they agree, a shared payment can be agreed so that quick growing trees and shrubs can be planted along their waterfront property. At one site along their property that is most likely to contribute the least amount to erosion, access can still be achieved by providing a narrow walkway.

Salmonid Spawning Site Twenty-six

A few undercut banks, due to both their height and the absence of long plant roots, could use reinforcement from coconut fiber rolls. These rolls, wherever they are agreed to be installed at, will encourage seed recruitment, and the eventual establishment of trees and shrubs, which will lead to a significant increase in bank stabilization. Willow posts can be placed as a short to midterm fix both in extreme cases (where coconut fiber rolls are also installed), and where erosion is negligible but can still be easily managed by this cost-effective technique. Although only willow posts would be initially planted, vegetation heterogeneity will greatly increase through time.

Salmonid Spawning Site Twenty-seven

Placing shrub species on the adjacent banks and LWD a good distance into the stream would both be sound strategies at this location. Furthermore, due to the slow to moderate flow velocities and the wide bankfull width, light infiltration is great along this reach. Growing trees with more canopy cover in addition to the white cedar along the banks would benefit this site through decreased water temperatures, provide a future supply of LWD, as well as provide nutrients to the stream.

Salmonid Spawning Site Twenty-eight

Despite the minimal flow velocity and the adjacent bank erosion from the poorly managed riverbank, percentage of fines is not at a terrible level. Revegetating erosion site thirteen, first with native shrubs located at the toe of the bank and with trees at the terrace, would be enough to eventually manage this issue. As always, the landowner has to agree upon the conditions of the restoration project, and the plants need to successfully establish themselves, in order for it to be successful. Older plants would be more expensive, so based on the eagerness of the landowner and the project budget, will determine which plants at which growth stage (i.e. plug, seedling, transplant) should be planted at this site. In a variable time period, plus the addition of LWD alternating along the east and west banks, will transform this site into a much higher quality salmonid spawning site. Remember that not only percentage of fines is important, but also oxygen flux through the substrate, which would be expected to be considerably low at such a slow flow velocity of 19.5 cm/sec.

Salmonid Spawning Site Thirty-one

Deposited fines on the west bank, where patchy distributions of herbaceous growth exists, sometimes leads to erosion into the bank at this spawning site. This can be seen from visually inspecting the bottom substrate along this bank and then comparing it to the opposite bank, where a higher percentage of coarse substrates exist. Strategic plantings of shrub species at this site would lead to a coarsening of the substrate (consult table 3). Placing LWD along the opposite bank, and protruding into the stream at an acute angle (i.e. 30°), would further stabilize the east bank where dense vegetation already is evident.

Salmonid Spawning Site Thirty-two

Most of the LWD in this stretch is water-logged and is now only exerts a small physical influence on stream morphology. As of this writing, the shallow riffle section is in the middle of the stream profile. If maximum velocity flows were deflected to the west of its current position, which is along the vertical east banks of the stream, a high proportion of fines will be flushed from the substrate and the bankside erosion will subdue. Positioning LWD at an angle away from the east bank will be able to more effectively manage this goal. Wherever banks are near failure, larger pieces can be placed parallel to the bank.

Salmonid Spawning Site Thirty-three

Directly behind the LWD is an apparent storage area for fines, especially silt. Despite this partial sorting of substrates, the spawning habitat quality at this site is low. LWD positioned along the east bank would best serve to attempt to decrease the level of fines. After this is attempted, dormant post plantings of shrubs can be positioned along the erosion site on the downstream side. These two methods will fundamentally decrease the percentage of fines, but there is a long way to go to reach the 15% threshold that is ideal for salmonid reproduction.

Salmonid Spawning Site Thirty-four

These banks are thus eroded, despite the presence of LWD. Planting of a few more tree species with long roots would be a suggestion, as well as installing a coconut fiber roll to prevent total bank failure.

Erosion Site Habitat Restoration

The main goal of the proposed restoration is to ensure that the delivery of fines to salmonid spawning sites is minimized, which will ensure more high quality habitat for these fish. Despite the degradation exhibited here likely caused by a combination of natural and anthropogenic influences, restoration of erosion sites along the study reach are highly practical for a few reasons: (i) access for restorationists can easily be achieved by Greengarden Road, (ii) it is more economically feasible to initiate restoration activities in the short term while most restoration techniques are less costly compared to high cost restoration on highly degraded streams, and (iii) it is a transition between a steep gradient, gravel-bed river to a gentle gradient, alluvial river, which means that the spawning sites located along the study reach are likely the first that spawning salmonids encounter as they migrate upstream.

Erosion Site One

Log and rootwad revetment installed at the toe of the bank and portions that are seasonally submerged due to high flows is the preferred strategy at this location. These structures will effectively divert flow around the structures, thereby reducing erosion at this site. Additionally, these structures will encourage deposition of fines instead of at spawning locations, which will encourage plant colonization on the banks. Dormant post plantings should also be considered. These structures can be located along the seasonally submerged section, which will greatly increase bank stability, and encourage seed recruitment during high flow events at the microscale. Together, these two structures can easily deflect flows away from this major erosion site, encourage revegetation, and decrease the proportions of fines (currently at 31.37%) at the first quality spawning site located directly downstream.

Despite this difference in distance to the erosion site, the second spawning site has an even higher proportion of fines (31.83%) than the spawning site located directly upstream. This can be due to the slightly greater depth at this location that would facilitate the deposition of fines. Also, there is a house located on the high terrace of the east bank, so human influences could be the case at this site. Despite this fact, the banks under the ownership of this landowner are fairly vegetated. Because of this, no other restoration strategies need be implemented than the one on the major erosion site located upstream from the previous spawning site.

Erosion Site Two

Brushlayering is the prefered restoration method at this site. These live cuttings can be installed into streambanks in the seasonally submerged and bank sections up to the terrace. Runoff velocity is effectively reduced by live cuttings that protrude beyond the face of the streambank, which will lower the input of fines into the stream channel. At this particular location, steep banks comprised of sandy-loam soils are prone to large sliding events, which can be seen from Figure. These structures will reinforce the bank so that these events occur less frequently and at a lesser magnitude, so that the adjacent salmonid spawning area, which has a moderate composition of fines (26.5%), is influenced less by deposition of fines, and spawning habitat quality is increased.

Erosion Site Four

Because this site is located along the edge of the floodplain, the hydraulic gradient imposed by the river is eroding at the clay sediments located along this 18.9 m high terrace. As a restoration strategy, the geotechnical setting of this particular erosion site, along with the high incidence of clays, is comparable to restoration site one. Just like site one, log and rootwad revetment installed at the toe of the bank and portions that are seasonally submerged due to high flows is the preferred strategy at this location. Remember that this site has an adjacent pool that is fairly deep. These revetment structures will be required to be large (i.e. large stumps with by strong dense roots) in order to reach the stream-bottom so that undercutting of the bank underneath the structures is prevented, and be anchored to the streambank to discourage transport by high flows. Dormant post plantings is also encouraged to supplement this strategy. Because of the high incidence of clays and the high slope, however, this restoration strategy will not prove to be 100% successful, but the plants that do survive to maturity will ensure further plant recruitment and bank stabilization over a long time period.

Erosion Site Five

Despite this, most of the root depth (30-49%) and root density (15-29%) expose nearly vertical banks to erosion during flood events. During the time of study, this site had deposited sediments at the toe of the bank for a horizontal distance of approximately one meter, meaning that the natural process of restoration that the LWD exerts on this site is already underway. However, during high flow events, this exposed sediment is readily able to be transported, and can be a candidate for restoration. As discussed previously, high flow events typically occur during spring and autumn months, which coincides with salmonid spawning times, but unfortunately did not coincide with the timing of this study. Branchpacking should be considered to stabilize the failing banks at this location to discourage the excess downstream transport of sediment. Over time, these stabilized sediments will level out (decreasing slope) and will encourage further colonization of riparian plant species. Branchpacking is a procedure that is used to repair holes in the streambank, as can be seen from Figure, which can prevent the surcharge exerted by the failing vegetation from eroding excess sediment.

Erosion Site Six

Flow velocity adjacent to this area also was not able to be effectively measured because of the eddy that this deep pool created. Caution must be used when approaching this site because the whole river channel is too deep to be able to safely transverse up- or downstream with waders. Together, with the low flow velocities and depth, this site in the river channel has become a huge storage site for fine sediment, a great majority of it undoubtedly originating from the adjacent erosion site. These high terraced clay banks can only be approached by the same manner as previous examples. Log and rootwad revetment, and dormant post plantings, should stabilize the banks in this example like it should in the related previous examples. The bankside sediment only needs to be stable for long enough for vegetation colonization to occur, and for quick growing species to establish themselves. This erosion site concludes the sequence of sites in this study reach that are exposed to high clay terraces, which are largely responsible for the river's namesake "Chocolay". Protection from clay erosion into the river channel can be a challenging process, but as we have seen, is an essential process in the success of salmonid reproduction and recruitment nonetheless.

Erosion Site Seven

Characteristics of the adjacent channel include a flow velocity of 24.1 cm/sec, an average depth of 53.3 cm, and a bankfull width of 11 m. Underneath the LWD, however, depth is even higher and the high incidence of silt combine to make for treacherous wading conditions. Branchpacking can be used as a strategy to repair a few small sections of the failing banks, especially where undercutting has occurred underneath a mature tree, which is present at two cases at this site. Together, with the naturally occurring LWD, branchpacking will stabilize the banks (and the trees that grow upon it), and will encourage deposition at the toe of the bank to a point that slope angle is lowered, and enable subsequent seedling recruitment.

Erosion Site Eight

Coconut fiber rolls will be able to reinforce the vegetation at this site from falling into the river. Since the LWD from falling vegetation would be a welcomed addition here, of which there is none currently, placing a few LWD structures into the flow at an acute angle and pointed downstream would have a positive influence on depositing materials along the bank, instead of eroding. After a variable time period, the banks will decrease in slope, vegetation will establish itself and propagate, and the erosion will be miniscule. Characteristics of the adjacent channel include a flow velocity of 61 cm/sec, a depth of 28 cm, and a bankfull width of 14 m. These numbers are all typical for the midsection of the study area, which is reasonable considering that this is only a low to moderate erosion site.

Erosion Site Nine

On the upstream side of the erosion site, some of these ash trees, which are quite large in size, have fallen into the stream channel. This has created a moderate to large sized log jam on the upstream side of this erosion site along the riverbend, which extends outward to over half of the stream's channel width. Remember that most of the upstream spawning sites from this location are characterized by a steep gradient, quick flow velocity, and low incidence of LWD. The first highly suitable location for many of these small to large pieces that enter the stream at these upstream locations is at this site. The deep pool on the downstream side of the log jam has expanded in surface area since the introduction of this log jam, resulting in channel widening and erosion.

Characteristics of the adjacent channel include a flow velocity of 39.9 cm/sec, a depth of 93.9 cm (which is an average measurement, greater depths do occur), and a bankfull width of

13.4 m. Redistributing the LWD from this site to other sites would be a preferred restoration method. Pool surface area and depth would decrease slightly over time, which would exert less influence on the adjacent eroding banks. The actual erosion of these banks appears to be a few meters away from the stream channel.

One possible factor for this distance of erosion away from the channel could be due to the weight surcharge exerted on the bank by the ash trees, which are dead and no longer able to stand upright on moderate to steep slopes. Another possible explanation could be meandering since the LWD structures were formed, but since that emerald ash borer is a relatively recent phenomenon in Michigan's Upper Peninsula, this scenario is highly unlikely. Dormant post plantings of native trees at this location would be an efficient strategy to restoring this site, since future erosion adjacent to the current channel is likely to be moderated by the supply of LWD. These plantings will be able to replace the void left from the departure of the ash trees. For a complete list of native trees that are worth considering, consult table 3.

Erosion Site Ten

Depth at the channel margin is great enough as to cause undercutting of the bank. These undercut banks, due to the depth and flow carried beneath them, make excellent salmonid habitat. Because of this, it would be a restoration move that would be somewhat sideways, meaning that it would increase the quality of one component of salmonid habitat and decrease the quality of another. Restoration of this site should therefore be concentrated at the upstream side of this 13.4 m long erosion site. Vegetation density along the bank where the erosion occurs is good, but because of the very steep bank angle, restoration can be achieved by the placement of one large rootwad at the toe of the bank along the upstream side of this site. This restoration method may not be able to greatly influence the percentage of fines at the next spawning site located 51.2 m downstream, but it will make a small difference in the overall supply of fines, and provide a LWD structure for habitat, causing a net positive impact.

Erosion Site Eleven

Flow velocity along the water surface that intercept the bank are not quick, however, depths are great enough to encourage the failure of noncohesive bank material, especially during high flow events. There is no LWD to protect the bank at this location. This location could benefit from the planting of large native trees on the terrace, planting shrubs along the bank, and providing log and rootwad revetment along the toe of the bank. These large logs and rootwads would be able to provide significant mass that would protect the bank against erosion from the stream bottom to a variable distance above baseflow, which will protect the bank against higher flows. This is important in order to ensure that the shrubby vegetation positioned along the 80° banks encounter less harsh conditions so that they are able to persist.

Erosion Site Twelve

The best thing that can be done with this small section is to reposition the LWD so that it offers adequate bank protection. Two shrubs can be planted to revegetate this section. Herbaceous growth will establish itself naturally over time, especially after spring flood waters have receded and deposited the vegetative seeds and propagules they contain. Along the midsection of the erosion site, deep water and flow that periodically intersects these vertical banks, has caused some apparent erosion. Spruce trees at this location presently keep these banks together, but will eventually be felled into the river unless restoration is initiated. Tree revetment should be enough to protect against the majority of the spruce trees on the bank from falling into the channel, but a few trees have a lot of lean to them and may be considered LWD by the time of project initiation.

At another location, a small valley with a spring provides cool water, but since the height of this spring is above terrace height, it inevitably erodes some finer materials into the channel. It is noteworthy that this is where the greatest depth occurs along this erosion site, so precautions need to be made by project workers. Brushlayering is a technique that will effectively filter sediment out of the slope runoff when positioned between the toe and terrace. The overbank spring flow, together with the streamflow, will provide paths for which seeds can establish themselves when they get caught in the live cuttings protruding beyond the face of the streambank. Furthermore, when vegetative roots expand into greater depths, they will essentially ‘anchor’ into these brushlayering structures, further adding to overall bank cohesiveness.

Erosion Site Thirteen

The adjacent channel has a flow velocity of 49.4 cm/sec, a depth of 48.2 cm, and a bankfull width of 19.5 m. The wide bankfull width is an apparent result of the human caused erosion at this site. The first step in the restoration of this site, would be to contact the landowner. If they agree upon restoration, then a plan can be negotiated. Most landowners with stream front property may be hesitant in surrendering their view of the river that they live on, but it is important to persuade them that the imposed restoration will return the adjacent stream to more natural and beautiful conditions.

Many shrubs used for streambank restoration are beautiful, provide essential ecosystem functions, and may even provide wild edibles for people and animals. Such shrubs would actually increase the scenic beauty of the stream at this location instead of deducting from it. To ensure that these shrubs are able to establish themselves, some carefully placed LWD structures can be positioned into the stream to protect the bank from erosion. The structures could have their external limbs removed so that they are more appealing, and still provide nearly the same benefits as an untrimmed LWD structure. This would serve an aesthetic function for the adjacent landowner. If they desire stream access, then steps that lead from a path at a specific point along their waterfront property can be installed, with a few rocks placed along these steps to ensure structural stability.

Erosion Site Fourteen

This can only mean that the design of the downstream bridge would need to be adjusted, but to do so may be beyond the budget of this project. A live cribwall would be the best structure to be placed at this site. Of all of the natural vegetative restoration structures, this one is the most expensive, but it also offers the highest bank protection. This erosion site can be seen from the bridge, so people who pass by would be able to witness this project being carried out first-hand.

The result would be increased curiosity of the project and the stream itself, which can only be a good thing. A live cribwall is a structure that is filled with suitable backfill material and layers of live cuttings that root inside the crib structure and extend into the slope. Given that this erosion site is located along vertical banks, this strategy will degrade the slope over time. In addition to providing immediate protection against erosion, this structure also provides excellent habitat. A design of this structure can be seen in Appendix A.

Erosion Site Fifteen and Sixteen

Underneath the bridge vegetation cannot grow, however, along the banks, tall grasses, willow, and maple make up the dominant herbaceous, shrub, and tree layers respectively. Interestingly, three logs are positioned vertically into the depositional area on the east bank below the bridge. More can be done here than this. Burying a wall of logs underground at the edge of the exposed silt and clays would ensure that a lot of these fine sediments don’t dislodge into the channel. As great as the large rocks and boulders look underneath the bridge, and the fast flows they create, they confine the majority of the flow for too narrow of an area.

What has been an attempt to remedy this situation has resulted in large placement of riprap along the west bank to protect the bridge infrastructure. Because of the size of these rocks, they are not easily displaced by the flowing water, and must repositioned by people. This will lead to much of the huge downstream pool decreasing in size, but will have a net positive effect on salmonid habitat both upstream and downstream from the bridge. Both sites have little vegetative cover, but due to the absence of sunlight underneath the bridge, this is acceptable. Some erosion along the east bank extends a ways downstream from the bridge and can easily be managed by planting shrub species. Overall, the replacement of the rocks and the filling in of the deep pool may be seen as negative by the local residents, but would only benefit the salmonids, both at this site, and elsewhere.

Erosion Site Seventeen

The exertion that this erosion site enacts upon the adjacent channel result in a flow velocity of 34.4 cm/sec, a depth of over 122 cm, and a bankfull width of 13.7 m. Log and rootwad revetment, along with dormant post plantings, need to be done to restore the erosion at this site. Root depth is only 15-29%, with root density and total surface protection slightly higher at 30-54% each. The above restoration methods, once they have time to work, will encourage herbaceous growth along this erosion site so that surface protection is increased. Trees planted on the terrace will lead to further bank cohesiveness through their long roots. Also, these trees will provide shading at this stream location, of which there is little. Trees can even be planted on the south (east) bank, where overstory vegetation is also sparse, to shade this location further.

Erosion Site Eighteen

LWD is in short supply, and tall grass species comprise a majority of the vegetation on the banks, besides the odd cedar. As with many other erosion sites, restoration of this site would be to place LWD protruding along the banks at an acute angle, and revegetating this site with both shrub and tree species along the bank to terrace.

Erosion Site Nineteen

Caution must be taken for those who attempt to restore this site. A large cedar tree is ready to fall into the bank along where the LWD is located. Elsewhere on the bank, grass species comprise a majority of the vegetation along the plane of failure, with overstory trees such as spruce and cedar located further from the bank. It is interesting to note that surface protection (30-54%), root density (30-54%), and bank slope (90-119°) were responsible for this site's BEHI score, not root depth (50-89%). Most of these roots seem to be originating from the spruce trees located further from the bank, hence the lower root density, and the lower overall bank protection they provide. Obviously the log jam at this location is providing more harm than good in terms of salmonid spawning habitat and should be redistributed accordingly. Anchoring rootwads and large logs to the river-bottom should be done at the toe of the erosion to provide bank protection and to prevent further mass collection of LWD. The rest of the LWD can be used at other spawning sites or erosion sites as needed.

Placing trees that have the potential to grow long roots should be done closer to the plane of failure than the current distribution of vegetation. Precautions need to be made when placing these trees too close to the bank's steep slopes. For example, the surcharge exerted by the weight of vegetation is sometimes likely to produce mass bank failure in itself, therefore, these trees should not be placed too close to the plane of failure. Lets examine the likely influence of the

LWD first. The LWD will encourage deposition of fines behind the structure.

Given that depth is great adjacent to the erosion, the toe to terrace height is actually much greater than the 2.4 m bank height, given that this height was given from the surface of the water. We need to know at which bank angle would be suitable for the tree species that are planted here, without them falling into the channel, and causing more bank erosion than what would occur without restoration. Deposition of fines from the stream bottom up until the vertical position of the LWD itself will vary depending on stream velocity around and underneath these structures, and also on seasonal flushing of fines from flood events too, of course.

LWD, from where it touches the bank until its furthest distance away from the bank in the channel, will affect flow and microscale deposition of fines itself differently depending upon shape, size, and number of limbs of LWD. Now that we have talked about deposition, now we will talk about erosion. These LWD structures, since they will be anchored, will be able to effectively trap sediment that erodes from these steep banks. This will lead to a gentler bank slope over time, and instead of these sediments being carried downstream, will lead to restructuring the bank. In conclusion, more research needs to be conducted in order to determine these microscale deposition of fines and erosion of bankside sediment due to the introduction of LWD, and how this ultimately affects bank slope along an erosion site. Nevertheless, the trees that are placed at the terrace should be a few meters away from the plane of failure in order to negotiate around these negative consequences. In addition, large transplants will be more able to effectively stabilize the banks, due to the magnitude of the anticipated erosion likely to occur here over a short time period. As a final note, when digging a hole for the root structures of these transplants, care should be taken so that total bank failure does not occur, which is important.

Synthesis

The Chocolay River got its name in the late 1800s by French explorers who noted the dark brown color of the water (Chocolay Township unpublished data). This is attributed to erosion of its high clay banks following rainfall. Deposition of clays has been shown to be detrimental to salmonid egg survival in two ways: (i) clay particles create a zone of low oxygen supply around the eggs and (ii) clay particles restrict the transport of oxygen across the egg's chorion by physically blocking the pore canals in the egg chorion (Greig et al. 2007). Because of these negative impacts, restoration of sites with a high soil clay content will be striving for increased quality of salmonid spawning habitat, but ironically, will lead to a decrease in the stream's load of fine sediments for which the stream was originally named.

Planting Clay-Tolerant Trees and Shrubs

There are four major erosion sites, and many less severe erosion sites, that were inventoried along the Chocolay River with high proportions of exposed clays along the river channel. These sites were often unvegetated because of the harsh growing conditions exhibited. Figure 4 shows the plant hardiness zones in Michigan, which determines which species are able to withstand the climatic conditions in a particular area. Tables 6 and 7 show which trees and shrubs native to the north-central region of Michigan's Upper Peninsula are well adapted to growing in clay soils. These trees and shrubs can be selected based on the specific characteristics of a given site. Clay soils are typically alkaline with a pH from 7 to 8.5 The USDA zones listed in the tables represent the northernmost zone that a particular tree or shrub can adapt to. The Chocolay Watershed is positioned in zone 4 (note that the lower the zone number, the more northerly the zone and more severe the winter temperatures are).

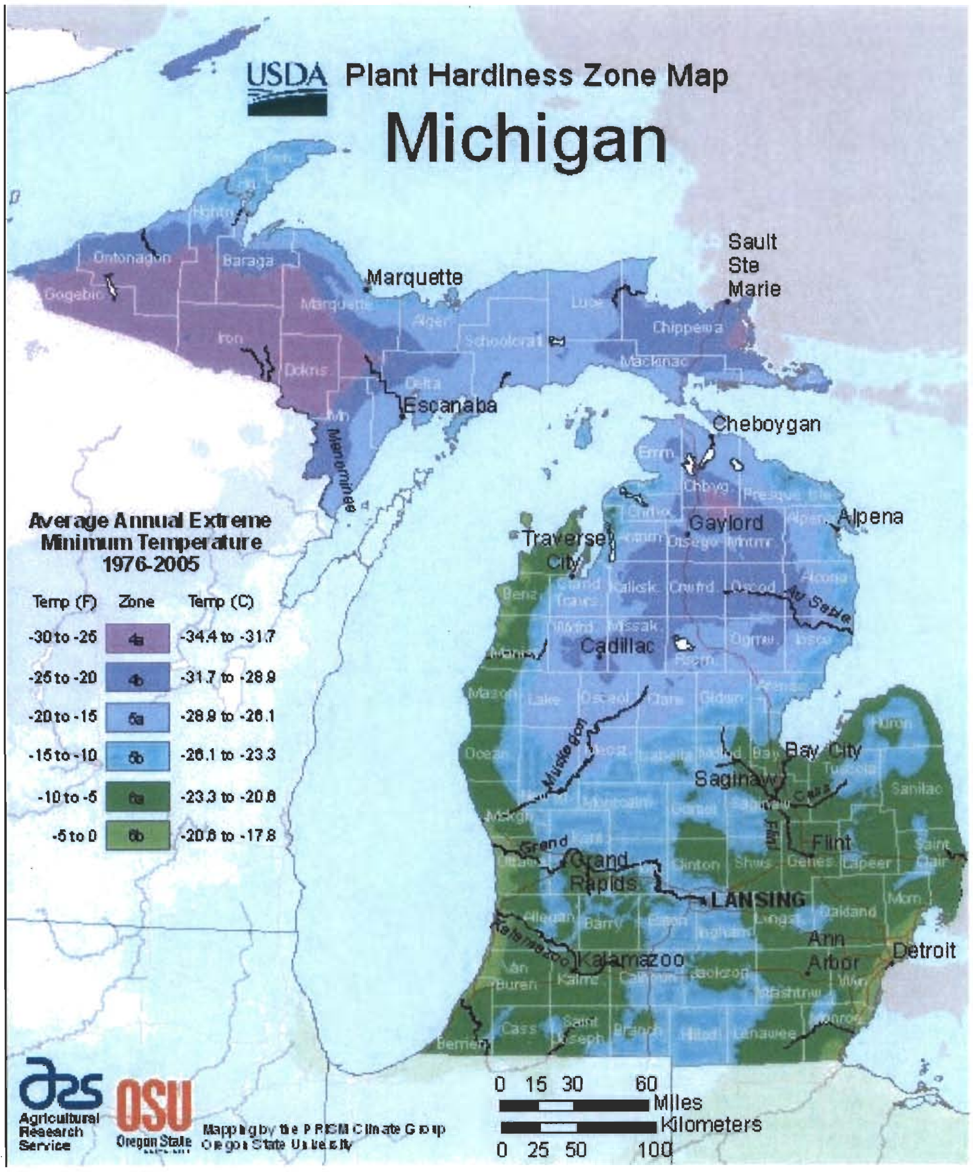


Figure 56: Michigan's USDA Plant Hardiness Zones Map

Table 6

Native Tree Species Adapted to Clay Soil. Trees marked with an asterisk are particularly well-suited to clay soils. § When more than one zone is listed (eg: 3-4 or 4-5), some species are not hardy in the cooler zone

Scientific name	**Common name**	**USDA zone**	**Comments**
Abies balsamea	Balsam fir	3	Prefers acidic soils
Acer rubrum	Red maple	3	Needs acidic soils
Carpinus caroliniana	Blue beech	4	
* ***Crataegus*** **species**	Hawthorn	3-4 §	Needs well-drained soils
Fraxinus americana	White ash	3	
* ***Fraxinus nigra***	Black ash	3	
* ***Fraxinus pennsylvanica***	Green ash	3	
* ***Larix laricina***	Tamarack	2	
* ***Malus*** **species**	Apple, crabapple	3	Prefers acidic soils
Picea glauca **var.** ***densata***	Black Hills spruce	4	
Pinus strobus	White pine	3	Prefers acidic soils
* ***Populus*** **species**	Aspen, cottonwood	2	
* ***Pyrus*** **species**	Pear	4-5 §	
* ***Salix*** **species**	Willow	2	Prefers moist to wet soils
* ***Tilia*** **species**	Linden, basswood	3	
* ***Ulmus*** **species**	Elm	4	

Table 7

Native Shrub Species Adapted to Clay Soil. Shrubs marked with an asterisk are particularly well-suited to clay soils. § When more than one zone is listed (eg: 3-4 or 4-5), some species are not hardy in the cooler zone

Scientific name	**Common name**	**USDA zone**	**Comments**
Amelanchier **species**	Serviceberry	4	
*Aronia melanocarpa	Chokeberry	3	
*Cephalanthus occidentalis	Buttonbush	4	
*Cornus alba	Tatarian dogwood	3	
Cornus alternifolia	Pagoda dogwood	4	Needs moist, acidic soils
*Cornus racemosa	Grey dogwood	3	
*Cornus sericea	Red osier dogwood	3	
Hamamelis virginiana	Witch hazel	4	
Ilex verticillata	Winterberry	4	Needs acidic soils
Juniperus **species (most)**	Juniper	3	Needs well-drained soils
*Physocarpus opulifolius	Common ninebark	2	
*Potentilla Fruticosa	Potentilla	2	
Rhus species	Sumac	2	Prefers well-drained soils
*Ribes odoratum	Clove currant	2	
*Salix species	Willow	2	
Sambucus canadensis	American elderberry	3	
Spiraea **species**	Spirea	3-4 §	Needs well-drained soils
*Symphoricarpos albus	White snowberry	3	
*Syringa species	Lilac	2	
*Thuja occidentalis	Arborvitae, white cedar	3	
*Viburnum lentago	Nannyberry viburnum	2	
*Viburnum trilobum	Highbush cranberrybush	2	

Project Costs

As with any habitat restoration plan, an approximate project budget must first be established. The following tables (Table 8 and Table 9) give the minimum, maximum, and average costs of initiating a particular restoration method at a given size. These costs have been compiled from various sources (Virginia Department of Conservation and Recreation 2004; Landphair & Li 2001; United States Army Corps of Engineers 2008; Allen & Leech 1997). Notes are given for site specific conditions that must be accounted for. The restoration methods employed at each site can be referenced in Appendix A, where site specific criteria for each design structure is listed. In total, an average cost of $42,352.13 for spawning site restoration and $79,726.75 for erosion site restoration for a grand total of $122,078.87 is estimated for total restoration of the study reach on the Chocolay River. These costs account for restoration activities only, and do not include activities such as post-project and fish population monitoring. To fund this restoration, the United States Fish & Wildlife Service offers grants for "The Wildlife and Sport Fish Restoration Program", which can be applied to. Partnering with a local non-profit conservation group, such as the Lake Superior Watershed Partnership and Land Trust, could provide the means to initiate this project.

Table 8

Cost of Restoration at Spawning Sites

Site	Method	Size (m)	Minimum	Maximum	Average	Notes
9	LWD	24.7	318.63	4063.15	2190.89	3 Structures
10	LWD	27.1	349.59	4457.95	2403.77	4 Structures
11	LWD	23.8	307.02	3915.1	2111.06	4 Structures
12	LWD	28	361.2	4606	2483.6	3 Structures
13	Coconut Fiber	10	109.85	984.26	547.06	33 ft x 39 in
14	LWD	27.1	349.59	4457.95	2403.77	4 Structures
14	Shrub Vegetation	10	31.06	164.1	97.59	
14	European Thistle	10	40	40	40	Estimated 2
15	LWD	54.9	708.21	9031.05	4869.63	2 Structures
15	Overstory	50	155.3	820.5	487.9	
16	LWD	71	915.9	11679.5	6297.7	4 Structures
16	Shrub Vegetation	70	217.42	1148.7	683.06	
17	LWD	63.7	821.73	10478.65	5650.19	4 Structures
17	Shrub Vegetation	60	186.36	984.6	585.48	Sparse
18	Shrub Vegetation	60	186.36	984.6	585.48	
18	Overstory	60	186.36	984.6	585.48	
22	European Thistle	20	80	80	80	Estimated 4
23	LWD	8.5	109.65	1398.25	753.95	1 Structure
24	LWD	16.2	208.98	2664.9	1436.94	2 Structures
26	Shrub Vegetation	40	124.24	656.4	390.32	
26	Coconut Fiber	20	219.7	1968.51	1094.11	Use two 33 ft x
27	LWD	10.7	138.03	1760.15	949.09	3 Structures
27	Shrub Vegetation	10	31.06	164.1	97.58	
27	Overstory	10	31.06	164.1	97.58	
28	LWD	20.1	259.29	3306.45	1782.87	4 Structures
31	LWD	7	90.7	1151.5	621.1	1 Structure
31	Shrub Vegetation	7	21.74	114.87	68.305	
32	LWD	12.4	159.96	2039.8	1099.88	2 Structures
33	LWD	17.4	224.46	2862.3	1543.38	1 Structure

Table 9

Cost of Restoration at Erosion Sites

Sit	Method	Size	Minimum Cost	Maximum Cost	Average Cost	Notes
1	Log and Rootwad Revetment	33.53	432.54	5515.69	2974.115	
1	Dormant Post Planting	33.53	208.35	1100.46	654.405	Clays exposed
2	Brush Layering	37.49	25091.73	52274.45	38683.09	Clays exposed. 17 structures
2	Remove European Thistle	37.49	80	80	80	Estimated 4 manhours
3	Brush Layering	4.27 x	2639.37	5498.69	4069.03	Clays exposed. 4 Structures
4	Dormant Post Planting	24.4 x	151.62	800.81	476.215	Clays exposed
4	Log and Rootwad Revetment	24.4	309.6	4013.8	2161.7	
5	*Branch Packing	17.1 x	1513.41	1891.76	1702.585	One exposed slump
6	Log and Rootwad Revetment	19.2	247.68	3158.4	1703.04	
6	Dormant Post Planting	19.2 x	119.31	630.15	374.73	Clays exposed
7	*Branch Packing	23.8 x	1366.3	1707.88	1537.09	
8	*Coconut Fiber Roll	16.5	219.7	219.7	219.7	Two 33 ft x 39 in rolls. 3.62 m
8	*LWD	16.5	212.85	2714.25	1463.55	2 Structures
9	Dormant Post Planting	16.8 x	52.2	275.69	163.945	
9	Log Jam Redistribution /	16.8	160	320	240	Estimated 8-16 manhours
10	*Rootwad Reventment	13.4	200	1700	950	1 Structure
11	Log and Rootwad Revetment	18.9	243.81	3109.05	1676.43	
11	Shrub Vegetation	18.9 x	58.72	310.15	184.435	
11	Overstory Vegitation	18.9 x	58.72	310.15	184.435	

Table 10

Cost of Restoration at Erosion Sites (continued)

Site	Method	Size (m)	Minimum Cost	Maximum Cost	Average Cost	Notes
12	Shrub Vegetation	15.8 x 2	49.09	259.28	154.185	
12	Log and Rootwad	15.8	203.82	2599.1	1401.46	
12	*Brush Layering	15.8 x 2	1244.1	2591.87	1917.985	2 structures
13	Shrub Vegitation	39.6 x 1.4	123.04	649.84	386.44	Contact landowner
13	Path Access and Install	4 x 2	382.72	984.26	683.49	
14	Live Cribwall	17.1 x 2.3	4656.79	11853.64	8255.215	Built from stream bottom
15	*Buried Wall Structure	25.9 x .91	212.44	1062.18	637.31	East bank. Half the length of
15	*Shrub Vegetation	25.9 x .91	40.24	212.51	126.375	Downstream from bridge only
16	Reposition Boulders	12.2	160	160	160	Confined flow along the west
17	Dormant Post Planting	15.2 x 2.4	47.23	249.44	148.335	
17	Log and Rootwad	15.2	196.08	2500.4	1348.24	
17	Overstory Vegitation	15.2 x 10	47.23	249.44	148.335	Increased shading
18	Shrub Vegetation	18.3 x 1.8	56.86	300.31	178.585	
18	Overstory Vegitation	18.3 x 10	56.86	300.31	178.585	
18	*LWD	18.3	236.07	3010.35	1623.21	
19	Shrub Vegetation	24.4 x 2.4	75.81	400.41	238.11	
19	Overstory Vegetation	24.4 x 10	75.81	400.41	238.11	
19	Log and Rootwad	24.4	314.76	4013.8	2164.28	Redistributed from log jam
19	*Deconstruct Most of Log	24.4	160	320	240	Estimated 8-16 manhours

Closing Remarks

In total, 37 spawning sites and 26 erosion sites were inventoried during the summer of 2013 extending 5,572 m along the middle reaches of the Chocolay River in Marquette County, Michigan. This reach includes low to high quality spawning gravel comprising a total area of 10,151.8 m^2. Given that there's a significant statistical relationship between spawning site distance to erosion sites and percentage of fines at spawning sites, prioritization of restoration can be made. As a case study, this fact can be extrapolated and applied to other stream restoration projects in areas of similar soil and fluvial characteristics. Methods of spawning site and erosion site restoration applied in this study can be applied elsewhere, as long as specific site characteristics are considered.

Water temperature at spawning sites ranged from 12°C to 18°C and averaged 15.6°C during the study period. These temperatures were often near the daily maximum due to the time of day that measurements were taken (solar noon ± 3 hours). Water temperatures for salmonids are particularly important during the spring and autumn months when spawning occurs because egg incubation periods are controlled largely by temperature (Harper & Ferguson 1995). Brown trout (*Salmo trutta*) spawn in late autumn to winter at temperatures of 0-12°C (Kemp et al. 2011). Considering that the mean daily water temperature that salmonids can withstand is around 20°C and at a maximum of 24°C (Southern California Edison Company 2007), water temperature is unlikely to adversely affect salmonids directly based on the readings from this study. That is, unless future climate change and alterations to the channel and/or bankside vegetation is likely to cause a severe increase in stream temperatures (Battin et al. 2007). The Chocolay River, being a fourth order stream in the study reach, may even be more sensitive to these changes because of its relatively small size, meaning that a slight change can cause an increase in stream temperatures to a point that is unsuitable for salmonids (Battin et al. 2007).

Flow velocity at spawning sites ranged from 28.65 cm/sec to 135.94 cm/sec and averaged 58.52 cm/sec. These results are encouraging considering that the peak aquatic insect production has been found to be at riffles with flow velocities of about 60.96 cm/sec (Oglesby et al. 1972). Increased food for salmonids of various life stages is the result. Once the embryos hatch, however, their small size makes them relatively weak swimmers, and must quickly find refugia close to the spawning sites, or else be displaced by the current (Harper & Ferguson 1995), Contrary to expectations, flow velocity was found to have no significant relationship with percent fines (sig. 0.057 at 95% confidence). This would suggest that stream flow velocity alone cannot accurately determine sediment size class composition at salmonid spawning riffles in this study. Franssen et al. (2012) observed that by increasing flow velocity and oxygen flux through substrates with elevated proportions of sand and silt, there was no significant relationship with egg to emergence survival. Instead, coarsening of the substrate was found to be most beneficial for survival. This implies that the supply of fines needs to decrease to ensure the coarsening of the substrate to an acceptable level adequate for egg to emergence survival. Essentially, coarsening of the substrate will lead to higher interstitial flow velocities, which will increase the supply of oxygen across the egg membrane (Franssen et al. 2012), and will increase natural flushing of harmful metabolic waste products excreted by embryos (Greig et al. 2007), leading to higher survivability rates.

Despite the obvious practicality of this research, future research needs to address rates of fish passability beyond flow obstructions. For example, large log jams may prevent fish of a certain size to reach upstream locations, which could be a problem given that spawning salmonids require cool and well-oxygenated water, and coarse substrates, that are often evident there. There could be either an inherent apprehensiveness of certain individuals from wanting to pass these obstructions or they physically cannot fit between the voids between the obstructions. Downstream from the study reach stream gradient is too low to provide valuable salmonid spawning habitat, which is the primary cause of the high number of log jams evident in this reach. Given that flow velocities averaged 58.52 cm/sec and stream temperatures averaged 15.6°C during the warmest part of the year, the study reach is highly suitable for salmonid habitat. We just need to make sure that salmonids can reach these locations in the first place.

Wherever riparian revegetation efforts are initiated, it is important to consider that riparian vegetation has a progressively larger influence on a stream's hydrology and sediment budget the closer it is located to the channel. Through this logarithmic relationship, prioritization of revegetation adjacent to the channel and then restoring vegetation along the terrace and beyond can be made. This factor, when considering the severity of erosion and the spatial impact to spawning sites located a short distance downstream, will allow for restoration prioritizations to be made. The total project budget may equal $122,078.87, but it is important to note that some restoration is better than none if this figure cannot be achieved.

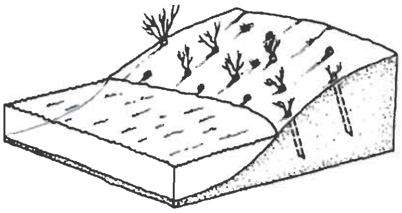
As for the adjacent riparian area, the restoration activities will greatly increase diversity and abundance of riparian vegetation. This will increase habitat quality of both aquatic and terrestrial species, which will subsequently increase in abundance. The return of more spawning salmonids to the Chocolay River will increase the vitality of the riparian vegetation, meaning there will be an increase in spawning habitat as more salmonid derived nutrients are delivered to the system. The exertion of the vegetation of fluvial geomorphology will provide coarser substrates for salmonids to use as spawning habitat. It is the ultimate goal of the proposed restoration is to increase salmonid stock populations and quality without even stocking a single fish. As a long-term strategy, this method should be employed more often as a means to ensure greater genetic diversity of our fisheries, which will increase the sustainability of this resource through time.

APPENDIX A

BIOTECHNICAL STREAM RESTORATION TECHNIQUES

Live Stakes

Live, rootable woody cuttings inserted and tamped directly into soil. Root system binds soils together; foliages help reduce flow energy.



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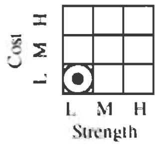


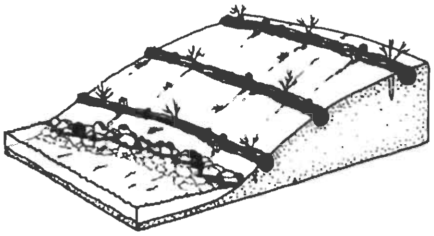
Application and Properties:

- Most effective when used on small, simple problem sites.
- Suitable for streambanks with gentle slopes.
- Enhance performance of surface erosion control materials such as rolled erosion control products (RECPs).
- Stabilize transitional areas between different biotechnical techniques.
- Inexpensive.

Applied Zones:

Live Fascines

Live cuttings tied together in linear cylindrical bundles. Installed in shallow trenches that normally match contours.



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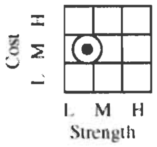
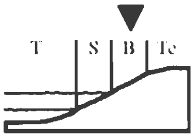


Application and Properties:

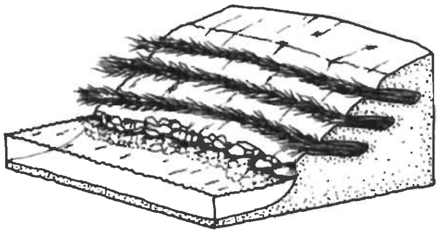
- Terrace and check dam-like structures break up slope length and reduce sheet flow velocity.
- Protect slopes from shallow slide failures (1 to 2 feet in depth).
- Effective on gentle slopes (less than 33%).
- Cause little site disturbance if installed properly.
- Other techniques such as live staking, post plants and RECPs can be easily applied together.

Applied Zones:



Brushlayering

Live cuttings installed into streambanks between layers of soil in crisscross or overlapping pattern.



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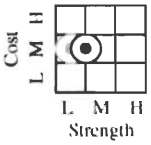
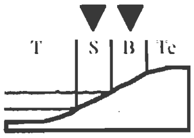


Application and Properties:

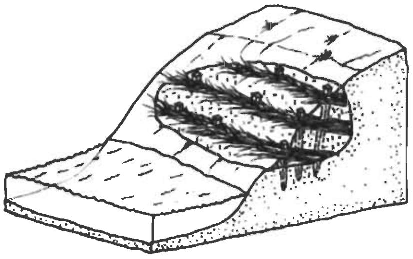
- Live cuttings protruding beyond the face of the streambank increase the hydraulic roughness which reduces runoff velocity.
- Layers of live cuttings can filter sediment out of the slope runoff.
- Stabilize slopes against shallow sliding.
- Cuttings installed inside the streambanks reinforce slopes by the root-stem-soil structure.
- Preferred on fill rather than cut slopes.

Applied Zones:

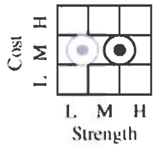


Branchpacking

Brushlayering with wood staking and compacted backfill, used to repair small slumps and holes in streambanks.



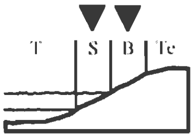
Cost/Strength Matrix:



Application and Properties:

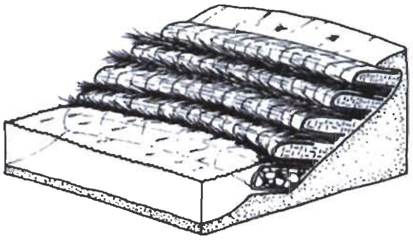
- Effective and inexpensive method to repair holes in streambanks that range from 0.75 to 1.5 meters in height and depth.
- Provides immediate soil reinforcement.
- Not effective in slump areas greater than 1.5 meters deep or 1.5 meters wide.

Applied Zones:

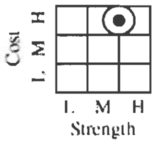


Vegetated Geogrids

Brushlayering incorporated with natural or synthetic geotextiles wrapped around each soil lift between the layers of live cuttings.



Cost/Strength Matrix:



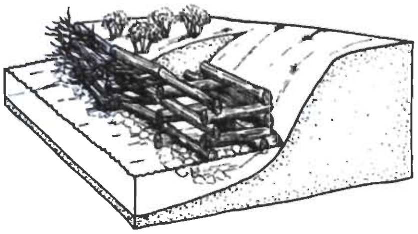
Application and Properties:

- High strength technique that stabilizes steep slopes up to 1:1.
- The system must be built during low flow conditions.
- Labor intensive; can be complex and expensive.
- Useful in restoring outside bends where erosion is a problem.
- Capture sediments, which rapidly rebuilds to further stabilize the toe of the streambank.
- Provide immediate stabilization without vegetation growth.

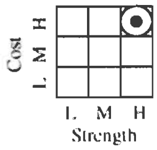
Applied Zones:

Live Cribwall

Box-like interlocking arrangement of untreated log or timber members. Structure is filled with suitable backfill material and layers of live cuttings that root inside the crib structure and extend into the slope.



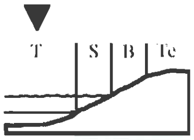
Cost/Strength Matrix:



Application and Properties:

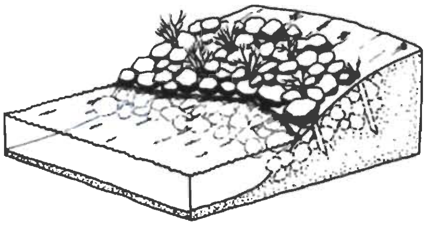
- Effective on outside bends of streams where high strength is needed.
- Appropriate at the base of a slope as a toe protection.
- Effective where a steep slope face is needed and a more vertical structure is required.
- Maintains a natural appearance and provides excellent habitats.
- Provides immediate protection from erosion, while established vegetation provides long-term stability.
- Has to be battered if the system is built on a smooth, evenly sloped surface.
- Can be complex and expensive.

Applied Zones:

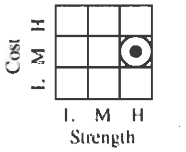


Joint Planting

Rock ripraps with live stakes tamped into joints or openings between rocks.



Cost/Strength Matrix:



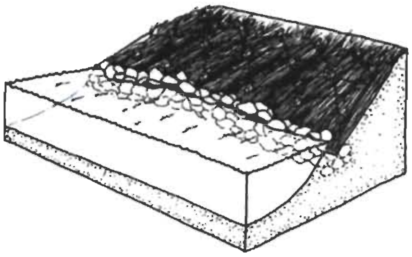
Application and Properties:

- Enhance aesthetics of existing rock ripraps.
- Provide better habitats than riprap alone.
- Improve the strength of ripraps alone.
- Provides immediate protection and is effective in reducing erosion on actively eroding banks.
- Many available design guidelines because the riprap is widely used.

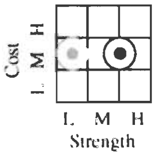
Applied Zones:

Brushmattress

Live cuttings installed with branches parallel to the slope direction to form a mattress. Cut ends of live cuttings keyed into the toe protection at the slope bottom.



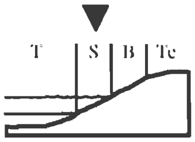
Cost/Strength Matrix:



Application and Properties:

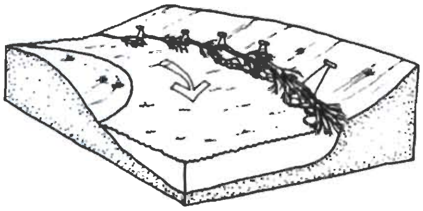
- Provide immediate but low-strength protection on streambanks.
- Effective on streambanks with steepness less than 50 percent.
- Captures sediment during floods.
- Rapidly restores riparian vegetation and streamside habitat.

Applied Zones:



Tree Revetment

A series of whole, dead trees cabled together and anchored by earth anchors in the streambank.

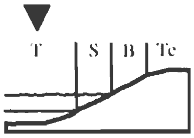


N/A

Application and Properties:

- Semi-permanent; has a limited life.
- Uses inexpensive, readily available materials.
- May require periodic maintenance to replace damaged or deteriorating trees.
- Has self-repairing abilities following damage after flood events if used in combination with biotechnical techniques.
- Should be used in combination with other biotechnical techniques.
- Not appropriate near bridges or other structures where downstream damage is possible if the revetment dislodges during flood events.

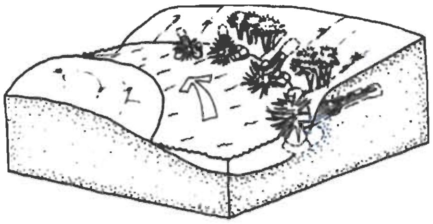
Applied Zones:



Log and Rootwad Revetment

Logs and rootwad systems anchored on streambanks that provide wildlife and fish habitats.

(Rootwad is shown below.)



N/A

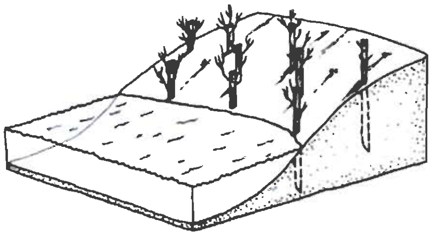
Application and Properties:

- Have limited life depending on climate and tree species used.
- Create instream structures for improved fish habitat.
- Effective on meandering streams with out-of-bank flow conditions.
- Sustain high shear stress if logs and rootwads are well anchored.
- Should be used in combination with other biotechnical techniques.
- Enhance diversity of riparian corridor.

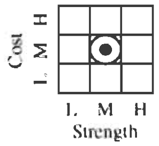
Applied Zones:

Dormant Post Plantings

Woody live posts planted along streambanks in a square or triangular pattern.



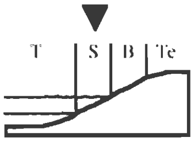
Cost/Strength Matrix:



Application and Properties:

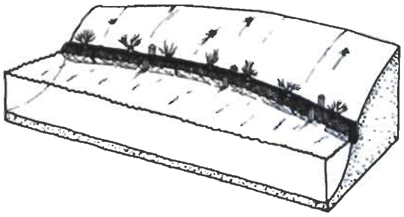
- Enhance conditions for colonization of native species.
- Self-repairing, damaged posts can develop multiple stems.
- Can be used in combination with other biotechnical techniques.
- Posts protruding out of streambanks can deflect higher streamflows and trapping sediment.
- Well suited to smaller, non-gravely streams where ice damage is not a problem.

Applied Zones:

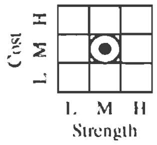


Coconut Fiber Rolls

Coconut husk fibers bound together with twine woven from coconut to form a cylindrical structure. Installed at the toe of the slope, generally at the stream-forming flow stage.



Cost/Strength Matrix:



Application and Properties:

- Trap sediment that encourages plant growth within the fiber roll and provides toe protection.
- Flexible; can mold to existing curvature of streambank.
- Produce a well-reinforced streambank with little site disturbance.
- Prefabricated materials can be expensive.
- Should be used in combination with other biotechnical techniques.

Applied Zones:

APPENDIX B

CHOCOLAY RIVER INVENTORY FORMS

APPENDIX B

CHOCOLAY RIVER SALMONID HABITAT INVENTORY FORM

Inventory Number: ______ Waypoint ID: ______ Coordinates: ________________

Size of Spawning Area (m x m): ________ Number of Pictures: __________

Percent Volume Silt Sediments: _________ Depth (m): __________

Percent Volume Fine Sediments: ________ Flow Velocity (m/sec): ________

Percent Volume Medium Sediments: ______ Bankfull Width (m): _________

Percent Volume Coarse Sediments: ________ Bank Slope (deg): ________

Dominant Overstory Vegetation: __________ Bank Height (m): _________

Dominant Understory Vegetation: _________ LWD Present: Y/N

Eroded Banks Adjacent to Spawning Gravel: Y/N Invasive Species Present: Y/N

Notes: ____

____

CHOCOLAY RIVER EROSION INVENTORY FORM

Upstream Management Concern: Road Crossing/Exposed Sediments/Developed

Waypoint ID: __________ Coordinates: _____________ Size of Area (m x m): ___________

Land Ownership: State/Federal/Private/Unknown Exposed Sediment: Y/N

Distance to Spawning Gravel (m/km): _________ Invasive Species Present: Y/N

Flow Velocity Adjacent to Area (m/sec): ___________ LWD Present: Y/N

Depth Adjacent to Area (m): __________ Bankfull Width (m): _________

Bank Height (m): __________ Dominant Overstory Vegetation: __________________

Bank Slope (deg): _________ Dominant Understory Vegetation: _________________

Notes: ____

____

MODIFIED BANK EROSION HAZARD INDEX (BEHI) FIELD FORM

Date:____________________ **Personnel:**_______________________________________

Location:____

(Circle one in each column)

Root Depth (% of BH)	Root Density (%)	Surface Protection (Avg. %)	Bank Angle (degrees)
90-100	80-100	80-100	0-20
50-89	55-79	55-79	21-60
30-49	30-54	30-54	61-80
15-29	15-29	15-29	81-90
5-14	5-14	10-14	91-119
< 5	< 5	< 10	> 119

Comments:____

APPENDIX C

DATA TABLES

Table 11

Salmonid Spawning Habitat Stream Technical Data

Spawning Site	Latitude	Longitude	Gradient	Distance to Erosion (km)	BEHI	Percent Rock	Percent Gravel	Percent Sand	Percent Silt	Percent fines	Depth (cm)	Flow velocity (cm/sec)
1	46.435	-87.252	0.0144	0.0664	32.95	0.521	0.166	0.306	0.008	0.314	25.4	74.1
2	46.435	-87.253	0.0158	0.1763	32.95	0.379	0.303	0.303	0.015	0.318	28.0	74.1
3	46.435	-87.256	0.0167	0.0200	30.4	0.594	0.130	0.268	0.008	0.277	33.0	76.2
4	46.434	-87.257	0.0267	0.0114	21.35	0.594	0.130	0.268	0.008	0.277	17.8	56.1
5	46.435	-87.258	0.0338	0.0708	35.45	0.637	0.221	0.133	0.010	0.143	22.9	135.9
6	46.435	-87.258	0.0402	0.0626	21.8	0.406	0.271	0.305	0.018	0.323	50.8	37.5
7	46.436	-87.257	0.0321	0.0341	28.85	0.669	0.170	0.154	0.007	0.161	12.7	62.5
8	46.436	-87.256	0.0579	0.0342	12.85	0.637	0.142	0.212	0.010	0.222	17.8	34.4
9	46.436	-87.256	0.1533	0.0683	12.85	0.505	0.232	0.253	0.011	0.263	30.5	68.6
10	46.436	-87.256	0.0722	0.0959	12.85	0.488	0.260	0.234	0.019	0.253	58.4	82.3
11	46.437	-87.256	0.0653	0.1713	12.85	0.584	0.117	0.292	0.008	0.299	50.8	33.2
12	46.437	-87.256	0.1511	0.2120	12.85	0.430	0.273	0.281	0.016	0.297	33.0	82.0
13	46.437	-87.257	0.1242	0.2260	12.85	0.524	0.185	0.277	0.015	0.292	33.0	61.6
14	46.437	-87.257	0.0397	0.2677	12.85	0.475	0.173	0.345	0.008	0.353	17.8	36.9
15	46.438	-87.258	0.0315	0.3690	12.85	0.594	0.198	0.198	0.010	0.208	30.5	65.2
16	46.438	-87.258	0.0359	0.4485	12.85	0.731	0.078	0.183	0.008	0.191	28.0	62.5
17	46.439	-87.259	0.0369	0.0898	14.3	0.692	0.130	0.173	0.006	0.179	15.2	90.8
18	46.440	-87.259	0.0629	0.1760	14.3	0.590	0.148	0.246	0.017	0.263	30.5	92.4
19	46.440	-87.260	0.0712	0.0163	23.8	0.731	0.197	0.061	0.011	0.072	48.3	40.2
20	46.440	-87.260	0.0712	0.0181	23.8	0.577	0.115	0.308	0.000	0.308	64.3	39.9
21	46.441	-87.260	0.0533	0.0512	15.85	0.517	0.239	0.239	0.005	0.244	50.8	46.3
22	46.441	-87.259	0.0522	0.0198	21.8	0.497	0.186	0.311	0.006	0.317	38.1	71.9
23	46.441	-87.259	0.0698	0.0434	15.8	0.451	0.208	0.300	0.041	0.341	76.2	38.4
24	46.442	-87.259	0.0569	0.0701	15.8	0.394	0.189	0.394	0.024	0.417	71.1	34.4
25	46.442	-87.260	0.0427	0.1656	15.8	0.582	0.090	0.313	0.015	0.328	48.3	40.2

Table 11- Continued

Spawning Site	Latitude	Longitude	Gradient	Distance to Erosion (km)	BEHI	Percent Rock	Percent Gravel	Percent Sand	Percent Silt	Percent fines	Depth (cm)	Flow velocity (cm/sec)
26	46.443	-87.260	0.0329	0.2340	15.8	0.483	0.145	0.362	0.011	0.373	33.0	49.4
27	46.444	-87.260	0.0249	0.0000	14.3	0.691	0.099	0.203	0.007	0.210	48.3	49.4
28	46.443	-87.261	0.0263	0.1492	14.3	0.610	0.128	0.244	0.017	0.261	40.6	19.5
29	46.443	-87.262	0.0362	0.0236	17.8	0.580	0.134	0.268	0.018	0.286	38.1	117.3
30	46.444	-87.262	0.0799	0.0347	23.8	0.637	0.136	0.212	0.015	0.228	48.3	66.8
31	46.444	-87.262	0.1269	0.0476	23.8	0.545	0.198	0.248	0.010	0.257	53.3	28.7
32	46.444	-87.262	0.0580	0.0879	23.8	0.616	0.118	0.252	0.015	0.266	45.7	39.9
33	46.444	-87.263	0.0368	0.0000	13.8	0.456	0.101	0.430	0.013	0.443	34.3	72.8
34	46.445	-87.263	0.0087	0.0000	21.35	0.444	0.248	0.296	0.012	0.308	50.8	33.2
35	46.447	-87.258	0.0082	0.0000	0	0.769	0.154	0.062	0.016	0.077	38.1	78.9
36	46.448	-87.258	0.0031	0.0081	32.45	0.143	0.114	0.714	0.029	0.743	40.6	33.2
37	46.461	-87.261	0.0041	0.4939	28.85	0.053	0.143	0.798	0.007	0.804	58.4	39.6

Table 12

Salmonid Spawning Habitat Stream Technical Data and Adjacent Riverbank Data

Spawning Site	Date	Time	Water Temp (°C)	Bankfull width (m)	Bank Slope (°)	Bank Height (m)	Dominant Overstory	Dominant Understory	LWD Present	Eroded Banks	Invasive Species
1	8/17/2013	6:30 PM	15	13.4	90	0.74	maple	grass	no	yes	no
2	8/17/2013	5:49 PM	15	13.4	74	2.36	spruce	grass	yes	no	no
3	8/17/2013	4:52 PM	14.5	13.1	90	1.80	spruce/maple	grass/ferns	no	yes	no
4	8/17/2013	3:09 PM	14.5	20.1	90	3.12	spruce/maple	grass	yes	yes	no
5	8/14/2013	3:15 PM	15	18.3	35	1.93	maple	ferns	yes	yes	no
6	8/14/2013	2:47 PM	15	15.2	74	2.59	spruce/maple	grass	yes	no	no
7	8/11/2013	4:50 PM	16	21.9	90	1.68	spruce	grass	yes	no	no
8	8/11/2013	4:26 PM	16	17.4	82	2.21	spruce	grass	no	no	no
9	8/11/2013	4:10 PM	16	17.4	85	2.19	spruce	ferns	yes	no	no

Table 12- Continued

Spawning Site	Date	Time	Water Temp (°C)	Bankfull width (m)	Bank Slope (°)	Bank Height (m)	Dominant Overstory	Dominant Understory	LWD Present	Eroded Banks	Invasive Species
10	8/11/2013	3:41 PM	16	13.4	79	2.23	spruce/maple	grass	yes	no	no
11	8/11/2013	3:16 PM	15.5	17.4	64	2.21	spruce	grass	yes	no	no
12	8/11/2013	2:55 PM	15.5	18.0	52	1.45	cedar/spruce	grass	yes	no	no
13	8/9/2013	3:30 PM	16	14.6	90	1.45	spruce	grass	yes	no	no
14	8/9/2013	3:14 PM	16	12.8	25	1.32	spruce/maple	alder	yes	no	yes
15	8/9/2013	2:36 PM	16	15.5	78	1.65	spruce/maple	alder	no	no	no
16	8/9/2013	1:55 PM	16	14.0	90	1.98	spruce	grass	no	yes	no
17	8/9/2013	1:30 PM	16	15.2	79	2.19	cedar	ferns	no	no	no
18	8/9/2013	1:05 PM	16	13.7	43	2.67	spruce	alder	no	no	no
19	8/4/2013	2:08 PM	16	13.4	80	2.44	spruce	alder	yes	yes	no
20	8/4/2013	1:28 PM	16	11.9	100	1.62	spruce/ash	alder	yes	yes	no
21	8/3/2013	11:19 AM	14.5	14.6	47	2.84	white pine/spruce	ferns	yes	no	no
22	8/3/2013	12:00 PM	15	13.7	35	2.44	cedar	grass	yes	yes	yes
23	8/3/2013	12:45 PM	15.5	11.3	58	1.62	ash	alder	no	no	no
24	8/3/2013	1:31 PM	15.5	10.1	85	1.91	birch/spruce	grass	yes	no	no
25	7/5/2013	2:20 PM	18	13.4	80	1.83	cedar/alder	grass	no	yes	no
26	7/5/2013	2:25 PM	18	17.4	70	2.44	spruce/cedar	grass	yes	no	no
27	7/5/2013	2:52 PM	18	19.5	55	1.37	cedar	grass	no	yes	no
28	7/5/2013	3:13 PM	18	16.2	65	2.13	cedar/alder	grass	no	no	no
29	7/3/2013	1:00 PM	13.5	9.6	70	0.91	n/a	grass	no	no	no
30	7/3/2013	2:00 PM	14	13.7	70	1.83	cedar	grass	yes	no	no
31	7/3/2013	2:08 PM	14	14.3	70	2.44	cedar	grass	yes	no	no
32	7/3/2013	2:20 PM	14	15.5	90	1.68	cedar	grass/ferns	yes	no	no
33	7/5/2013	12:22 PM	18	18.6	70	1.83	cedar	grass	yes	yes	no
34	7/5/2013	12:45 PM	18	12.8	90	2.44	spruce	grass	yes	yes	no
35	7/2/2013	12:00 PM	13	21.3	35	3.96	maple	grass	yes	yes	no
36	7/2/2013	1:00 PM	12	18.3	80	1.52	cedar	grass	no	yes	no

Table 13

Salmonid Spawning Habitat Site Notes

Spawning Site	Notes
1	Rapids and boulders throughout. Large erosion upstream
2	House on west bank. Lots of large rocks and boulders
3	Upstream from large erosion (wp90). Lots of large boulders and rapids
4	The river gets wide and shallow here. It has erosion adjacent and is just downstream from another huge erosion spot
5	Banks eroded on upstream bend. Rapids throughout
6	First gravel upstream from huge erosion (wp83)
7	High clay banks immediately upstream. The channel is split here with an island
8	Lots of shallow water less than four inches deep
9	Nice riffle with large rocks too
11	Mainly large rocks too large for spawning
12	Deep hole on upstream side of rapids with spawning gravel. Sample taken from rapids
13	Rapids just upstream and a deep hole immediately below
14	much larger cobbles. European thistle on banks
15	lots of large rocks and boulders
16	Many large rocks and swift flowing water
17	long stretch of continuous gravel and large cobble stones
18	long, shallow stretch of spawning gravel
19	Gravel depths varies greatly
20	Small feeder creek located upstream at bend
21	Shallow spawning gravel. Measurements/sample taken from upstream section of segment
22	European thistle present. Spawning gravel begins at erosion site upstream and ends at bottleneck from LWD downstream
23	Upstream from log jam
24	Downstream from log jam. Concentrated on west side of stream
25	Developed area. House on the west side. Rock pile on same side. Larger rocks on top of sediment
26	All samples and measurements taken from the best quality spawning gravel in the middle of the long, 150 foot section. Depths vary
28	Some rocks may be too large for salmon in this stretch
29	First spawning gravel below Greengarden bridge
30	Long run of gravel of various sizes
32	Best spawning gravel is on the upstream side near the tire
33	Deep hole downstream at bend
34	Deep on both sides of gravel run. Two erosion sites upstream
35	Three erosion sites immediately upstream before next spawning site
36	Pictures taken before inventory form picture
37	Two erosion sites immediately upstream

Table 14

Erosion Site Qualitative Data

Erosion Site	Management Concern	Latitude	Longitude	BEHI Score	Area (m)	Flow Velocity (cm/sec)	Depth (cm)	Bankfull (m)	Bank Height (m)	Bank Slope (deg)
1	Exposed Sediment	46.436	-87.251	32.95	694.91	12.5	71.02	12.80	20.73	43
2	Exposed Sediment	46.435	-87.256	30.4	662.76	27.4	76.20	12.80	17.07	69
3	Exposed Sediment	46.434	-87.257	21.35	71.53	56.1	17.68	20.12	3.12	90
4	Exposed Sediment	46.434	-87.258	35.45	460.80	12.2	121.92	15.24	18.90	82
5	Exposed Sediment	46.435	-87.258	21.8	62.43	57.3	25.30	15.85	2.31	85
6	Exposed Sediment	46.436	-87.257	28.85	427.26	0.0	121.92	11.58	22.25	65
7	Exposed Sediment	46.436	-87.256	12.85	57.97	24.1	53.34	10.97	1.62	90
8	Exposed Sediment	46.439	-87.259	14.3	35.12	61.0	28.04	14.02	1.98	90
9	Exposed Sediment	46.440	-87.259	23.8	81.75	39.9	93.88	13.41	2.44	90
10	Exposed Sediment	46.440	-87.260	15.85	24.53	39.9	63.40	11.89	1.62	100
11	Exposed Sediment	46.441	-87.259	21.8	57.60	36.3	91.44	10.67	2.13	80
12	Exposed Sediment	46.441	-87.259	15.8	38.65	31.7	121.92	10.97	1.98	90
13	Developed	46.444	-87.260	14.3	108.70	49.4	48.16	19.51	1.37	55
14	Exposed Sediment	46.443	-87.261	23.35	57.23	3.7	121.92	17.98	1.07	90
15	Road Crossing	46.443	-87.262	17.8	37.16	27.7	121.92	13.72	0.91	30
16	Road Crossing	46.443	-87.262	14.3	157.93	103.6	121.92	24.08	0.91	25
17	Exposed Sediment	46.443	-87.262	23.8	46.45	34.4	121.92	13.72	2.44	80
18	Exposed Sediment	46.444	-87.263	13.8	22.30	72.8	35.66	18.59	1.83	70
19	Exposed Sediment	46.446	-87.258	23.35	29.26	27.7	121.92	13.11	1.52	90
20	Exposed Sediment	46.447	-87.258	32.95	78.04	78.9	38.10	21.34	3.96	35
21	Exposed Sediment	46.448	-87.258	32.45	13.01	33.2	40.54	18.29	1.52	80
22	Exposed Sediment	46.450	-87.258	34.95	60.94	30.5	121.92	18.90	1.68	80
23	Exposed Sediment	46.445	-87.263	21.35	59.46	33.2	121.92	12.80	2.44	90
24	Exposed Sediment	46.445	-87.261	21.8	37.16	36.3	121.92	18.59	1.22	90
25	Exposed Sediment	46.457	-87.261	28.85	37.16	43.6	121.92	9.45	1.52	90

Table 15

Erosion Site Qualitative Data

Erosion Site	Exposed Sediment	Severity	LWD present	Invasives Present	Dominant Overstory	Dominant Understory	Notes
1	yes	high	no	yes	spruce/maple	n/a	Lots of erosion from clay
2	yes	high	yes	yes	spruce	grass	Lots of exposed clay and European thistle
3	yes	medium	no	no	maple	ferns	Needs more surface protection and deeper roots
4	yes	high	yes	no	spruce	n/a	High, exposed clay banks. Needs action
5	yes	medium	yes	no	spruce/maple	grass	Eroded material is exposed clay
6	yes	high	yes	yes	n/a	grass	High clay banks that provide clay to the river. Invasives
7	yes	medium	yes	no	hickory	ferns	Immediately upstream from spawning gravel (wp80)
8	yes	medium	no	no	spruce/maple	grass	
9	yes	high	yes	no	ash	grass	Most ash trees have ash borer and are dead
10	yes	medium	yes	no	spruce/ash	alder	Adjacent to spawning gravel (wp65)
11	yes	medium	no	yes	n/a	grass	High, grassy banks. No trees
12	yes	medium	yes	no	spruce	ferns	Some exposed clay on downstream side
13	no	medium	no	no	apple	grass	Mowed lawn directly down to stream bank
14	yes	high	no	no	cedar	ferns	First erosion upstream from bridge
15	yes	medium	no	no	maple	grass	At bridge
16	yes	medium	no	yes	n/a	willow	Rocks/rapids present under bridge. Large, deep hole
17	yes	high	no	no	cedar	ferns	High, eroding banks on cutbank side. Needs LWD
18	yes	medium	yes	no	cedar	grass	Needs vegetation with longer roots on high banks
19	yes	medium	no	no	maple	raspberry	
20	yes	medium	yes	no	maple	grass	cutbank side
21	yes	high	no	no	cedar	grass	
22	yes	high	yes	no	n/a	grass	
23	yes	high	yes	no	spruce	grass	Very steep exposed sediment, could use LWD
24	yes	high	yes	no	spruce	ferns	
25	yes	high	yes	no	maple	alder/ferns	High, clay banks on cutbank side and point bar opposite

Table 16

Rosgen's BEHI Data

BEHI No.	Date	Root Depth	Root Depth Score	Root Density	Root Density Score	Surface Protection	Surface Protection Score	Bank Angle (deg)	Bank Angle Score	**Total Score**
1	8/17/2013	<5	10	<5	10	<10	10	21-60	2.95	**32.95**
2	8/17/2013	<5	10	5-14	8.5	15-29	6.95	61-80	4.95	**30.40**
3	8/17/2013	30-49	4.95	55-79	2.95	10-14	8.50	61-80	4.95	**21.35**
4	8/14/2013	<5	10	<5	10	10-14	8.5	81-90	6.95	**35.45**
5	8/14/2013	30-49	4.95	15-29	6.95	55-79	2.95	81-90	6.95	**21.80**
6	8/11/2013	<5	10	15-29	6.95	15-29	6.95	61-80	4.95	**28.85**
7	8/11/2013	90-100	1.45	80-100	1.45	80-100	1.45	91-119	8.5	**12.85**
8	8/9/2013	90-100	1.45	55-79	2.95	55-79	2.95	81-90	6.95	**14.30**
9	8/4/2013	30-49	4.95	15-29	6.95	30-54	4.95	81-90	6.95	**23.80**
10	8/4/2013	90-100	1.45	55-79	2.95	55-79	2.95	91-119	8.5	**15.85**
11	8/3/2013	15-29	6.95	30-54	4.95	55-79	2.95	81-90	6.95	**21.80**
12	8/3/2013	50-89	2.95	55-79	2.95	55-79	2.95	81-90	6.95	**15.80**
13	7/5/2013	15-29	6.95	55-79	2.95	80-100	1.45	21-60	2.95	**14.30**
14	7/5/2013	50-89	2.95	15-29	6.95	30-54	4.95	91-119	8.5	**23.35**
15	7/2/2013	50-89	2.95	15-29	6.95	30-54	4.95	21-60	2.95	**17.80**
16	7/3/2013	90-100	1.45	30-54	4.95	30-54	4.95	21-60	2.95	**14.30**
17	7/3/2013	15-29	6.95	30-54	4.95	30-54	4.95	81-90	6.95	**23.80**
18	7/5/2013	50-89	2.95	55-79	2.95	55-79	2.95	61-80	4.95	**13.80**
19	7/5/2013	30-49	4.95	30-54	4.95	30-54	4.95	91-119	8.5	**23.35**
20	7/2/2013	<5	10	<5	10	<10	10	21-60	2.95	**32.95**
21	7/2/2013	5-14	8.5	5-14	8.5	10-14	8.5	81-90	6.95	**32.45**
22	7/2/2013	<5	10	<5	10	<10	10	61-80	4.95	**34.95**
23	7/5/2013	50-89	2.95	30-54	4.95	30-54	4.95	91-119	8.5	**21.35**
24	7/5/2013	50-89	2.95	15-29	6.95	30-54	4.95	81-90	6.95	**21.80**
25	7/2/2013	30-49	4.95	<5	10	15-29	6.95	81-90	6.95	**28.85**

APPENDIX D

BANK EROSION HAZARD INDEX (BEHI) METHODOLOGY

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BANK EROSION HAZARD INDEX (BEHI) METHODOLOGY

Acquired from the Michigan Department of Natural Resources
(www.michigan.gov/.../deq/wb-nps-**BEHI**-SOP_246873_7.doc)

STANDARD OPERATING PROCEDURE

ASSESSING BANK EROSION POTENTIAL USING ROSGEN'S BANK EROSION HAZARD INDEX (BEHI)

1.0 Overview

While stream bank erosion is a natural process that occurs in every watershed, excessive erosion has serious adverse consequences for the physical and biological function of rivers. Eroding stream banks can be a major source of sediment to a stream (up to 80% of the annual load; Simon and Thorne, 1996), and human activities such as urbanization or dam construction can accelerate bank erosion rates by more than an order of magnitude. It is often difficult, however, to distinguish between stream banks that are eroding at a natural rate from those that are or have the potential to erode at unnaturally high rates due to altered watershed hydrology or sediment loads. The Bank Erosion Hazard Index (BEHI), created by Dave Rosgen of Wildland Hydrology, Inc. (Rosgen, 2001), is one of several procedures for assessing stream bank erosion condition and potential. It assigns point values to several aspects of bank condition and provides an overall score that can be used to inventory stream bank condition over large areas, prioritize eroding banks for remedial actions, etc. This standard operating procedure (SOP) describes two versions of the BEHI technique.

2.0 Procedure

Below are descriptions of two BEHI procedures. The first describes the complete BEHI procedure created by Rosgen, including identification of bankfull width. The second describes a modified BEHI procedure, which does not require identification of bankfull width. The modified BEHI procedure is intended for use by workers who lack experience in identifying bankfull indicators, including volunteer monitors. Correctly identifying appropriate bankfull indicators requires considerable experience, and is the most subjective step in the original BEHI procedure.

In truth, both procedures described below are 'modified', in that the step of calculating BEHI scores has been simplified such that there is only a single score for each metric, rather than the range of possible scores provided in Rosgen's original paper. This simplification is intended to remove some unnecessary subjectivity from the field observations, without overly reducing the utility of the procedure.

A. Complete BEHI Procedure

The complete BEHI procedure consists of five metrics; four observational and one requiring some measurements. They are:

1. Ratio of bank height to bankfull height
2. Ratio of root depth to bank height
3. Root density, in percent
4. Bank angle, in degrees
5. Surface protection, in percent

Brief descriptions of each metric are provided below.

Point values for these metrics (Table 1) should only be assigned after a sufficient length of the stream channel (the 'stream reach') has been examined (at least 100'; 2 to 3 meander lengths is preferable), so that representative conditions are identified. Conditions on both banks should be assessed, and scored separately if they are consistently different. See Section 4 for further advice on where to make – and not make – the observations.

Ratio of bank height to bankfull height. This is the most challenging of the BEHI metrics, as it requires accurate identification of bankfull indicators. A full discussion of different bankfull indicators is beyond the scope of this SOP, but it is thoroughly discussed in Williams (1978), and a useful free video is available from the U.S. Forest Service (2003). Common bankfull indicators in stable southern Michigan streams include top of bank, top of point bars, and other changes in channel slope. Vegetative indicators are seldom useful in southern Michigan streams. Bankfull indicators in unstable streams (i.e., incising or aggrading streams) can be more difficult to identify, but are usually less than top of bank.

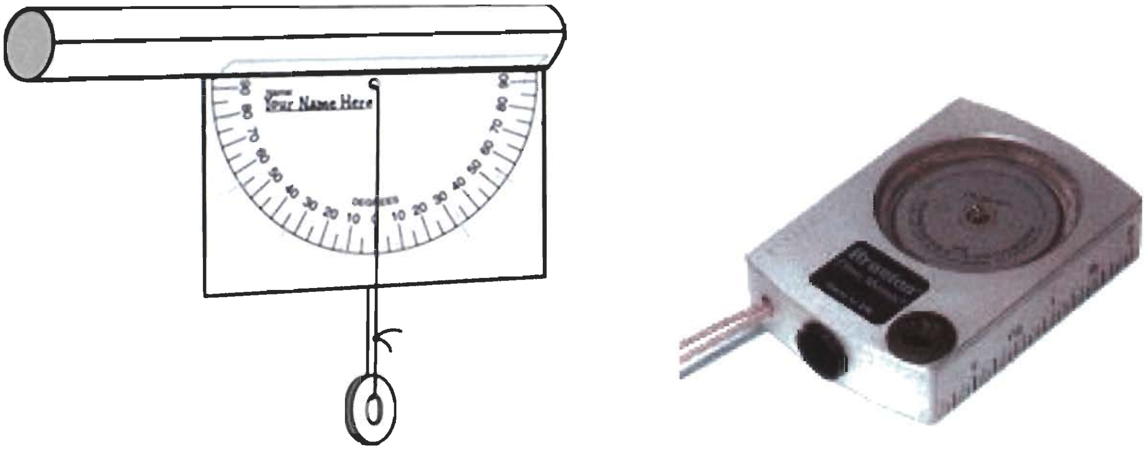
Ratio of root depth to bank height. Root depth is the ratio of the average plant root depth to the bank height, expressed as a percent (e.g., roots extending 2' into a 4' tall bank = 0.50.)

Root density. Root density, expressed as a percent, is the proportion of the stream bank surface covered (and protected) by plant roots (e.g., a bank whose slope is half covered with roots = 50%).

Surface protection. Surface protection is the percentage of the stream bank covered (and therefore protected) by plant roots, downed logs and branches, rocks, etc. In many streams in southern Michigan, surface protection and root density are synonymous.

Bank angle. Bank angle is the angle of the "lower bank" – the bank from the waterline at base flow to the top of the bank, as opposed to benches that are higher on the floodplain. Bank angles great than 90° occur on undercut banks. Bank angle can be measured with an inclinometer (Figure 1), though given the broad bank angle categories (Table 1), visual estimates are generally sufficient. Bank angle is perhaps the metric most often estimated incorrectly.

Figure 1. Simple and More Expensive (~ $100) Inclinometers



B. Modified BEHI Procedure

If the field staff lack experience with identifying bank full indicators, it is recommended that the bank height/bankfull height ratio metric be dropped from the BEHI calculation, leaving four metrics:

1. Ratio of root depth to bank height
2. Root density, in percent
3. Surface protection, in percent
4. Bank angle, in degrees

Observations for these metrics are made as described in Section 2A, and the overall BEHI score is calculated using Table 2.

3.0 Data Calculation and Interpretation

A draft field sheet for recording observations for the modified BEHI procedure is in Appendix 1. Overall scores for the Complete BEHI are calculated by summing the scores for each individual metric using the values in Table 1, and scores for the Modified BEHI are similarly calculated using the values in Table 2. The overall BEHI score corresponds to an erosion hazard category. It should be noted that the overall BEHI scores and categories were created by Rosgen's work in the Rocky Mountain states, and in the future these may be modified for conditions in Michigan. Illustrated examples from southern Michigan streams are in Appendix 2.

BEHI scores have several potential uses, including ranking multiple stations for further study or remedial actions (Figure 2).

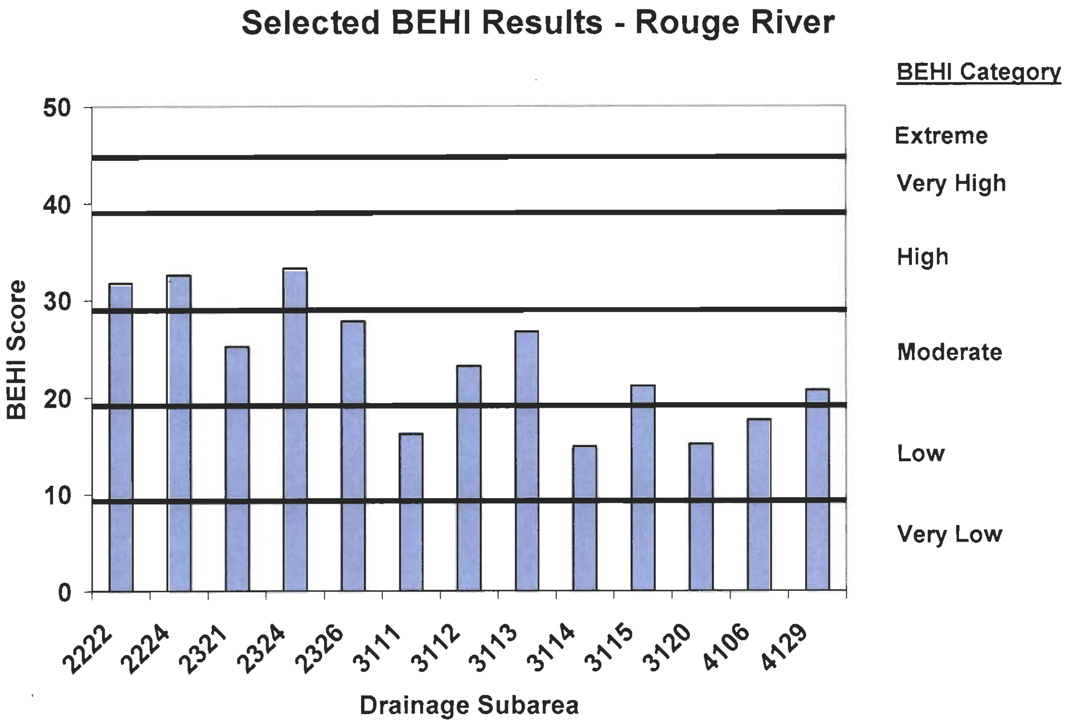
Table 1. Scores for the Complete BEHI.

BEHI Category	Bank Height/ Bankfull Height	BH/BFH Score	Root Depth (% of BFH)	Root Depth Score	Root Density (%)	Root Density Score	Surface Protection (Avg. %)	Surface Protection Score	Bank Angle (degrees)	Bank Angle Score	Total Score, by Category
Very low	1.0-1.1	1.45	90-100	1.45	80-100	1.45	80-100	1.45	0-20	1.45	≤ 7.25
Low	1.11-1.19	2.95	50-89	2.95	55-79	2.95	55-79	2.95	21-60	2.95	7.26 – 14.75
Moderate	1.2-1.5	4.95	30-49	4.95	30-54	4.95	30-54	4.95	61-80	4.95	14.76 – 24.75
High	1.6-2.0	6.95	15-29	6.95	15-29	6.95	15-29	6.95	81-90	6.95	24.76 – 34.75
Very high	2.1-2.8	8.5	5-14	8.5	5-14	8.5	10-14	8.5	91-119	8.5	34.76 – 42.50
Extreme	>2.8	10	< 5	10	< 5	10	< 10	10	> 119	10	42.51 - 50

Table 2. Scores for the Modified BEHI.

BEHI Category	Root Depth Values	Root Depth Scores	Root Density (%)	Root Density Scores	Surface Protection (Avg. %)	Surface Protection Scores	Bank Angle (degrees)	Bank Angle Scores	Total Score, by Category
Very low	90-100	1.45	80-100	1.45	80-100	1.45	0-20	1.45	≤ 5.8
Low	50-89	2.95	55-79	2.95	55-79	2.95	21-60	2.95	5.8 – 11.8
Moderate	30-49	4.95	30-54	4.95	30-54	4.95	61-80	4.95	11.9 – 19.8
High	15-29	6.95	15-29	6.95	15-29	6.95	81-90	6.95	19.9 – 27.8
Very high	5-14	8.5	5-14	8.5	10-14	8.5	91-119	8.5	27.9 – 34.0
Extreme	< 5	10	< 5	10	< 10	10	> 119	10	34.1 - 40

Figure 2. BEHI Score Example



4.0 Quality Control Issues

(1) Accuracy: Accuracy as traditionally defined is difficult to assess for this largely subjective, observational procedure. When performed by volunteers, however, the accuracy of their observations can be maximized by training from others more experienced in river morphology studies, and verified by spot-checks of their work by the trainers.

(2) Precision: Precision as traditionally defined is also difficult to assess for this largely subjective, observational procedure. Spot-checks within a few weeks of volunteer observations can be used to assess precision as well as accuracy.

(3) Reference reaches: In addition to the erosion hazard categories generated by this procedure, it can also be useful to make these observations at reference reaches – stream reaches in portions of the same watershed, or an adjacent watershed, that are believed to be (relatively) undisturbed by urban development, stream channelization, etc. A good document describing how to choose and document conditions at a reference site is the U.S. Forest Service report by Harrelson, et al. (1994). Alternatively, contact the author of this SOP for advice on selecting a representative reference reach. In general, reference reaches are best established in the same watershed as the stream reach of interest, in a stream of the same size (e.g., same stream order, or baseflow wetted width) and with similar soil type and channel slope.

(4) Stream reach selection (Representativeness): Selection of specific stream reaches for BEHI observations will depend on the objectives of the study, but a few general rules apply:

- Stream bank conditions are naturally variable even in stable streams, and to characterize a stream reach it is recommended that at least 200’ of the stream reach be viewed before the BEHI observations are made.
- Stream banks adjacent to riffle areas tend to be the most stable section of a stream channel, while banks in meander bends tend to have the highest erosion rates – even in geomorphically stable streams.
- Stream banks in ‘high traffic’ areas (parks, livestock crossings, etc.) are not representative of average conditions and should be avoided – unless they are the specific focus of the study.

While volunteers can collect large amounts of useful BEHI data with adequate training and supervision, experience has shown that they are prone to overemphasizing small, atypical bank erosion “hot spots,” even when asked to score more representative banks.

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Modified Bank Erosion Hazard Index (BEHI) Field Form

Date:____________________ **Personnel:**____

Location:____

(Circle one in each column)

Root Depth (% of BH)	Root Density (%)	Surface Protection (Avg. %)	Bank Angle (degrees)
90-100	80-100	80-100	0-20
50-89	55-79	55-79	21-60
30-49	30-54	30-54	61-80
15-29	15-29	15-29	81-90
5-14	5-14	10-14	91-119
< 5	< 5	< 10	> 119

Comments:____

Date:____________________ **Personnel:**____

Location:____

(Circle one in each column)

Root Depth (% of BH)	Root Density (%)	Surface Protection (Avg. %)	Bank Angle (degrees)
90-100	80-100	80-100	0-20
50-89	55-79	55-79	21-60
30-49	30-54	30-54	61-80
15-29	15-29	15-29	81-90
5-14	5-14	10-14	91-119
< 5	< 5	< 10	> 119

Comments:____

Date:____________________ **Personnel:**____

Location:____

(Circle one in each column)

Root Depth (% of BH)	Root Density (%)	Surface Protection (Avg. %)	Bank Angle (degrees)
90-100	80-100	80-100	0-20
50-89	55-79	55-79	21-60
30-49	30-54	30-54	61-80
15-29	15-29	15-29	81-90
5-14	5-14	10-14	91-119
< 5	< 5	< 10	> 119

Comments:____

Appendix 2. Examples of Different Bank Conditions in Southern Michigan Streams

Figure A. Tributary, Kalamazoo River watershed

Bank Height/Bankfull Height ≈ 1.0-1.1

Root Depth/Bank Height ≈ 0.9-1.0

Root Density ≈ 80-100%

Bank Angle ≈ 0-20° ?

Surface Protection ≈ 80-100%

BEHI Score = 7.25 (Very low)

Figure B. Kalamazoo River

Bank Height/Bankfull Height ≈ 1.0-1.1

Root Depth/Bank Height ≈ 0.9-1.0

Root Density ≈ 30-54%, not counting sod slump

Bank Angle ≈ 81-90°

Surface Protection ≈ 30-54%

BEHI Score = 19.75 (Moderate)

Note sod slumping into channel – a sure indication of an unstable bank, presumably because streamside vegetation = mowed grass, not woody vegetation. Otherwise the channel is in pretty good shape.

Figure C. Rouge River

Bank Height/Bankfull Height ≈ 1.0-1.1 (assuming top of bank = bankfull)

Root Depth/Bank Height ≈ 0.9-1.0

Root Density ≈ 5-14%

Bank Angle ≈ 81-90°

Surface Protection ≈ 10-14%

BEHI Score = 26.85 (High)

Interesting site – roots extend to waterline, but are so few that they provide minimal bank protection. Also, this site is downstream from a dam, where erosion is usually atypically high due to "hungry water" created by the impoundment.

Figure D. Hagar Creek , Ottawa County

Bank Height/Bankfull Height ≈ > 2.8

Root Depth/Bank Height ≈ 0.3-0.49 at best

Root Density ≈ 5-14%

Bank Angle ≈ 81-90°

Surface Protection ≈ 10-14%

BEHI Score = 38.9 (Very high)

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