Application of Natural Channel Design Techniques in Sub-Arctic Alaska

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AUTHOR’S NOTE

The findings and conclusions in this report are those of the author and do not necessarily represent the views of the Bureau of Land Management

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1.0 INTRODUCTION AND PURPOSE

1.1 INTRODUCTION

The Bureau of Land Management (BLM) is responsible for permitting and inspecting placer-mine operations throughout Alaska. Mining operations with legal claims are allowed to mine on federal land but must follow a variety of requirements, including mining and reclamation plans. Specifically, the 43 CFR 3809 (1981 and 2001) regulations require miners to rehabilitate the stream corridor during the reclamation phase to support fisheries habitat. Environmental impact statements developed in the late 1980's defined fisheries habitat rehabilitation as reclamation that returns the stream corridor to a condition that provides for the recovery of fish habitat and channel stability (BLM, 1998a,b,c,). Recent policies developed by the BLM define rehabilitation of fisheries habitat as a stable channel form with adequate vegetation to reduce erosion, dissipate energy, and promote the recovery of instream habitats. In 2014, BLM Alaska issued specific policy for reclamation effectiveness monitoring based on quantitative measures and current science (BLM Handbook H-3809-1, 2012). This policy established the link between hydraulic and geomorphic functions and the rehabilitation of fisheries habitat. All of these documents and policies focus the reclamation phase on channel stability and habitat rehabilitation / recovery.

By almost every account the reclamation process has fallen short of the requirements and intentions stated above (Tidwell et al., 2000; Arnett, 2005; Carlson et al., 1998, Milner and Piorkowski, 2004; BLM, 1998a,b,c, and Brady et al., 2018). Reclaimed channels have not met performance standards of achieving channel stability and aquatic habitat recovery. A typical reclamation approach has been to grade a pilot channel and re-contour valley bottoms as shown in Figure 1 without the use of hydrology, hydraulics, or geomorphology design criteria. The lack of attention to a design process, combined with the harsh Alaskan climate has led to extensive channel and sometimes valley erosion. Common reclamation results are shown in Figures 1 and 2.

FIGURE 1: **Placer mine near Central, Alaska. Photo taken during the reclamation phase.**

FIGURE 2: **Common result of reclamation showing bank erosion and lack of pool habitat. This photo represents 20 years of natural recovery.**

A study completed by the BLM in 2018 quantified the observations described above. Brady et al. (2018) assessed 40 natural streams (used to determine reference condition) and 10 reclaimed placer-mined streams in the sub-arctic region of the Alaskan interior. The placer-mined sites ranged from 1 to 50 years post reclamation. The assessment method included over 50 instream and riparian indicators of channel stability and habitat; however, three indicators were considered in greater detail: channel incision, bank cover and stability, and riparian vegetation complexity. Results showed that 6 out of 10 sites had channel incision values that were rated as "functioning-at-risk" based on a moderate departure from reference condition. Eight of the reclaimed sites had bank cover and stability values and riparian vegetation complexity that were "not functioning" based on a major departure from reference condition. The results were attributed to the fact that rehabilitation efforts primarily rely on natural recovery processes rather than a quantitative assessment and design process that is followed by construction practices that install properly sized channels, pool habitats, and robust vegetation.

Miner-led reclamation is not the only approach to instream and riparian rehabilitation that has not performed well. Densmore and Karle (2009) evaluated a reclamation project in Denali National Park that had been placer mined for over 80 years. The mining caused channel incision, bank erosion, and the removal of riparian vegetation. The rehabilitation approach included a hydraulic design assessment with a new channel dimension sized to carry flows slightly larger than the bankfull discharge, with the floodplain carrying the 100-year discharge. Shear stress analysis was used to guide the design of a stable channel. A variety of bioengineering methods were used to provide bank and floodplain re-vegetation, including brush bars, willow cuttings, and brush layering. Monitoring results showed that significant channel and floodplain erosion occurred during moderate to large flood events; however, there were a variety of lessons learned from the post-flood monitoring. First, the authors noted that the channel had been improperly sized due to poor data and improper assumptions about channel forming discharge theory. Second, the grain-size distribution of the bed sediments were finer for the rehabilitation project than the prior condition due to mining operations. The authors estimate that the average size of the bed material decreased by 50% and that the armor layer was removed by mining. The design process did not include reintroducing an armor layer that was resistant to bed erosion. Finally, the lack of streambank and floodplain vegetation contributed significantly to streambank and floodplain erosion. The brush bars and layers did perform well where installed. The authors conclude that "future projects in similarly disturbed watersheds will require a better understanding of the available sediment and its source, channel forming discharge, sediment transport characteristics, and natural re-vegetation." The authors did not call out icing as a specific cause of reclamation damage; however, BLM reports have often observed icing build up on reclaimed mine sites resulting in channel avulsions, bank erosion, and floodplain erosion (personal communication with BLM hydrologists and fish biologists).

A recent demonstration and applied research project implemented by BLM experienced similar problems. The project, known as Demo 1, was constructed in 2015 in the Jack Wade Creek Watershed near Chicken, Alaska. The project used hydrology, hydraulic, and geomorphology principles and a design approach called Natural Channel Design (see Section 2.5 for a description of Natural Channel Design). During the design process, the decision was made to construct a meandering channel in order to create pool habitat for grayling. Constructed riffles and log sills were used to provide grade control. And for the first time, transplants with toe wood were used to provide lateral stability. The project was stable through numerous bankfull events but had major adjustments during the first floodplain event. Several meander bends migrated down valley, the riffles widened, and many of the transplants were destroyed. Interestingly, the pools remained in the meander bends, and in some cases pool depth, volume, and length improved. The lessons learned from this project are still being processed and an adaptive management plan is being developed. The most likely solution will be to replace the meandering design with a step-pool approach.

Fortunately, successful rehabilitation projects have been completed in Alaska. The U.S. Forest Service has completed several placer-mine reclamation projects on the Kenai Peninsula (Bair et al., 2008). The BLM has completed three additional demonstration projects in the Alaskan Interior (40 Mile Watershed) using step-pool approaches. Early monitoring results show that these projects are remaining stable and have improved aquatic habitat. However, minor adaptive management has been necessary. The lessons learned from what has and hasn't worked will be shared in chapters 6 and 7 to include recommendations on how to create more resilient designs. More emphasis will be placed on successful Interior projects because the Kenai Peninsula is quite different from the Interior. The Interior sites often have more icings, less amounts of large wood, and less precipitation (Shulski and Wendler, 2007).

1.2 STUDY PURPOSE

The purpose of this project is to provide criteria and guidance that will help the BLM and miners develop resilient reclamation designs that meet the regulatory requirements and policy guidelines stated above. This document is not a design manual; however, it will provide background science, data, and recommendations that can be used to develop a design manual. The problems cited above from past methods combined with working in a harsh climate with slow vegetation growth and frequent icings will be explored by assessing reference condition streams that are stable and functioning. In addition, a function-based assessment will be completed of a reclaimed mine site that is in the same watershed as some of the reference streams. These sites are in the Nome Creek Watershed, which is north of Fairbanks, Alaska.

To achieve this overall purpose, the study includes several key components. Each is introduced below and then described in greater detail in the background section of the report.

- **Permafrost hydrology and Icing processes** – The problem statement mentions an overarching concern by many BLM hydrologists and biologists, as well as miners and other practitioners that icings (aufeis) cause channel and floodplain instability post mining. This section of the report includes a literature review of permafrost hydrology and icing processes to provide insights on how water moves, freezes, and potentially causes problems that need to be mitigated in the design. These insights are used to help inform new ideas about reclamation approaches that are discussed in the application section of the report.
- **Stream Functions Pyramid Framework** –The Stream Functions Pyramid Framework is a function-based approach to stream assessments, which will be used to evaluate the Nome Creek Stream Reclamation Project. Background information is provided in this section and then applied to the Nome Creek project.
- **Overview of Natural Channel Design** – Natural channel design (NCD) is a stream restoration/reclamation/rehabilitation approach used throughout the United States (ELI, 2016). However, it has not been used extensively in Alaska. This section of the report provides a brief overview of NCD to provide background information for the last section of the report on Applying NCD in Sub-Arctic Alaska. Emphasis will be placed on developing Alaska-specific tools and design criteria that can improve stream reclamation outcomes and attainment of regulatory requirements.

2.0 BACKGROUND

The background section provides information on permafrost characteristics, permafrost hydrology, icing processes, the Stream Functions Pyramid Framework, and Natural Channel Design (NCD). Within the NCD overview, additional background information is provided about Bankfull Regional Curves and Developing Design Criteria from reference reach surveys. This information is used to support the methods, results and recommendations presented later in the report.

2.1 PERMAFROST

Permafrost is defined as a layer of soil and rock beneath the ground surface where the temperature has been below 32° F for at least two years. It is the zone where most of the soil water is frozen. Above the permafrost layer is the active zone or active layer, where biological activity in the soil takes place. The active layer is typically less than three feet in depth but can vary widely. It is a zone that seasonally freezes and thaws (Shulski and Wendler, 2007). Continuous permafrost covers the northern third of Alaska while the coastal areas are generally permafrost free. Between these two regions is an area of discontinuous permafrost, where permafrost is often found on north-facing slopes and areas with poor drainage. Permafrost is colder and deeper with increasing latitude (Shulski and Wendler, 2007). The work completed in this study was in the region of discontinuous permafrost (Woo, 2012).

Many regional and local conditions influence the development of permafrost and the thickness of the active layer. Regionally, latitude, elevation, and continentality are major drivers of permafrost development. Locally, the insulating properties of snow can prevent the development of permafrost (Nicholson and Granberg, 1973). Water bodies, such as lakes and rivers, inhibit or warm permafrost and often maintain a talik near the bed (Jorgenson et al., 2010). Talik is a perennially unfrozen zone below, within, or above the permafrost (Woo, 2012). Continuous flowing groundwater carries heat and can maintain taliks in permafrost. In discontinuous permafrost, large valleys can have taliks due to deep snow and groundwater movement (Nicholson and Thom, 1973).

Vegetation communities and patterns also influences the local development of permafrost by influencing albedo and thereby heat transfer to the ground. In forested areas with an understory of shrubs and groundcover of lichen and moss mats, the trees and shrubs provide shade and moderate heating in the summer while influencing the distribution of snow in the winter. The moss and lichen layer is particularly important to regulating ground temperatures. This ground cover buffers the ground from summer heating and maintains a thinner active layer than would typically be found beneath bare ground (Woo, 2012).

2.2 Permafrost Hydrology

Woo (2012) defines permafrost hydrology as the study of direct and indirect effects of perennial frozen ground on the properties, occurrence, distribution, movement, and storage of water. He provides a conceptualized drawing of the circulation and storage of water in permafrost terrain, which is redrawn below in Figure 3. A complete description of the illustrated processes is not provided in this document but is covered by Woo (2012). Of particular importance for this paper is the movement of water within the active layer, river, and taliks, especially during the winter and spring seasons. However, the effect of the permafrost layer on this movement is also important.

Groundwater discharge in winter freezes above ground and typically within the active layer. Once thawed, it flows within the active layer or emerges as springs or feeds downgradient streams, rivers, and lakes. The permafrost layer below the active layer acts as an aquiclude or aquitard, limiting the amount of water storage in the active zone and potentially increasing surface storage (e.g., wetlands) or runoff. Taliks can deliver water from beneath the active layer to the surface as a spring or discharge into a lake or stream. However, groundwater circulation can occur above (suprapermafrost), within (intrapermafrost), and beneath (subpermafrost) the permafrost (Tolstikhin and Tolstikhin, 1976; Williams and Waller, 1966). Figure 4 provides a conceptualized drawing of the occurrences of groundwater in permafrost.

FIGURE 3: **Conceptualized circulation and storage of water in permafrost regions, recreated from Woo (2012).**

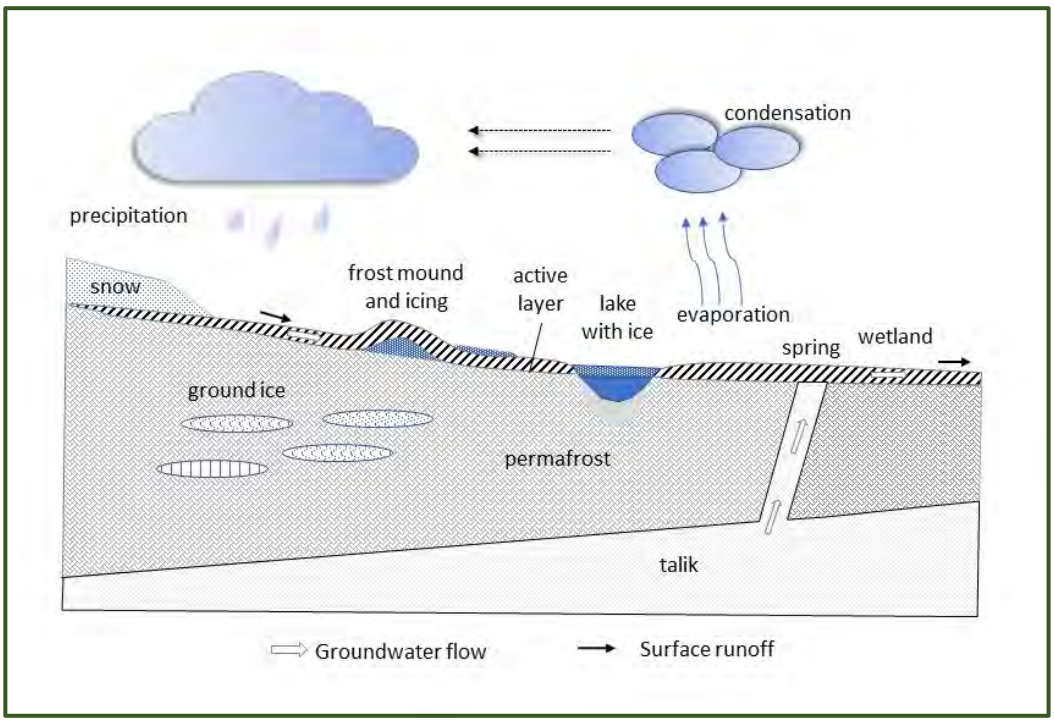
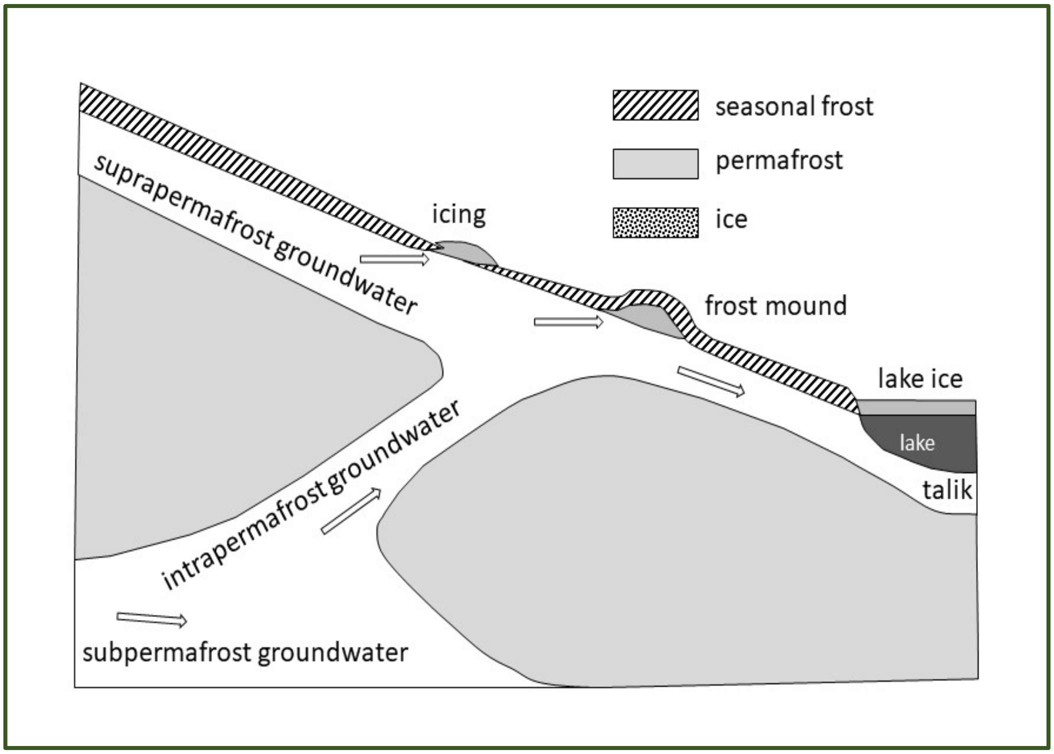


FIGURE 4: **Occurrence of groundwater in permafrost with seasonal frost in active layer, icing, and frost mounds (Woo, 2012).**



2.3 Icings

Woo (2012) defines icings as the freezing of water that seeps from the ground, flows from a spring or emerges from beneath a river bed or through fractures in river ice. Icings are not restricted to permafrost areas. In Alaska, icings are commonly referred to as the German word *aufeis*, which means "on ice" or "top ice." Daly et al. (2011) defines *aufeis* as ice that is formed from the freezing of successive flows of water over previously formed ice. Carey (1973) characterizes *aufeis* in three categories based on their mode of occurrence: ground, spring, and river. He describes ground icing as seepage that saturates the ground surface in summer, which then freezes in winter. The seepage may come from soil pores, rock cracks, root channels, or animal burrows. However, the supply of water is normally limited and ends partway through winter. Ground icing formations tend to be relatively small and flat to slightly arched; however, they can form icefalls on steep slopes.

Carey (1973) describes spring icing as the discharge of deeper groundwater from well-defined points on the ground that flows to stream channels. Spring icings typically create larger formations than ground icings. Source water can come from fault zones, water-bearing rock strata, and taliks.

2.0 Background

In a river channel, the supply of water and the loss of heat drive the development of river icing formation (Woo, 2012). Hu and Pollard (1997) described a three-stage process governing the development of river icing. The first stage is ice coverage in the stream channel. In the second stage, ice growth occurs from the continual build-up of ice, the accumulation of snow, and freezing of the net seepage within the reach. The third stage is the freezing of water that drains as recession flow after seepage into the reach stops. Extensive icing can be found in discontinuous permafrost where there is a continuous supply of water to the river. Carey (1973) noted that river icings are often supported by high levels of discharge and are therefore thicker and larger than ground or spring icings. An example of river icing is shown in Figure 5.

FIGURE 5: **Example of River Icing. Photo by Ben Kennedy, BLM.**

In summary, *aufeis* is a combination of natural process that typically occur as ground, spring, or river icings. These natural processes can be altered by human activities that remove vegetation and change the topography, thus altering water flow and thermal regulation. Carey (1973) explained that ground icing is rare in undisturbed landscapes but can become the dominant form of icing in disturbed landscapes. Groundwater seeping from cut slopes, such as highways or even trails, can spread across the ground surface and freeze. Often, these disturbances create a discharge point for groundwater flowing between the frozen upper portion of the active layer and the permafrost below. Hydrostatic pressure forces the water up onto the land surface. As the hydrostatic pressure and volume of flow increases, the height of the *aufeis* increases. River and spring *aufeis* can be exacerbated by large land clearing and grading operations, such as placer mining. Figures 6 and 7 below shows examples of river and spring aufeis at active placer mines.

FIGURE 6: **Example of aufeis in an active placer mine. Photo courtesy of the Bureau of Land Management.**

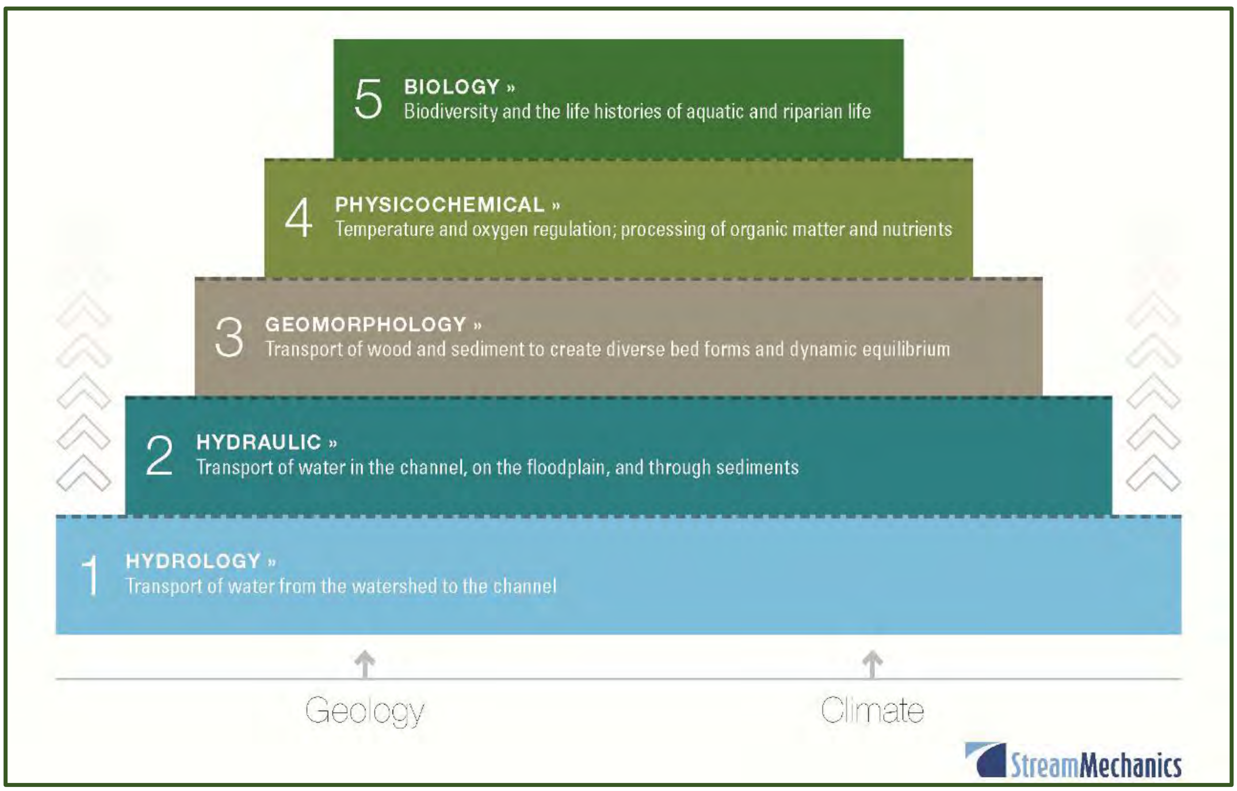
FIGURE 7: **Example of aufeis in an active placer mine. Photo courtesy of the Bureau of Land Management.**

2.4 STREAM FUNCTIONS PYRAMID FRAMEWORK

The Stream Functions Pyramid Framework (SFPF) provides a function-based approach to developing stream assessment programs. The BLM has used the SFPF to develop a methodology for assessing and inspecting placer mines. Many other agencies across the United States have used the SFPF to develop stream assessment tools for evaluating the functional lift and loss associated with compensatory stream mitigation programs (ELI, 2016; WSTT, 2018; TDEC, 2018; USACE Savannah District, 2018). For this project, the SFPF is used to evaluate the Nome Creek Stream Reclamation Project and determine the functional lift or loss by function-based parameter and overall functional category.

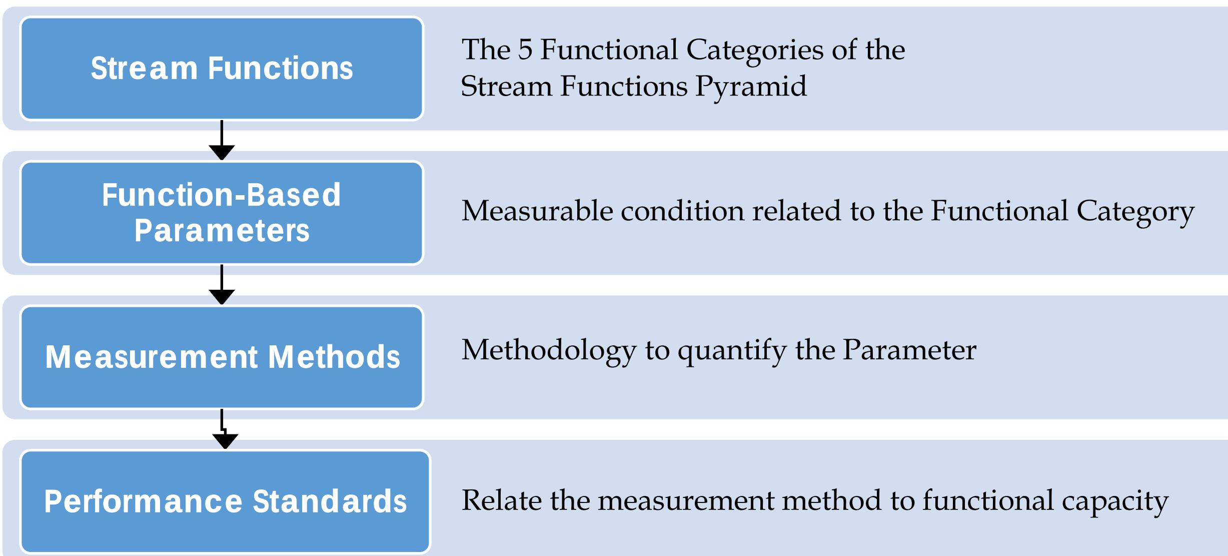
The SFPF is described in detail in *A Function-Based Framework for Stream Assessment and Restoration Projects* (Harman et al, 2012), published by the U.S. Environmental Protection Agency and the U.S. Fish and Wildlife Service. In general, the Stream Functions Pyramid (Figure 8), includes five functional categories: Level 1: Hydrology, Level 2: Hydraulics, Level 3: Geomorphology, Level 4: Physicochemical, and Level 5: Biology. The Pyramid organization recognizes that lower-level functions generally support higher-level functions (although the opposite can also be true) and that all functions are influenced by local geology and climate. Each functional category is defined by a functional statement.

FIGURE 8: Stream Functions Pyramid. Image courtesy of Harman et al. 2012.



The SFPF illustrates a hierarchy of stream functions but does not provide specific mechanisms for addressing functional capacity, establishing reference/performance standards, or communicating functional change. The diagram in Figure 9 expands the hierarchical or pyramid concept into a more detailed framework to quantify functional capacity, establish performance standards, evaluate functional change, and establish function-based goals and objectives.

FIGURE 9: Stream Functions Pyramid Framework



This comprehensive framework includes more detailed forms of analysis to quantify stream functions and functional indicators of underlying stream processes. In this framework, function-based parameters describe and support the functional statements of each functional category, and the measurement methods are specific tools, equations, and/or assessment methods that are used to quantify the function-based parameter. Performance standards are measurable or observable end points of stream restoration. The SFPF organizes the performance standards into three categories of Functioning, Functioning-At-Risk, and Not Functioning, each of which are described in Table 1.

TABLE 1: Performance Standards in Relation to Reference Condition

FUNCTIONAL CAPACITY	DEFINITION
Functioning [F]	A functioning score means that the measurement method is quantifying or describing the functional capacity of one aspect of a function-based parameter in a way that does support a healthy aquatic ecosystem. In other words, it is functioning at reference condition. The reference condition concept used here aligns with the definition laid out by Stoddard, et al. (2006) for a reference condition for biological integrity. It is important to note that a reference condition does not simply represent the best attainable condition; rather, a functioning condition score represents an unaltered or minimally impacted system.
Functioning-At-Risk [FAR]	A functioning-at-risk score means that the measurement method is quantifying or describing one aspect of a function-based parameter in a way that can support a healthy aquatic ecosystem. In many cases, this indicates the function-based parameter is adjusting in response to changes in the reach or the catchment. The trend may be towards lower or higher function. A functioning-at-risk score indicates that the aspect of the function-based parameter, described by the measurement method, is between functioning and not functioning.
Not Functioning [NF]	A not functioning score means that the measurement method is quantifying or describing one aspect of a function-based parameter in a way that does not support a healthy aquatic ecosystem. In other words, it is not functioning like a reference condition.

2.5 Natural Channel Design

Natural Channel Design, also called Rosgen Geomorphic Channel Design, is a common approach to assessing and restoring stream channels across the United States and is the most common method used in compensatory stream mitigation (ELI, 2016). The method is described in detail in the National Engineering Handbook, Park 654, Chapter 11: Rosgen Geomorphic Channel Design (NRCS, 2007). The overall goal of natural channel design is to restore the dimension, pattern, and profile of a disturbed stream system by emulating the natural, stable river. It does not necessarily mean returning a stream to a pristine condition. Because the goal of natural channel design focuses on channel form (dimension, pattern, and profile), it has been referred to in the literature as a “form based” approach to stream restoration and compared against a so-called “process based” approach. The goal of the process-based approach is to reestablish normative rates and magnitudes of physical, chemical, and biological processes that create and maintain stream systems (Beechie et al., 2010). There has been much debate in the literature and at professional conferences over which approach is better (Simon et al., 2011). However, many practitioners acknowledge that a comprehensive stream restoration design includes both form- and processed-based approaches. Furthermore, natural channel design does include both form and process-based approaches because hydrology, hydraulic, and sediment transport processes are quantified as part of the design approach. Some academicians (Simon et al., 2007) focus on the Rosgen stream classification as the principal component of the design process. However, Natural Channel Design includes eight different phases, which are listed below for reference and to illustrate the comprehensiveness of the approach.

1. Phase I – Restoration objectives
2. Phase II – Developing local and regional relations in geomorphic characterization, hydrology, and hydraulics
3. Phase III – Watershed and river assessment
4. Phase IV – Passive recommendations for restoration
5. Phase V –The stream restoration and natural channel design methodology
6. Phase VI – Selection and design of stabilization and enhancement structures
7. Phase VII – Design implementation
8. Phase VIII – Monitoring and maintenance

Two key components of the natural channel design method are the development of bankfull regional curves and reference reach data sets (both are part of Phase II). A large part of this study includes the development of bankfull regional curves and reference reach data, so a more detailed overview of these NCD components are provided below.

2.5.1 Bankfull Regional Curves

The bankfull discharge is the stream flow that fills a channel to the elevation of the active floodplain and represents the breakpoint between channel forming processes and floodplain or depositional processes (Knighton, 1998). In this way, bankfull informs sediment transport processes because it results in the average or typical channel dimension developed by the full range of stream flows and sediment transport rates. In mountain settings, the breakpoint is between the channel and an area that is more of a flat or mildly sloping bench. In lower gradient streams the breakpoint or bankfull indicator can be the top of streambank, top of point bar, or a scour line (McCandless et al., 2015).

Bankfull regional curves plot the cross-sectional area, width, mean depth, and discharge data from a riffle cross section against drainage area. Power function equations are developed for each metric. These graphs and equations are used to help identify the bankfull indicator in disturbed settings and as an aid in designing the riffle dimension. Since channel size is related to the total precipitation and runoff relationship of a watershed, these curves should be generated as close to a project site as possible (Mulvihill et al., 2009). A regional curve from a region with a different precipitation/runoff relationship cannot be used. For example, regional curves developed in Southeast Alaska where annual precipitation is high cannot be used in the Alaskan Interior where rates are much lower. Channels in the Interior would likely be smaller than channels in the Southeast.

2.0 Background

For this project, regional curves are being developed to assist stream reclamation practitioners with sizing channels in the Alaskan Interior. More detail about selecting study sites, data collection methodology, and results is provided in later sections of the report.

2.5.2 Reference Reach Data

Rosgen (2001) calls the reference reach the "blueprint" for a Natural Channel Design because it is used to develop design criteria based on measured geomorphological relationships at a stable stream. Specific data are collected from the channel's dimension, pattern, and profile and then normalized by the bankfull dimension or channel slope so that values can be compared from a variety of stream sizes. For example, pool spacing is measured from the profile and then divided by the bankfull width to create a dimensionless pool spacing ratio. Unlike regional curves, reference reach streams do not have to come from watersheds with the same precipitation/runoff relationship. However, the project reach and reference reach must have the same stream type, valley type/slope, bed material composition, and similar boundary condition from riparian vegetation communities (Hey, 2006).

Since placer mines are often located in headwater mountain valleys (colluvial or confined alluvial), this study focused on similar reference reach streams. More detail about selecting study sites, data collection methodology, and results is provided in later sections of the report.

3.0 STUDY SITES

The data collection was a collaborative effort between Stream Mechanics, Ecosystem Planning and Restoration (EPR), APC Services, the Bureau of Land Management (BLM) and the National Park Service (NPS). Stream reaches from three different, but complimentary, field assessment efforts were used. Each study reach location and description is provided below in Table 2. The 40-Mile data set was collected in 2013 and 2014 to develop a bankfull regional curve and reference-reach information for the Jack Wade Creek demonstration projects. These reference streams are located in low gradient valleys (less than 2%) and are not included as reference streams in this study; they are only used for regional curves.

The Nome Creek data set was collected in the summer of 2017 as part of an overall assessment of reference-quality and impaired streams within settings known to have *aufeis*. Sites along the Denali Highway and the Valdez Creek Watershed were used to develop localized regional curves and reference reach data sets. Both the Nome Creek and Valdez data-collection efforts were funded by the Bureau of Land Management. Study sites within Denali National Park were all within the Eldorado Creek Watershed in the Kantishna region.

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TABLE 2: **Study Sites. Notes: Reference reach sites are also used to develop regional curves, whereas regional curve only sites are not used as reference reaches. A * indicates that these reference reaches are not included in this study other than for the development of regional curves.**

SITE NAME	LATITUDE, LONGITUDE	REGION	PURPOSE
Cherry Creek	64.061043, -141.162477	40-Mile	Reference Reach*
Walker Fork Gage	64.075967, -141.631745	40-Mile	Regional Curve Only
Jack Wade Creek Above Dredge	64.117852, -141.55123	40-Mile	Regional Curve Only
Jack Wade near Confluence	64.077555, -141.622817	40-Mile	Reference Reach*
Alder Creek	64.356618, -141.415233	40-Mile	Regional Curve Only
O'Brien Creek	64.358381, -141.410018	40-Mile	Regional Curve Only
Uhler Creek	64.196860, -141.594390	40-Mile	Regional Curve Only
Wade Creek	64.119587, -141.556331	40-Mile	Regional Curve Only
Little Champion	65.44068, -146.59739	Nome	Reference Reach
Unnamed Trib to Nome Creek	65.36995, -146.5763	Nome	Reference Reach
Nome Creek above Campground	65.38548, -146.56815	Nome	Reference Reach
Nome Creek at Bridge	65.340649, -146.713213	Nome	Reclaimed Reach**
Eldorado Creek above Canyon	63.51347, -151.00345	Kantishna/Eldorado	Reference Reach
Iron Creek Middle	63.4971333,-151.010133	Kantishna/Eldorado	Reference Reach
Iron Creek Confluence	63.49891,-151.01909	Kantishna/Eldorado	Reference Reach
Reinhart	63.50341,-151.0219	Kantishna/Eldorado	Reference Reach
Tiny XS 1	63.49720, -151.02312	Kantishna/Eldorado	Regional Curve Only
Tiny XS 2		Kantishna/Eldorado	Regional Curve Only
Slate Creek near Confluence	63.49113, -151.02339	Kantishna/Eldorado	Regional Curve Only
Eldorado below Confluence	N/A	Kantishna/Eldorado	Regional Curve Only
Eldorado below Mine Camp	63.50082, -151.02119	Kantishna/Eldorado	Regional Curve Only
Eldorado Upper	63.14867,-147.21634	Valdez/Denali Highway	Reference Reach
Eldorado Lower	63.15166,-147.21587	Valdez/Denali Highway	Reference Reach
Lily Creek Upper	63.33443,-148.27249	Valdez/Denali Highway	Reference Reach
Lily Creek Lower	63.15166,-147.21587	Valdez/Denali Highway	Regional Curve Only

3.1 Bankfull Regional Curve Site Selection Criteria

Bankfull regional curve sites were selected based on the following criteria and using methods published in previous studies (McCandless et al., 2015; Rosgen, 2014).

1. The bankfull indicator had to be an obvious and stable feature. Examples include the top of the streambank or bench and a break in slope in steep-gradient or naturally entrenched systems. Photographic examples of bankfull features are shown in Figures 10 and 11.
2. The selected riffle cross section must be free to adjust from the transport of water and sediment interacting with bed and bank materials. The riffle cross section could not be armored with unnatural materials like rip rap.
3. The study site did not have to be pristine, but it did have to be stable, even if it was only for a short reach length.
4. A range of drainage areas were required to develop regional curves that would represent planned natural channel design projects.

FIGURE 10: **Bankfull equals top of streambank**

FIGURE 11: **Bankfull equals top of bench / break in slope.**

3.2 Reference Reach Site Selection Criteria

Methods similar to selecting regional curves sites were also used to select reference reach sites, but with a few key differences. These differences include the following:

1. The reference reach had to be stable for at least 20 times the bankfull width.
2. The site had to exhibit identifiable riffle/cascade-pool or step-pool features. The site could not exhibit obvious signs of past mining or channel alteration.
3. The average channel slope had to range from greater than 2% slope and less than 15% slope.
4. Note: reference reach sites were also used as regional curve sites.

3.3 Nome Creek Reclamation Project

The project team selected a former placer-mine reclamation site in the Nome Creek Watershed for a variety of reasons. First, the study site is located in a watershed with known *aufeis* issues. Second, it is a site with historical data and is well known by the BLM staff. And finally, the Nome Creek site has good accessibility. The selected site is immediately downstream of the Nome Creek Bridge.

4.0 STUDY METHODOLOGY

Multiple methods were used to meet the study objectives of developing regional curves, creating reference reach data summaries, assessing a former reclamation project, and providing natural channel design criteria and recommendations. The methods used for each objective are described below.

4.1 REGIONAL CURVE DEVELOPMENT

The development of regional curves requires both office and field efforts. Prior to collecting field data, potential sites were selected using aerial photographs and topographic maps. A range of drainage areas was selected to create regional curves applicable to small and medium sized projects, e.g. less than one square mile to tens of square miles. In the field, the final reach was selected based on the criteria listed above.

The field work consisted of laser-level surveys and bed material samples. The survey included a riffle cross section that encompassed the bankfull and floodprone widths (Rosgen, 2014; Harrelson et al., 1994). Each major break in slope was surveyed along with key features, including the top of streambank, bankfull indicators, edge of channel, edge of water surface, and the thalweg. The survey also included a measurement of the average channel slope, which is the change in water surface elevation over a distance of approximately 20 times the bankfull width. In addition, a zig-zag pebble count procedure was used to sample 100 particles along the entire length of the study riffle.

The latitude and longitude coordinates were recorded at the riffle cross section and then used in the office to locate each site. A geographic information system (GIS) was used to calculate the drainage area for each project reach. The data from the field survey and bed material samples were entered into the Reference Reach Spreadsheet, Version 4.3L (Mecklenburg, 2006) to calculate channel dimensions, channel slope, and grain size distributions. From the channel dimension calculations, the bankfull width, cross sectional area, and mean depth were plotted against drainage area to develop the curves. The spreadsheet tool uses the grain-size distribution as input into a suite of roughness equations to estimate a Manning's n value, which can be used as a default value or overridden with a user-defined "n" to estimate the bankfull velocity. Both methods were used in this study. The velocity was then multiplied by the bankfull cross sectional area to yield a bankfull discharge.

The bankfull area, width, mean depth, and discharge were plotted against drainage area to create the bankfull regional curves. The curves were plotted on a log-log scale and a power function equation was used to create the best-fit line. The correlation coefficient and regression equation were also provided. Microsoft Excel was used to create the curves and create the regression equations.

4.2 Reference Reach Surveys

In general, the reference reach surveys were completed as described by Rosgen (1998) using field procedures described in Rosgen (2014) and Harrelson et al. (1994). This process typically includes a survey of channel dimension, pattern, and profile. However, since this study focuses on steep-gradient, non-meandering streams, channel pattern was not assessed. The field measurements are converted into dimensionless ratios as described in Rosgen (1998).

The most critical and difficult part of completing a reference reach survey in steep gradient streams is identifying the bedforms. Key bedforms include riffles or cascades, steps, and pools. Once these features are identified a longitudinal profile is surveyed. Figure 12 illustrates the pool spacing plan view of mountain streams. Pools are separated be either a step or a riffle/cascade structure. For this study, riffles and cascades are considered as the same feature. Since cascades tend to be in steep systems, the term will be used more than riffle. The key point in Figure 12 is that small micro pools within a cascade are not included in the pool spacing measurement. For a feature to be considered a pool, it must provide a geomorphic function and not just a habitat function. Geomorphic functions considered include energy dissipation, connection to subsurface flow, and habitat. These pools are located downstream of cascades/riffles or steps and consume at least half of the channel width. The pools are concave in shape, have water surface slopes that are flatter than the average channel slope, and depths that are deeper than the riffles. The pool forming process includes scour from water plunging over the cascade or step and backwater from the downstream cascade or step. An example of a cascade-pool followed by a step- pool sequence is shown in Figure 13.

FIGURE 12: **Cascade-pool and step-pool sequence. Note that the small (micro) pool within the cascade is not included in the pool spacing measurement**

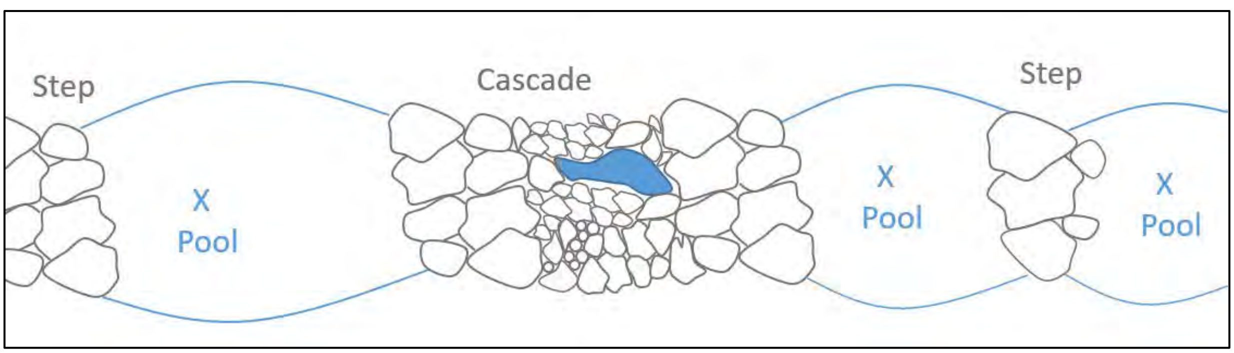


FIGURE 13: **Geomorphic pools separated by a step. Cascade feature upstream of first pool. Iron Creek near the confluence with Eldorado Creek in Denali National Park.**

Pool spacing varies depending on the feature between them. The length (spacing) between the two pools shown in Figure 13 is relatively short because the length of a step is short. If a cascade is between two pools the spacing is longer. Since these data will be used as criteria for designing and building steep-gradient streams, the pool spacing data is stratified by cascade/riffle-pool and step-pool. This provides better guidance for designers and will help ensure that design reaches have the correct percentage of riffles/cascade, steps, and pools. Table 3 provides the criteria used to identify cascades/riffles, steps, and pools.

TABLE 3: Criteria used to identify bedforms.

BEDFORM FEATURE	CRITERIA USED FOR IDENTIFICATION
Cascade	• Typically steeper than the average slope of the reach, unless there is a step at the downstream end. • Provides grade control and sets elevation of upstream pool. • The structure is one geomorphic unit. • Longer than 1 times the bankfull width. • May contain micro-pools and depth variability, but still contained within overall structure. • Steps may be located on downstream end of cascade. These steps are included with the cascade for pool spacing measurements. However, they are separated out for slope and step height measurements.
Step	• Shorter than 1 times the Bankfull Width. • Creates a vertical or near vertical plunge into a downstream pool. • Often includes boulder-sized sediment. • May be stand-alone structures or located at the downstream end of a cascade.
Pool	• Must include a scour and backwater process. Scour is caused by plunging water from upstream cascade or step. Backwater is caused from downstream cascade or step. • Width of pool is more than half the Bankfull Width. • Bottom width is concave shaped.

Past natural channel design projects and reference reach studies have simply lumped steps and cascades into one pool spacing value (Zink and Jennings, 2012). A common result of this approach is a design reach that includes too much pool length and not enough riffle length. This can impede sediment transport processes and lead to channel instability and realignment. An example of a project with too much pool length and not enough riffle length is the Carmel River in California. A reach of river was constructed following a dam removal project using a step-pool approach. No cascade features were used, resulting in a high percentage of pools. The channel was overwhelmed by the high sediment load from upstream supplies during flood events and the step-pool features were reconfigured into a cascade (Figure 14). A headcut migrated upstream and was arrested by bedrock. The after photo in Figure 14 shows a cascade-step-pool formation with the bedrock forming the step. The cascade is upstream of the step and the pool is downstream of the step. The pools associated with the design structures have been replaced with the cascade.

FIGURE 14: **Before and after photos of the Carmel River Restoration Project. Photos by Doug Smith.**

4.3 Nome Creek Reclamation Site

The Nome Creek reclamation site was assessed using common geomorphic monitoring methods including a longitudinal profile, cross sections, bed material samples, lateral stability estimates, and a visual assessment of riparian vegetation. Methods described in Harrelson et al. (1994) and Rosgen (2014) were used to complete the profiles, cross sections, bed material samples, and a portion of the lateral stability assessment. Methods described in Harman et al., (2012) and WYSTT (2018) were used to analyze the lateral stability data and summarize the function-based assessment.

A sub-set of function-based parameters from Harman et al. (2012) was used for this assessment. The parameters, measurement methods, and the rationale for their selection are provided in Table 4 followed by a brief description of how they were measured. A detailed description of each parameter is found in Harman et al., (2012) and a detailed description of how the metrics are typically assessed is in the WY Stream Quantification Tool user manual (WSTT, 2018). The overarching reason that these metrics were selected is that they align with the BLM reclamation guidelines for reclaiming aquatic and riparian habitat and channel stability. There is no requirement to improve or change the numbers of aquatic insects or fish, so physicochemical and biological metrics were not included. Hydrology metrics are also not included in the BLM guidelines.

TABLE 4: **Function-based parameters, measurement methods, and the rationale for their selection**

FUNCTIONAL CATEGORY	FUNCTION-BASED PARAMETER	MEASUREMENT METHODS	RATIONALE FOR SELECTION
Hydraulics	Floodplain Connectivity	Bank Height Ratio Entrenchment Ratio	This is a critical metric for channel stability. As channels become incised and entrenched, the potential for bed degradation increases.
Geomorphology	Bedform Diversity	Pool Spacing Ratio Pool Depth Ratio Percent Riffle	This is a measure of habitat quality for macros and fish, as well as a surrogate measure for sediment transport processes.
	Lateral Stability	BEHI/NBS Percent Erosion	This measure indicates if bank erosion is excessive.
	Riparian Vegetation	Visual	This metric is critical for providing lateral stability and supporting many aquatic functions.

4.3.1 Floodplain Connectivity

Floodplain connectivity is a function-based parameter used to quantify the frequency and extent of overbank flooding. Rather than directly measuring the number of flood events that occurs throughout time, two measurement methods are used to assess channel incision and entrenchment. Channel incision is measured using the bank height ratio (BHR), which is the channel depth from the bottom (thalweg) to the top of the streambank. The lower of the two streambanks is used because this is the elevation where water leaves the channel and spreads onto a flatter surface. This depth is then divided by the bankfull max depth. A ratio of 1.0 means that all flows greater than bankfull will leave the channel and spread across a floodplain or bankfull bench.

This measurement does not quantify how far water can spread once it leaves the channel. In wide alluvial valleys, floodwaters can spread out over a great distance. However, in confined valleys (like in mountain settings), the water may only be able to spread a few feet over a bankfull bench. The entrenchment ratio (ER) is used to quantify how far water can spread. It is a ratio of the flood prone area width divided by the bankfull riffle width. The flood prone area width is the width of the floodplain at a depth that is twice the bankfull maximum riffle depth (Rosgen 2009).

The BHR is measured from the midpoint of each riffle identified on the longitudinal profile. The BHR is then calculated as follows:

$$(1) \qquad \frac{Top\ of\ Low\ Bank\ Elevation - Thalweg\ Elevation}{Bankfull\ Elevation - Thalweg\ Elevation}$$

The bankfull elevation is taken from a best-fit-line through the bankfull points. The thalweg elevation is the same in both the numerator and denominator.

The ER is measured from the riffle cross section, if the cross section extends far enough across the valley. If it's determined that two times the max bankfull riffle depth will extend across the entire valley, then the valley width can be measured and entered as the floodprone width. This value is then divided by the riffle bankfull width as shown on the cross section. Typically, one ER is calculated per study reach. However, if the valley width undulates, multiple ER's can be measured and averaged.

4.3.2 Bedform Diversity

Bed forms include the various channel units that maintain heterogeneity in the channel form, including riffles, runs, pools and glides. The location, stability and depth of these bed features are responsive to sediment transport processes acting against the channel boundary conditions. Bed form diversity is a function-based parameter used to assess these bed form patterns, specifically riffle-pool and step-pool sequences in alluvial and colluvial valleys.

Natural streams rarely have flat uniform beds (Knighton, 1998). Instead, hydraulic and sediment transport processes shape the stream bed into myriad forms, depending on channel slope, type of bed material (sand, gravel, cobble, boulder, bedrock) and other factors. These bed forms reflect local variations in the sediment transport rate and represent lateral and vertical fluctuations in the stream bed (Knighton, 1998), dissipating energy and creating habitat diversity.

Numerous classifications of bed form exist (Knighton, 1998). At a broad level, bed forms can be grouped into three categories: sand bed forms (ripple, dunes and antidunes), gravel/cobble bed forms (riffle, run, pool and glide) and step-pool bed forms. At a sub-reach scale, the pattern of these bed forms, or channel units, inform the characterization of geomorphology at the reach scale, e.g., step-pool, riffle-pool, etc. (Buffington and Montgomery, 2013). Bed form diversity is important because channel patterns provide a diversity of habitats that aquatic organisms need for survival. For example, macroinvertebrate communities are often most diverse in riffle habitats, and fish rely on pools for resting, thermal, and solar refugia. Without the diversity of riffles and pools, there is also a potential loss of diversity in macroinvertebrates and fish communities (Mathon et al., 2013; Fischenich, 2006).

Three measurement methods are used to characterize bed form diversity: pool spacing ratio, pool depth ratio, and percent riffle. All three methods are measured from the longitudinal profile. Adequate pool spacing and the depth variability created from alternating riffles supports dynamic equilibrium and habitat-forming processes (Knighton, 1998, Hey, 2006). The pool spacing ratio metric measures the distance between the deepest location of sequential geomorphic pools (i.e., lateral-scour / meander bend pools or step-pools). The distance between geomorphic pools is divided by the bankfull riffle width to calculate the dimensionless pool spacing ratio. The pool spacing measurement is made from the longitudinal profile and the bankfull width is measured from a riffle cross section. The ratio is calculated as follows:

$$\frac{Distance\ between\ the\ \max depth\ of\ sequential\ pools\ (ft)}{Bankfull\ Riffle\ Width\ (Ft)} \tag{2}$$

The average or median pool spacing ratio is used to characterize the reach.

Studies have documented a connection between pool spacing ratios and channel stability and complexity (Langbein and Leopold, 1966; Gregory et al., 1994; Laub et al., 2012). If a meandering stream has a low pool spacing, the riffle length is also low and energy is transferred to the banks and sometimes the floodplain. Evaluations of numerous stream restoration and mitigation projects by the author has shown that sites constructed with low pool-spacing ratios resulted in excessive bank erosion and sometimes floodplain erosion.

In addition to the issues caused by low pool spacing outlined above, large pool spacing values are also problematic. A large pool spacing ratio essentially means that there are a small number of geomorphic pools in the reach. In alluvial valleys, this might mean that the reach is overly straight, and the habitat value is diminished because the length of pool habitat has been reduced. In colluvial or otherwise confined valleys, the lack of pools might mean there is not sufficient energy dissipation to achieve dynamic equilibrium.

The pool depth ratio measures the bankfull depth of the deepest point of each pool. Pool depths are measured from the longitudinal profile as follows:

$$\frac{Bankfull\ Elevation\ (ft) - Thalweg\ Elevation (ft)}{Mean\ Riffle\ Depth\ (ft)} \tag{3}$$

The bankfull elevation is measured from a best-fit-line through the bankfull points. The thalweg elevation is measured at the deepest part of the pool. The riffle mean depth is from the riffle cross section. Note, if more than one riffle cross section is assessed per project reach, the most stable cross section is used.

All pools, including both geomorphic pools and micro-pools, are included in this metric (note: this is different than the pool spacing metric above). The bankfull pool depth is normalized by the bankfull mean riffle depth to calculate the dimensionless pool depth ratio. The average pool depth ratio is used to characterize the reach. Pools provide fish habitat and thermal refugia, support thermal regulation, provide energy dissipation, and are an indication of how the stream is transporting and storing sediment (Knighton, 1998; Allan, 1995; Hauer and Lamberti, 2007). For example, if the outside meander bend has filled with sediment, this can be an indication of an aggradation problem. In other words, the channel cannot transport the sediment load through the meander bend. In combination with pool spacing ratio and percent riffle metrics, the pool depth ratio characterizes the bed form diversity of a stream reach (Harman et. al. 2012).

The percent riffle measures the length of riffles (including runs) within the sample reach. The total length of riffles and runs is divided by the total reach length to calculate the percent riffle. These measurements are made from the longitudinal profile as follows:

$$\frac{Sum\ of\ all\ riffle\ and\ run\ lengths\ (ft)}{Total\ Reach\ Length\ (ft)} \tag{4}$$

Pools and riffles are valuable habitat and both are needed to support various aquatic species and dissipate energy within a reach. The riffle is the natural grade-control feature of the stream, providing floodplain connection and vertical stability (Knighton 1998). The pool provides energy dissipation, habitat diversity, and more. Much of the discussion regarding stream function presented in the pool spacing ratio and pool depth metric summaries applies to the percent riffle metric as well. While the pool spacing ratio quantifies the frequency of pools within a reach, this metric quantifies the relative prevalence of riffle habitat length throughout the reach. Therefore, percent riffle works with the pool spacing ratio and pool depth ratio metrics to characterize the bed form.

4.3.3 Lateral Stability

Lateral stability is a function-based parameter used to characterize lateral erosion rates. This parameter is included because it provides information about sediment supply/transport and dynamic equilibrium processes. Lateral migration rates vary naturally by stream type and can be affected by changes in sediment processes at the watershed and reach scale (Roni and Beechie, 2013; Knighton, 1998).

The lateral stability parameter includes two measurement methods: dominant BEHI/NBS, and percent eroding streambank. The dominant BEHI/NBS measurement characterizes the magnitude of erosion, and the percent eroding streambank characterizes the extent of the problem. These methods are measures of channel condition that serve as indicators of altered processes, but do not characterize lateral migration rates or sediment processes themselves.

The Bank Erosion Hazard Index (BEHI) and Near Bank Stress (NBS) are two bank erosion estimation tools from the Bank Assessment for Non-point source Consequences of Sediment (BANCS) model (Rosgen 2006). BEHI and NBS ratings are determined based on collecting relatively simple measurements and visual observations. The streambank assessment includes the evaluation of streambank cover, height, depth and density of roots, and bank angle. From the streambank assessment, a categorical BEHI risk rating is assigned, from very low to extreme. Adjustments in the rating can be made based on soil material (clay banks have a downward adjustment and sandy banks have an upward adjustment) and bank material stratifications. Observations of channel flow characteristics, including water-surface slope, direction of velocity vectors and other methods, are used to assign an NBS risk rating, which can also range from very low to extreme.

The dominant BEHI/NBS is the rating that occurs most frequently based on length. For example, a dominant BEHI/NBS rating of High/High means that the majority of the assessed length, e.g., outside meander bends, has this rating. Assessed banks include the outside of every meander bend, whether it’s eroding or not, and any other place where there is bank erosion. Both left and right banks are assessed.

The percent of bank erosion estimates the percent of the streambank within a reach that is actively eroding, according to BEHI/NBS ratings. The percent eroding streambank metric provides a measure of the extent of bank erosion, whereas the dominant BEHI/NBS rating provides the magnitude of active bank erosion. The field value is calculated by adding the length of BEHI/NBS ratings that represent actively eroding banks from the left and right banks and dividing it by the total bank length (e.g., reach length times two). Note that riffle sections that are not eroding and depositional areas like point bars are not evaluated in the BEHI/NBS assessment, but these sections are included when calculating the total bank length (denominator) for this metric.

4.3.4 Riparian Vegetation

Riparian vegetation is a critical component of a healthy stream ecosystem. Riparian vegetation is defined as plant communities contiguous to and affected by surface and subsurface hydrologic features of perennial or intermittent water bodies. While these plant communities are a biological component of the stream ecosystem, riparian vegetation plays such a critical role in supporting channel stability and physicochemical and biological processes that it is included in the geomorphic level of the stream functions pyramid (Harman et al., 2012). Riparian areas support numerous instream and floodplain functions, including:

- Cover and shading
- Channel stability
- Filter excess nutrients, sediments, and pollutants
- Source of woody debris
- Floodplain roughness
- Carbon and nutrient contributions
- Terrestrial habitat
- Plant diversity, species richness, and functional integrity

The width of the riparian corridor and species composition were the two measurement methods used to assess riparian vegetation. The riparian width metric is the proportion of the valley width that currently contains riparian vegetation and is free from human disturbance. Once the width is determined, the species composition of the riparian corridor is determined. This study did not include a quantitative assessment of the riparian vegetation using plots or transects.

5.0 RESULTS

This chapter includes the final regional curves, descriptive statistics from the reference reach surveys, and results from the function-based assessment of the Nome Creek placer mine reclamation site. These results are then used to describe how Natural Channel Design Techniques can be applied to Sub-Arctic Alaska in Chapter 6.

5.1 BANKFULL REGIONAL CURVES

Four sets of bankfull regional curves were developed from the data set: Alaska Interior (all data), Fortymile Watershed, Valdez Creek, and the Eldorado Creek Watershed located in the Kantishna Region of Denali National Park. The regional curves are provided in Appendix A. The Alaska Interior curves were developed from the entire data set and therefore include data throughout the Alaskan Interior, roughly ranging from near Canada to the east, Denali National Park to the west, the Yukon River to the north, and the Denali Highway to the south. The Valdez Creek Regional Curves include data from the White and Valdez Creek Watersheds and points along the Denali Highway. The Eldorado Creek curves were developed from data exclusively within the Kantishna region and the Eldorado Creek Watershed. The Fortymile curves include data from the Jack Wade Creek Watershed, Cherry Creek Watershed, and streams along the Taylor Highway between Chicken and Eagle. The Fortymile, Valdez Creek, and Eldorado Creek curves should be used for stream assessment and design projects within the same region that the data were collected.

Table 5 provides the power function equation, correlation coefficient (R^2), and sample size (n) for each regional curve. These equations show that the Valdez Creek curves generate larger bankfull riffle dimensions than the other curves. The Eldorado Creek curves generate the smallest dimension. For comparison, a 5 square mile drainage area will produce a bankfull cross sectional area of 22 ft^2 using the Valdez curve and 17 ft^2 using the Eldorado curve. This result does not show a large difference between the max and min curves, which demonstrates that the precipitation/runoff relationship is similar throughout the sampling region.

TABLE 5: Power function equations, correlation coefficients (R^2), and sample size (n) for each regional curve.

REGIONAL CURVE	DISCHARGE (CFS)	AREA (SQFT)	WIDTH (FT)	MEAN DEPTH (FT)
Alaska Interior	$y = 29.69x^{0.73}$ $R^2 = 0.98$ n = 23	$y = 6.63x^{0.69}$ $R^2 = 0.96$ n = 30	$y = 9.08x^{0.40}$ $R^2 = 0.92$ n = 30	$y = 0.73x^{0.29}$ $R^2 = 0.91$ n = 30
Fortymile Watershed	$y = 40.24x^{0.65}$ $R^2 = 0.90$ n = 6	$y = 4.86x^{0.77}$ $R^2 = 0.98$ n = 8	$y = 9.31x^{0.39}$ $R^2 = 0.94$ n = 8	$y = 0.51x^{0.39}$ $R^2 = 0.90$ n = 8
Valdez Creek Watershed	$y = 41.13x^{0.57}$ $R^2 = 0.80$ n = 7	$y = 7.67x^{0.65}$ $R^2 = 0.94$ n = 10	$y = 9.38x^{0.40}$ $R^2 = 0.85$ n = 10	$y = 0.82x^{0.26}$ $R^2 = 0.97$ n = 10
Eldorado Creek Watershed	$y = 19.10x^{0.91}$ $R^2 = 0.91$ n = 7	$y = 6.03x^{0.63}$ $R^2 = 0.92$ n = 9	$y = 8.34x^{0.42}$ $R^2 = 0.87$ n = 9	$y = 0.73x^{0.21}$ $R^2 = 0.53$ n = 9

The discharge relationship shows that the Fortymile curve produces more bankfull discharge per unit drainage area than the Valdez Creek curve. This may or may not be true since the discharges were estimated using Manning's equation and have more error than the direct measurements of area, width, and mean depth. Therefore, more emphasis should be placed on sizing channels using the dimension curves, particularly the area, than the discharge curve.

Table 6 provides Rosgen stream classification results and other ancillary information. Overall, there were 30 sites representing the following stream types (the number in parentheses is the sample size): Aa+ (2), B4 (2), B4a (1), B3 (4), B3a (7), B3c (1), B4c (2), C4 (6), C3b (4), and C4b (1). Mulvhill (2009) showed that stratifying regional curves by stream type, in addition to the precipitation/runoff relationship can improve the correlation coefficient. Stratifying regional curves this way was not done for this project because the majority of the stream types represent confined valleys and step-pool bed morphologies. In other words, even though there are a wide range of stream types, their hydraulic and geomorphic functions are similar. For example, Aa+, all B stream types, and the Cb stream types reside in colluvial / confined valleys with step-pool bed morphologies. The only stream types from alluvial valleys with meandering processes are the C stream types. There are six C stream types, but they come from two different hydro-physiographic regions.

TABLE 6: **Rosgen stream classification data for study sites.**

SITE NAME	CURVE	DRAINAGE AREA (MI2)	WATER SLOPE (FT/FT)	CHANNEL MATERIAL (D50 MM)	ROSGEN STREAM TYPE	ENTRENCH-MENT RATIO	WIDTH / DEPTH RATIO
Cherry Creek	Jack Wade Creek	35.6	0.0074	36	C4	>5	13
Walker Fork Gage	Jack Wade Creek	396	0.0037	54	C4	18	29
Jack Wade Creek Above Dredge	Jack Wade Creek	35.4	0.0065	Not measured	B4c	<2.2	17
Jack Wade near Confluence	Jack Wade Creek	48	0.0095	Not measured	C4	18	15
Alder Creek	Jack Wade Creek	55	0.011	Not measured	B3c	97	15
O'Brien Creek	Jack Wade Creek	214	0.0030	Not measured	C4	>2.2	16
Uhler Creek	Jack Wade Creek	13.9	Not measured	Not measured	C4	2.3	24
Wade Creek	Jack Wade Creek	4.2	Not measured	Not measured	B4c	1.7	22
Little Champion	Interior (Nome)	1.59	0.063	100	B3a	2.2	19
Unnamed Trib to Nome Creek	Interior (Nome)	2.76	0.044	120	B3a	2.2	12
Nome Creek above Campground	Interior (Nome)	6.93	0.027	160	B3	1.8	21

(TABLE 6 Continued)

SITE NAME	CURVE	DRAINAGE AREA (MI2)	WATER SLOPE (FT/FT)	CHANNEL MATERIAL (D50 MM)	ROSGEN STREAM TYPE	ENTRENCH-MENT RATIO	WIDTH / DEPTH RATIO
Eldorado Creek above Canyon	Eldorado Creek (Denali)	11.58	0.025	29	B4	1.5	13
Iron Creek Middle	Eldorado Creek (Denali)	2.08	0.073	130	C3b	2.8	17
Iron Creek Confluence	Eldorado Creek (Denali)	2.35	0.049	120	B3	2.2	27
Reinhart	Eldorado Creek (Denali)	0.77	0.10	89	B3a	1.6	12
Tiny XS 1	Eldorado Creek (Denali)	0.25	>0.10	Not measured	Aa+	1.8	10.3
Tiny XS 2	Eldorado Creek (Denali)	0.25	>0.10	Not measured	Aa+	2.9	4.6
Slate Creek near Confluence	Eldorado Creek (Denali)	2.08	0.046	63	B4	2.1	20
Eldorado below Confluence	Eldorado Creek (Denali)	6.55	0.046	64	B3	2.4	11
Eldorado below Mine Camp	Eldorado Creek (Denali)	9.36	0.029	68	C3b	3.5	19
Eldorado Upper	Valdez Creek	1.09	0.081	84	B3a	2.3	13
Eldorado Lower	Valdez Creek	1.49	0.069	51	B4a	1.4	18
Lily Creek Upper	Valdez Creek	5.8	0.054	87	B3a	1.7	14
Lily Creek Lower	Valdez Creek	8.48	0.025	61	C3b	2.1	11
Rusty Creek	Valdez Creek	3.01	0.062	78	B3a	4.0	11
Brushkana	Valdez Creek	116	0.032	Not measured	B3	<2.2	26
Seattle	Valdez Creek	35.2	0.032	Not measured	C3b	>2.2	15
Upper White	Valdez Creek	5.6	0.023	53	C4b	>2.2	11
Lower White	Valdez Creek	9.1	0.043	66	B3a	1.8	15
Valdez Creek	Valdez Creek	37.6	0.0059	Not measured	C4	>2.2	28

5.2 Reference Reach Surveys

The reference reach survey results focus on the steeper gradient (greater than >2% slope) streams from the Nome Creek, Valdez Creek, and Eldorado Creek Watersheds. There are only three sites with slopes less than 2% (Cherry, Alder, and Valdez), so the sample size was too small to include. Table 7 summarizes the general characteristics of the reference sites. A more detailed summary table is provided in Appendix B.

TABLE 7: **General characteristics of the reference reach sites.**

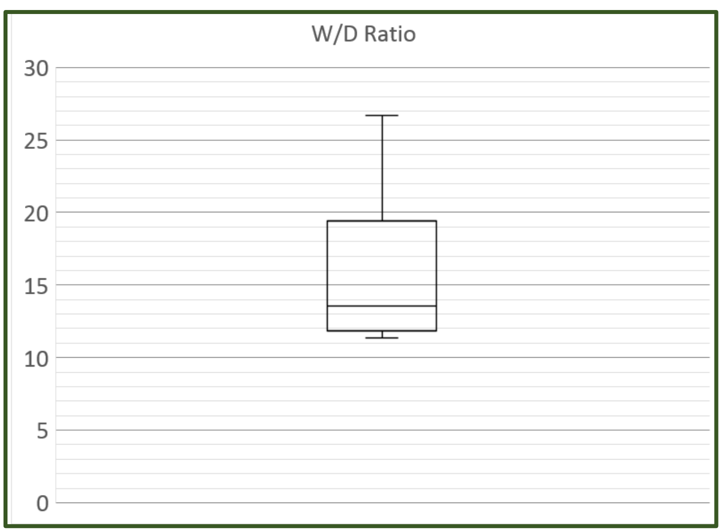
WATERSHED	SAMPLE SIZE (n)	STREAM TYPES (Rosgen)	SLOPE RANGE (%)	D_{50} RANGE (mm)	DRAINAGE AREA RANGE (mi^2)
Nome	3	B3, B3, B3a	2.7 to 6.3	100 to 160	1.59 to 6.92
Valdez	4	B3a, B4a, B3a, B3a	5.4 to 8.1	51 to 87	1.09 to 5.8
Eldorado	4	B4, C3b, B3, B3a	2.5 to 10.1	29 to 130	0.77 to 11.58

Overall, 11 reference reach streams are included in the study representing three B3, five B3a, one B4, one B4a, and one C3b stream types. All of these stream types are found in colluvial/confined valleys with step-pool bedforms. All but one site had a median bed material size in the cobble range. A summary of the results is provided below.

5.2.1 Bankfull Dimension Ratios and Hydraulic Relationships

One of the first steps in the NCD process is to design the bankfull riffle cross section. The design cross sectional area can often be calculated from the regional curves. However, the bankfull Width/Depth ratio is typically selected from a range of reference reach values. A box plot showing the range of values from the reference reach data set is provided in Figure 15.

FIGURE 15: **Distribution of bankfull W/D ratios from riffle cross sections.**

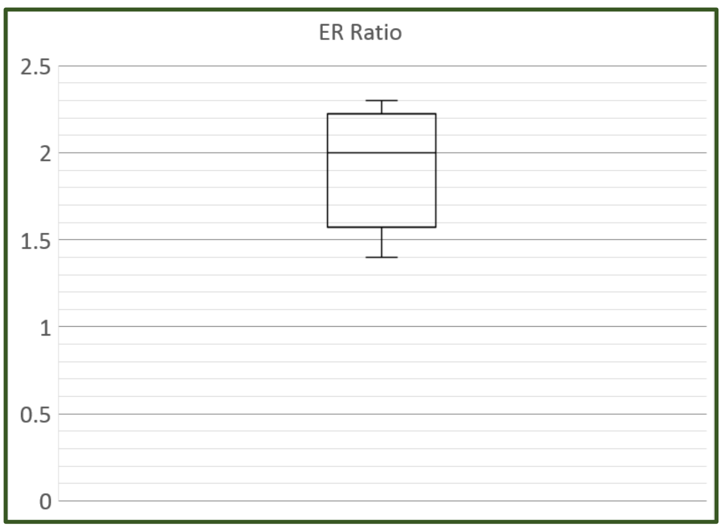


The overall range of W/D ratios observed in reference quality streams is 11 to almost 27 with a median value of 14 and a mean of 16. The 25th percentile is 12 and the 75th percentile is approximately 19. The box plot shows that the distribution is skewed to the right (up in the graph), which is why the mean is greater than the median. The right skewness also means that most W/D ratios are small with a few exceptionally large values. From a practical perspective, it means that a designer would likely select smaller W/D ratios than very large ratios within the range. Guidance for selecting a design W/D ratio is provided below in the Application of NCD to Sub-Arctic Regions of Alaska.

Another important NCD design metric that comes from riffle cross sectional surveys is the entrenchment ratio, which is the floodprone-area width divided by the bankfull width. In colluvial valleys, the entrenchment ratio is typically low to moderate since wide floodplains are not found in these systems. The entrenchment ratio is corelated to the width of a bankfull bench, with wider benches creating larger ratios. The distribution of entrenchment ratios is provided in Figure 16.

The entrenchment ratios range from 1.4 to 2.3 with a median value of 2.0. The 25th percentile is almost 1.6 and the 75th percentile is just over 2.2. Generally, designers will select the largest entrenchment ratio that the valley width will support.

FIGURE 16: **Distribution of bankfull entrenchment ratios from riffle cross sections.**



5.2.2 Bankfull Hydraulics

Results from the bankfull hydraulic calculations made in the Reference Reach Spreadsheet are provided in Table 8.

TABLE 8: Select hydraulic calculations from riffle cross sections.

STREAM NAME	DISCHARGE (CFS)	VELOCITY (FT/S)	MANNING'S N	SHEAR STRESS (PSF)	UNIT STREAM POWER (LBS/FT/S)
Eldorado Above Canyon	219	5.7	0.055	2.42	15.4
Iron Creek Middle	25.5	4.0	0.065	2.40	11.2
Iron Creek near confluence	39.1	3.8	0.060	1.78	7.5
Reinhart	20.9	4.8	0.068	3.55	18.8
Little Champion	53.8	4.3	0.073	3.03	13.9
Nome Creek Above Campground	170.2	4.3	0.068	2.22	9.9
Nome Creek Tributary	72.7	5.1	0.063	2.81	15.2
Eldorado Upper	40.3	4.5	0.080	3.99	19.0
Eldorado Lower	65.5	4.6	0.075	3.58	17.5
Lily Creek Upper	114	5.1	0.075	3.88	22.0
Rusty Creek	67.2	5.0	0.075	3.95	21.0

Bankfull velocity ranged from 3.8 to 5.7 ft/s with a mean of 4.7 ft/s. The national average is approximately 4.0 ft/s for C and E stream types. It's not surprising that the average for this study is slightly higher since the data set included mostly steeper-gradient B stream types. Bankfull velocity is an important design metric but is used more to test the hydraulic response of the dimension and slope design. Guidance for testing the bankfull velocity is provided below in the Application of NCD to Sub-Arctic Regions of Alaska.

The bankfull velocity and corresponding discharge were calculated in the Reference Reach Spreadsheet using Manning's equation. The Manning's n value was estimated using bed material samples and friction relationships provided in the spreadsheet (refer to the spreadsheet for more information). In a few cases, the spreadsheet-estimated n value was overridden if values seemed unreasonable, e.g. the n value yielded a velocity of 2 ft/s and a discharge that was well below what was reasonable. The Manning's n values ranged from 0.055 to 0.080 with a mean of 0.069. These are high values, but not atypical for high gradient mountain streams with large bed material. Estimating a resistance coefficient is more challenging in high gradient streams than lower gradient, alluvial streams. Manning's n was used in this study to estimate the bankfull discharge; however, practitioners may prefer to seek other methods for estimating roughness in design projects. Wohl (2010) provides several alternatives for estimating resistance coefficients in mountain rivers.

Table 9 also shows shear stress and stream power values, which help inform sediment transport processes. Shear stress is used to predict particle sizes that can be transported during a given flow, in this case the bankfull flow, and to calculate the required depth (Rosgen, 2007). Stream power is used in sediment transport capacity relationships. These values can be used as a comparison against design values. In other words, stream designs within the same valley and stream type as the reference data set should typically fall within the same range as what is shown.

5.2.3 Grain-Size Distributions

Bed material samples were collected at each study reach using the Wolman Pebble Count procedure. For most sites, two different samples were collected, one to classify the stream (Rosgen, 2014) and the other to characterize the study riffle for hydraulic and sediment transport computations. Results from the study riffle are provided below in Table 9.

TABLE 9: Grain size distributions from the study riffle.

STREAM NAME	D_{50} (mm)	D_{84} (mm)	D_{95} (mm)	COBBLE %	BOULDER %
Eldorado Above Canyon	29	90	210	20	4
Iron Creek Middle	130	400	800	62	23
Iron Creek near confluence	120	260	410	62	17
Reinhart	89	260	360	48	16
Little Champion	100	220	360	61	11
Nome Creek Above Campground	160	280	510	73	20
Nome Creek Tributary	120	210	330	74	10
Eldorado Upper	84	240	360	48	2
Eldorado Lower	51	110	200	32	3
Lily Creek Upper	87	290	570	48	19
Rusty Creek	78	210	350	57	12

Results show that the study riffles have coarse-grain bed material. All sites, except for Eldorado Above Canyon and Eldorado Lower have median (D_{50}) particles that are in the cobble range (the break between gravel and cobble is 64mm). It is common for these streams to have riffles that are comprised of more than 48% cobble. Only two study riffles had a cobble percentage less than 48%. In addition, all riffles included some boulders and many included a boulder percentage greater than 10% (the break between cobble and boulders is 256mm).

This observation is important because many placer-mines remove the boulders from the stream channel. For example, the Slate Creek mine site in Denali National Park only has 4% boulders and the median size is 45mm, a coarse gravel. Headcutting and bed degradation was observed in several locations. Karle and Densmore (1994) also observed a fining of the streambed resulting from placer mining. Given the high shear stress common in these systems, armoring from large cobbles and boulders is critical to the overall success of a reclamation project. *Aufeis* can exacerbate this problem by creating ice jams in the channel. When the jams break apart, flows with high shear stress and stream power can erode the bed if sufficient armoring is not in place.

5.2.4 Bed Form Characterization

The following metrics are used to characterize the bed forms: pool spacing ratio, riffle and pool lengths, pool depths, and cascade and pool slopes, and step heights. Results for each are provided below.

5.2.4.1 Pool Spacing Ratio

Results for the pool spacing divided by bankfull width ratio are shown on Figure 17. The results are stratified by the feature (riffle/cascade or step) that is between two successive pools. Therefore, riffle/cascade-pools have a longer spacing than step-pools. This ratio is used in the design process to establish the overall number of pools per reach and their spacing. A combination of cascade/riffle-pools and step-pools can be used as long as the other criteria, such as percent riffle, are met.

FIGURE 17: Pool spacing divided by bankfull width for riffles/cascade-pools and step-pools.

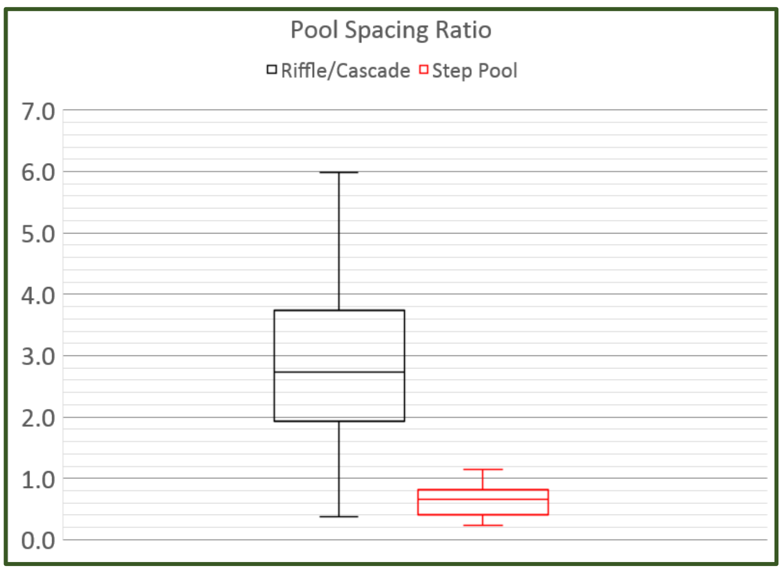


Figure 17 shows that the range of riffle/cascade-pool spacing is 0.4 to 6.0 times the bankfull width. The range is normally distributed with the 25th and 75th percentiles equaling almost 2.0 and 3.7, respectively. The median value is 2.7. The values for step-pool spacing are obviously much lower and the range is much tighter. Therefore, it makes sense to just focus on the overall range and median values. The range is 0.4 to 1.2 and the median is 0.7. Guidance on how to use these values in the design process is provided below in the Application of NCD.

5.2.4.2 Riffle and Pool Lengths (Percent and Ratios)

Mountain streams are dominated by cascades and riffles with pools serving as a form of energy dissipation and aquatic habitat (Wohl, 2010). The percent of riffles, pools, and steps are shown in Figure 18. Cascade/riffles range from 54 to 84% of the overall reach, with a median value of 63%. Pools make up the next greatest percentage of length with a median value of 30%; however, the distribution is heavily skewed to the left. The range of pool percentages is 12 to 39%. Steps make up the smallest percentage of stream length with a range from 3% to almost 16% and a median value of only 5%.

FIGURE 18: Percent of stream length that is cascade/riffle, pool, and step.

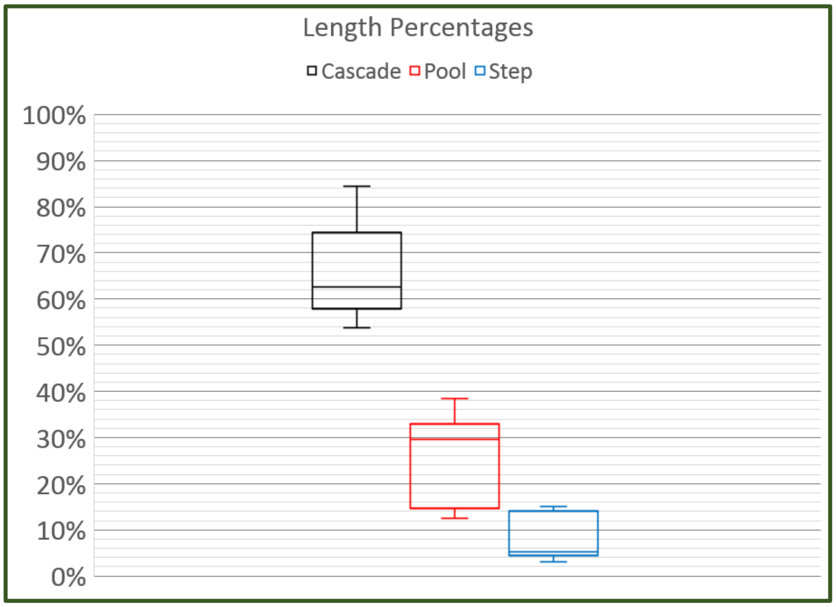
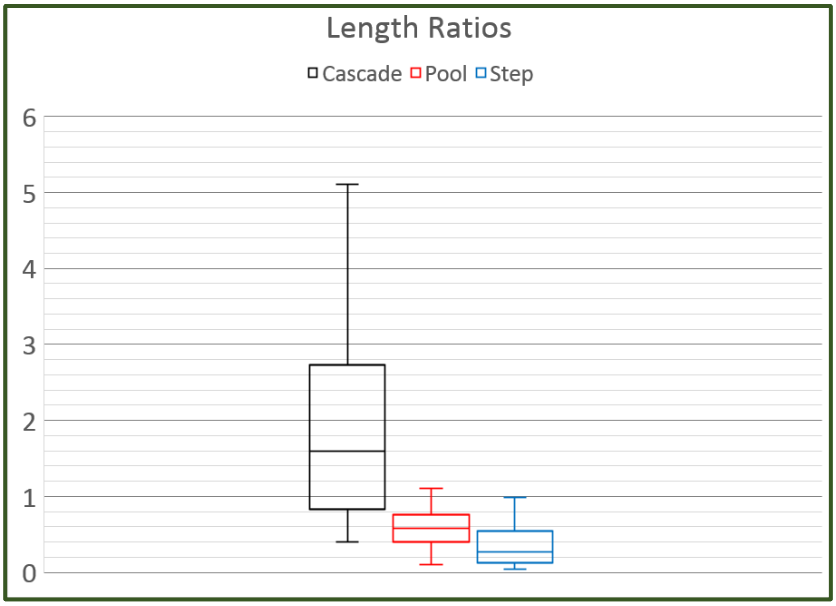


Figure 19 shows the length ratios for each bed feature. The ratio is the feature length divided by the bankfull width. Cascades/riffles are the longest feature with ratios ranging from 0.4 to over 5.0 times the bankfull width. The median is 1.6. Pools and steps are much shorter and the range is less. The range for steps is 0.1 to 1.1 with a median of 0.6. The range for pools is 0.1 to 1.0 with a median of just over 0.2. These values are used in the NCD process to design individual feature lengths. Once the number of pools (from pool spacing ratios) is determined, the feature lengths can be designed. The combined feature lengths can then be compared to the feature percentages.

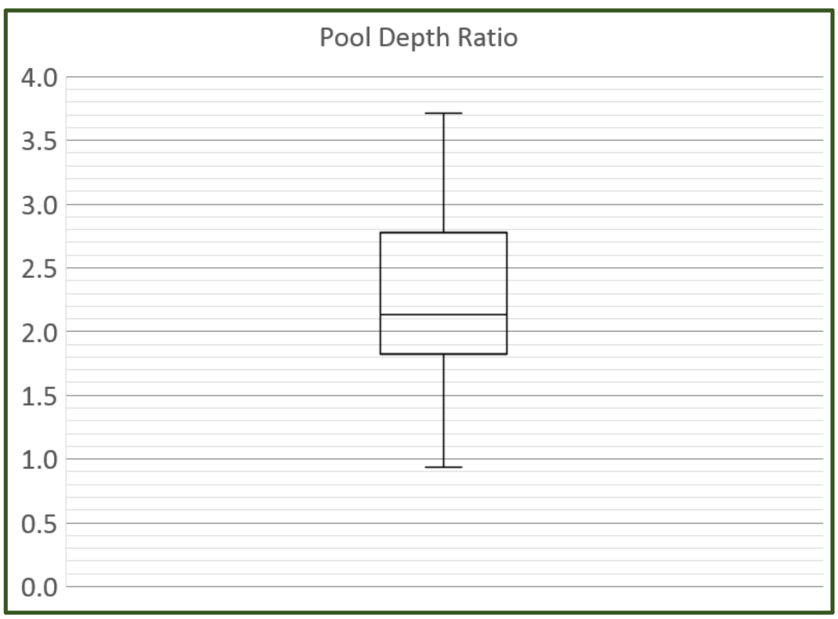
FIGURE 19: Feature length divided by bankfull width.



5.2.4.3 Pool Depth

Figure 20 shows the pool depth ratios, which is the bankfull pool depth divided by the riffle mean depth. The range is just under 1.0 to a max of 3.7 with a median value of 2.1. Values less than one occurred in small streams where the pool depth was limited by bedrock or large bed material. This ratio is used to design the pools depths and more guidance is provided below in the application section.

FIGURE 20: Bankfull pool depth divided by bankfull mean depth.



5.2.4.4 Feature Slope and Step Height

Figure 21 shows the feature slope divided by average channel slope ratios for cascades and pools. Step height divided by bankfull mean depth ratios are shown in Figure 22. A step height ratio is used instead of a slope ratio because steps are short with a near-vertical drop; therefore, lengths are not helpful for design. The actual step height is more useful than the slope. The slope ratio range for cascades is almost equal to the average slope of the channel on the low end with a max of almost two times the average. The median is 0.9, which means that the typical cascade slope is slightly less than the average slope. This is different than what is commonly seen in low gradient streams where the riffle slope is typically steeper than the average slope. The reason is that many of the cascades had steps at the downstream end and the step height/drop is not included in the cascade slope calculation. The very small cascade slope ratios are from steep channels with large steps.

FIGURE 21: Feature slope divided by mean channel slope.

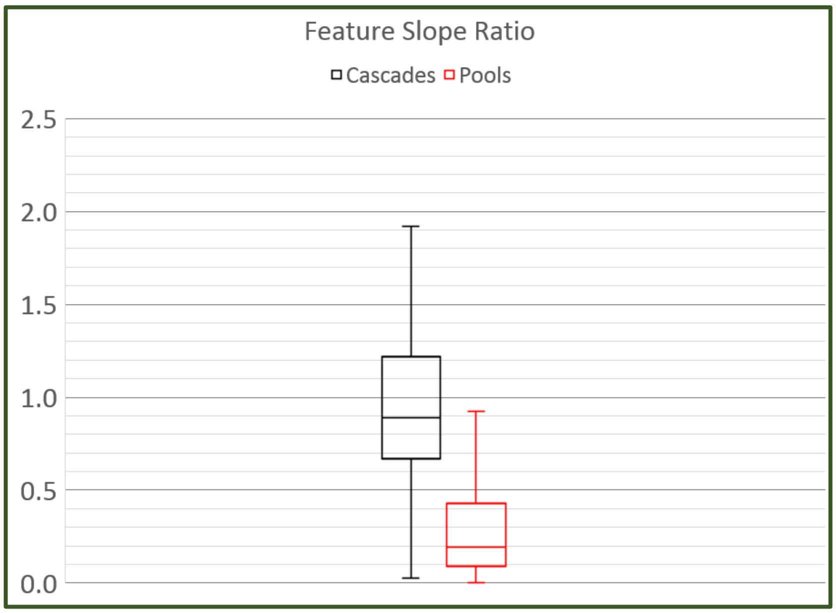


FIGURE 22: **Step height divided by mean riffle depth.**

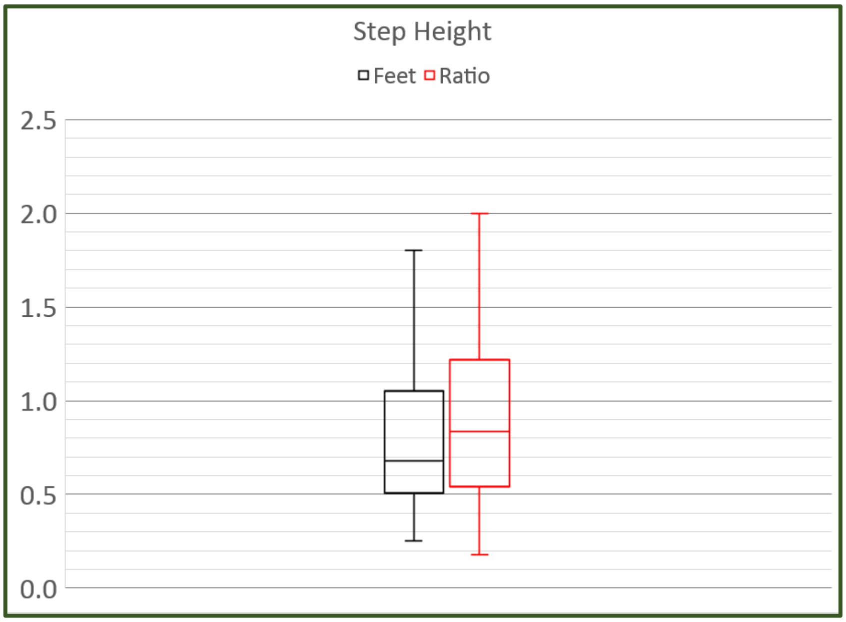


Figure 22 shows the actual step heights and the step height ratios. Actual step heights ranged from 0.3 feet to 1.8 feet while the ratio ranged from 0.2 to 2.0 times the bankfull riffle mean depth. The ratio is the value that would be used to design step heights as part of a NCD project.

5.3 Results of Function-Based Assessment of Nome Creek

Summary results of the function-based assessment of Nome Creek are included below in Table 10. The assessed reach classified as a Rosgen C3 stream type with an average slope of 1.1% and a median particle size of 86mm. The hydraulics category (floodplain connectivity) scored as functioning, meaning these functions are representative of reference conditions. Bed form diversity, lateral stability, and riparian vegetation all scored functioning-at-risk. Therefore, the overall functional capacity for geomorphology is functioning-at-risk. Detailed results of each parameter and measurement method are provided below. The summary information, profiles, cross sections, bed material data, and riparian vegetation list are included in Appendix C.

TABLE 10: **Results of the function-based assessment.**

FUNCTIONAL CATEGORY	FUNCTION-BASED PARAMETER	MEASUREMENT METHOD AND FIELD VALUE	FUNCTIONAL CAPACITY
Hydraulics	Floodplain Connectivity	Bank Height Ratio (<1.1)	Functioning
		Entrenchment Ratio (>3)	
Geomorphology	Bedform Diversity	Pool Spacing Ratio (8.1)	Functioning-At-Risk
		Pool Depth Ratio (2.4)	
		Percent Riffle (83%)	
	Lateral Stability	BEHI/NBS (Moderate/High)	Functioning-At-Risk
		Percent Erosion (23%)	
	Riparian Vegetation	Riparian Width (>50 feet with some bare areas)	Functioning-At-Risk

5.3.1 Hydraulics Functional Category

Floodplain connectivity was assessed as Functioning. The bank height ratio, which is a measure of floodplain inundation was near 1.0 for most of the project length. Figure 23 shows that bankfull is also the top of the streambank for most of the length. There are a few places near the downstream end where the top of bank is slightly above bankfull; however, this difference is not enough to create an incised channel. Once water accesses the floodplain, it can spread across the valley. This yields an entrenchment ratio that is greater than 3.0, meaning that flood flows can spread across a wide valley width (Figure 24).

FIGURE 23: **Longitudinal profile of reclaimed reach in the Nome Creek Watershed.**

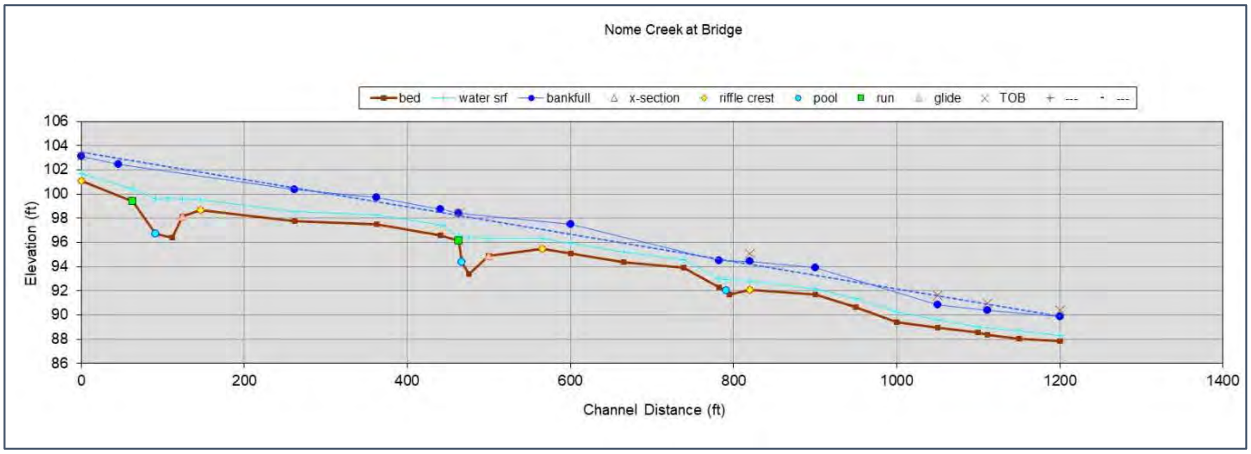


FIGURE 24: **Nome Creek Reach looking upstream towards the bridge. Bankfull is the top of the bank on the right side (looking upstream). Flood flows access the floodplain on both sides of the channel.**

5.3.2 Geomorphology

Three function-based parameters were assessed within the Geomorphology functional category, including bed form diversity, lateral stability, and riparian vegetation. Bed form diversity was assessed by measuring the pool spacing ratio, the pool depth ratio, and the percent riffle (which includes runs). The overall reach length was 1200 feet, and out of this length there were three pools. The first pool was associated with contraction scour through the bridge opening and the other two were lateral-scour pools associated with meander bends. The pool spacing ratios equaled 8.5 and 7.6 for an average of 8.1. There is very little data from Alaska on reference pool spacing ratios from meandering streams in alluvial valleys; however, it is likely that a ratio of 8.1 would be on the high side of what is found in highly functional systems. A ratio of 8.1 would yield a low number of overall pools that could provide fish habitat. Therefore, this metric was determined to be functioning-at-risk.

The three pool depth ratios equaled 3.1, 2.5, and 1.5 with an average value of 2.4. The 3.1 and 2.5 are fairly good values: they show that the pools are considerably deeper than the riffles. A value of 1.5 is not good; the max depth of a riffle is sometimes 1.5 times larger than the mean depth of the riffle, so a pool should be larger. A good value is typically at least 2.0. Therefore, the pool depth ratio was also assessed as functioning-at-risk.

The overall percent of the project reach equaling riffle habitat (which includes the runs) is 83. This means that only 17% of the reach is pool habitat. Like pool spacing, this metric shows that the reach is mostly riffle; not only are there a small number of pools, but they are also small in size. Again, there isn't a lot of data about the reference condition for percent riffle in this region of Alaska, but 83% is the high end of what is expected. Therefore, this metric was also assessed as functioning-at-risk. And, since all three metrics were assessed as functioning-at-risk, the overall assessment for bed form diversity is functioning-at-risk.

The second function-based parameter within the geomorphology functional category is lateral stability. This parameter is assessed using the dominant Bank Erosion Hazard Index with Near Bank Stress (BEHI/NBS), and the overall percent of the reach that is actively eroding. The dominant BEHI/NBS was Moderate/High, which is functioning-at-risk (Figure 25). The overall percent of erosion is 23%, which is not functioning. The overall lateral stability was assessed as functioning-at-risk. This outcome is a result of the channel adjusting laterally at rates that are greater than reference condition streams, which is likely caused by a lower than normal sinuosity for an unconfined, alluvial valley. In other words, the stream is slowly creating a new meander pattern by laterally migrating. Lateral stability was not assessed as not functioning because the rate of adjustment (Moderate BEHI) is not that high. The problem is widespread (23% erosion), but riparian vegetation is increasing, and the rate of erosion is likely decreasing.

FIGURE 25: **First meander bend downstream of bridge. The first half of the right bank scored a High/Moderate rating and the second half scored a Moderate/High Rating.**

Riparian vegetation was assessed by Tom Barrett with Ecosystem Planning and Restoration (EPR). Riparian width and a visual inspection of the riparian vegetation community were the two measurement methods. The left (looking downstream) riparian width was extensive, including the full width of the valley and the terrace. However, there was very little floodplain on the left since the stream was relocated against the valley edge at some point in the past. The riparian vegetation to the right was impacted downstream from the bridge by a parking area and gravel storage facility, presumably for the Alaska Department of Transportation. Downstream of this disturbed area, riparian vegetation extended for the full width of the valley. Where vegetation was present, the riparian communities were typical for this region of Alaska. A plant list is provided in Appendix C.

6.0 APPLICATION OF NATURAL CHANNEL DESIGN TECHNIQUES TO SUB-ARCTIC ALASKA

This section of the report focuses on developing NCD design criteria for sub-arctic Alaska, the foundation of a natural channel design. This report is not a design manual; however, the data and information provided in the report could be used in a future manual. Design criteria are provided for sizing the channel dimension, pattern, and profile. Considerations for hydraulic and sediment transport calculations are also provided. After channel geometry guidance is provided, considerations for vertical and lateral stability structures are provided. Much of this information came from the literature review and evaluation of the Jack Wade Creek demonstration projects. The last section provides thoughts and ideas on techniques that might be used to minimize *aufeis* problems.

The following information is only a guide based on data from the reference reach surveys, monitoring of the demonstration projects, the literature review, and discussions with BLM and mining professionals. Reclaiming streams in harsh climates (and all climates) requires expertise and experience. Adaptive management is common until permanent vegetation is well established. Over time, this information will evolve into best practices for applying Natural Channel techniques in Alaska. The lessons learned presented here represent the beginning of that process.

6.1 Channel Dimension

Past studies and observations from BLM staff show that placer miners place little attention on sizing stream channels for reclamation. Many projects simply use the width of a bulldozer or track hoe to excavate a channel. There is no formal design process. The bankfull regional curves provided in Appendix A can be used as an aid in designing the riffle cross section for reclamation projects. If the miner knows the drainage area to the project reach, the new riffle cross section can be calculated. Ideally, the predicted bankfull riffle area will be validated with bankfull riffle areas from upstream or downstream of the mining area and refined with sediment transport analyses. However, even in the absence of these additional assessments, using a regional curve to determine the riffle area is better than simply using the width of the available equipment.

Once the bankfull riffle area is calculated, the width/depth ratio can be selected from the range shown in Figure 15. The typical range will be between 12 and 19. Width/depth ratios near the lower end should be selected for projects trying to maximize sediment transport capacity. Higher width/depth ratios should be selected for projects concerned about high shear stress values. In other words, if the area is held constant, lowering the width/depth ratio will increase the mean depth, which increases sediment transport competency and therefore capacity.

The top of bank should be designed to equal the bankfull stage, i.e. a bank height ratio of 1.0. All flows greater than bankfull should spread onto a bankfull bench. The entrenchment ratio can be used as an aid in designing the width of the bankfull bench. In general, the bankfull bench should be as wide as possible. However, wider benches should be gently sloped towards the channel. This will help redirect flood waters towards the channel during ice breakup and storm events.

Design of the pool dimension follows the riffle. Pool widths should be about 10 to 30% larger than the riffle. Pools are also deeper than riffles. Figure 20 shows that the typical pool depth is 1.8 to 2.7 times deeper than the average depth of the riffle. The max ratio observed was 3.7. From a design perspective, it is better to use ratios near the higher end of the range to provide more energy dissipation and potential habitat. It's okay for overly deep pools to fill in some during storm events as long as the pools remain at least 1.8 times deeper than the riffles, and preferably greater than 2 times the riffle.

6.2 Pattern

Channel pattern design is the plan form geometry of the channel. In single-thread meandering channels, pattern measurements include sinuosity, meander wavelength, radius of curvature, belt width, and meander arc length. In Rosgen B stream types, the plan form geometry design primarily ensures that the stream is located in the lowest part of the valley. If the valley meanders slightly, the stream will too. However, sinuosity will remain low, e.g. less than 1.2. The other plan form measurements are typically not included in the design process.

Past monitoring from the Demonstration Project 1 in Jack Wade Creek showed that trying to design meandering streams in confined alluvial valleys should be avoided. First, it is much more difficult to design and construct. Second, the risks of lateral adjustment (streambank erosion) is much greater. And third, the additional functional benefit is questionable. Based on lessons from the literature, project tours, and the Demo 1 monitoring, it is recommended that placer-mine reclamation use low sinuosity values and dissipate energy through the profile design, along with the riffle and pool dimension designs as described above.

6.3 Profile

The riffle and pool dimensions along with the channel profile are the crux of a step-pool, B stream type design. The profile is the most complex part of the design and includes pool spacing stratified by cascade-pool and step-pool, riffle and pool length, riffle and pool percentage, and step height designs. Each is discussed below.

6.3.1 Pool Spacing

Pool spacing is the distance between the deepest parts of two consecutive pools. This value is divided by the bankfull width to create the pool spacing ratio. Step-pool channels are not literally a series of steps followed by pools. Step-pool is a generic term for high gradient mountain streams. These systems are actually dominated by riffles or cascades, which often have steps on their downstream end. Less frequently, a single step is between two pools.

Figure 17 can be used as an aid in designing cascade-pool and step-pool sequences. The 25th to 75th percentile range for the pool spacing ratio is roughly 2 to 4. Most cascade-pool sequences should stay within this range. The maximum value shown on Figure 17 for cascade-pool sequences is 6. It is reasonable for a small number of sequences per design reach to use a value of 6; however, it should not be used as the single design value. Using the max value of 6 for all spacings increases the risk of head-cutting (especially in newly built channels), reduces the number of pools per reach, and thereby reduces aquatic habitat.

The majority of the reach should include cascade-pool or cascade-step-pool sequences. A cascade-step-pool is a cascade with a step at the downstream end. A few step-pool sequences can be included within the reach to provide heterogeneity. Pool spacing with a step between the two pools is obviously shorter than cascades. Step-pool ratios range from 0.2 to 1.0. Unlike cascades, there is little risk in using the full range.

6.3.2 Feature Percentage

Three features are included in the profile design: the cascade/riffle, pool, and step. It is critical that the cascade/riffle feature have the highest percentage of length, followed by the pools and then the steps. Figure 18 can be used as a guide for designing the feature lengths, and then figure 19 can be used to determine if the design percentages fall within an appropriate range. Figure 18 shows that the median values for feature length percentage are approximately 63% cascade, 30% pool, and 7% step. It is more important to adhere to the cascade and pool percentages than the step percentage. The cascade percentage can vary; however, it should typically stay within the range of 55 to 75 percent in order to provide vertical stability and enough pools for adequate fish habitat.

6.3.3 Feature Slope and Step Height

Typically, cascade and pool slopes are tested after the overall profile has been designed. This means that the pool spacing, feature lengths, and feature percentages are designed and then the cascade and pool slopes are measured to ensure that they are within an appropriate range. Figure 21 shows the range in feature slope ratios, which is the feature slope divided by the average channel slope. The range of cascade slope ratio is 0.2 to 1.8. A value of 1.0 means that the cascade slope is equal to the average slope. Values less than 1.0 are flatter than the average slope. Typically, values of 1.0 or less will only be used if steps are designed for the lower end. In other words, much of the elevation loss is occurring over the step and a smaller portion over the length of the cascade. This combination of a cascade followed by a step reduces the risk of bed erosion over the cascade. The lower slope over the cascade reduces the shear stress and the step helps to provide grade control. As ratios increase above 1.0 the shear stress over the cascade also increases. To remain stable, these steeper cascades should have larger particle sizes. The construction of cascades and particle-size determination is discussed in more detail under the Constructed Cascade section.

It is generally easier to design step heights using the actual step height (in feet) rather than the ratio (Figure 22). The range of step heights observed was 0.3 to 1.8 feet. It is less risky to use lower step heights from a structure integrity / bed stability perspective. However, if the step height is too low, the downstream pool scour may be minimal. Generally, step heights should stay between 0.5 and 1.0 feet to help provide structure stability and pool quality.

6.4 Hydraulics and Sediment Transport

Table 8 provides a summary of the bankfull velocities, shear stresses, and stream power values for the reference sites. The average bankfull velocity of 4.7 ft/s is typical of alluvial- and colluvial-valley streams. Natural channel designs should aim for bankfull velocities that are close to this value. As the bankfull velocity increases, the potential for bed and bank erosion also increases. As the velocity decreases, the risk of aggradation increases. Aggradation is less of a concern than degradation in placer-mined streams in colluvial valleys.

The shear stress values shown in Table 8 are high due to the high channel slopes. It is not recommended that these values be automatically used in the design process. Designers should compare the design depth and slope to the grain-size distribution of the riffle material. As discussed in the Bankfull Hydraulics section above, the reference riffles are almost always of cobble size material with boulders spread throughout. The boulders help prevent the underlying cobble and gravel from becoming mobile. Placer-mined streams often remove the boulders and large cobble. They also introduce a lot of sand, making the beds even more mobile. Designs should seek to minimize the shear stress and or bolster the grain sizes of the cascades/riffles while maintaining sediment transport processes. More discussion about armoring cascades/riffles is provided below in the Constructed Cascade section.

6.5 Vertical Stability Structures

Designing a proper channel and floodplain bench dimension along with a cascade-step-pool profile are key elements in providing vertical stability; however, it may not be enough in highly modified placer-mined valleys. The grain-size distribution has been severely altered and all riparian vegetation has been removed such that sediment supply and bed mobility is high to extreme. As watersheds become more extensively mined, the risk increases. All of this means that some type of constructed grade control will be a routine part of the design process. Recommended structures include constructed cascades/riffles, steps, and in some cases log rollers and sills. Cross vanes and grade-control J-hook vanes are common grade control structures in NCD. However, these structures are not recommended in placer-mine reclamation due to their design and construction complexity. Each recommended structure is described below.

6.5.1 Constructed Cascades

Constructed cascades and riffles should be the primary method for providing grade control on placer-mine reclamation sites. These structures should include bed material sizes that are a mix of gravel, cobble, and boulders; however, the majority of the structure should be cobble and boulder sized particles. Care should be taken in sizing the cascade/riffle material and the design should consult appropriate design manuals for sizing rock. One design guide is the USDA-NRCS National Engineering Handbook, Part 654, Technical Supplement 14G: Grade Stabilization Techniques. The section titled “Rock Sizing for Loose Rock Structures,” starting on page TS14G-7 may be beneficial.

Monitoring from the Jack Wade Creek demonstration projects show that constructed cascades can be an effective method of providing grade control if they are constructed properly. These lessons learned have led to the following design criteria, which should be used in conjunction with rock sizing procedures.

1. The structure should extend well below the bed elevation and extend beyond the channel width. Generally, the structure depth should be 18 to 24 inches below the bed elevation and extend beyond the bankfull width, with more width being preferred.

2. Boulder sills should be used near the top, middle, and downstream end of the cascade, and these rocks should be placed first. The downstream sill can serve as a step.
3. Cobble should be placed after boulders with gravel supplied last. The material should be "washed in" by dipping a track hoe bucket into a water source.
4. Filter fabric may be placed on the upstream side of the cascade/riffle. This may help prevent stone transport/erosion under the sill.

Figure 26 shows a natural cascade with a mixture of gravel, cobble, and boulders. Figure 27 shows a constructed cascade using quarried boulders and onsite cobble. Miners can often use onsite boulders salvaged during the mining process.

FIGURE 26: **Natural cascade.**

FIGURE 27: **Constructed cascade.**

6.5.2 Steps

Boulder steps should be placed on the downstream end of most cascades to reduce cascade slope and to create a plunge into the pool. The step also provides grade control for the cascade. In addition, steps can sometimes be used to create a step-pool sequence, which is two pools separated by one step. However, this sequence should not be used as often as the cascade-pool sequence. Figure 27 shows a cascade-step-pool sequence and figure 28 shows a step-pool sequence. Each step should include a footer rock below the top rock and splash rocks downstream of the step. The steps should be lower in the center of the channel and slightly higher near the bank. And the structure should arc slightly, so the invert is farther upstream than tie-in to the bank.

FIGURE 28: **Constructed step-pool structure.**

6.5.3 Log Rollers and Sills

Log rollers and sills can be used in perennial streams to supplement cascade- and step-pool structures. They should not be the primary method used to provide grade control. A log roller includes two logs that span the bankfull width. The top log is at or near the streambed elevation and the footer log is buried. Filter fabric is secured to the upstream side of the log. The logs are angled upstream and have a low slope, making them more difficult to construct than a constructed cascade/riffle. This orientation rolls water away from one bank and towards the opposite bank. Typically, the bank receiving the flow is excavated away from the channel and protected with bank stabilization methods. A second set of logs is placed downstream to roll the water back towards the center of the channel. An example of a log roller is shown in Figure 29.

FIGURE 29: **Constructed Log Roller.**

Log sills can be used to occasionally replace a step structure. This technique works best on the downstream end of a cascade. Two logs and filter fabric are used as described above.

6.6 Lateral Stability Structures

Lateral stability is necessary in reclaimed placer-mining sites to maintain channel dimension, reduce sediment supply from bank erosion, and prevent the channel from migrating into un-vegetated areas. The primary method for providing bank stability is the use of transplants. Secondary methods include bioengineering techniques.

All of these methods are used to provide lateral stability in low sinuosity, step-pool channels. As mentioned under the pattern section, it is not recommended that placer-mine reclamation include a meandering design. Meandering designs will include additional methods to provide lateral stability along the outside meander bend.

6.6.1 Transplants

Transplanted vegetation includes the root mass of woody vegetation along with associated herbaceous vegetation. Lessons learned from the demonstration projects show that young willows growing within a herbaceous mat work best. However, larger willows, alders, and even trees such as birch mixed with black spruce have been successfully transplanted. Based on the monitoring and lessons learned from the demonstration projects, the following design criteria are suggested. An example of the transplanting operation is shown in Figure 30.

1. Transplants should be harvested near the project site. If possible, transplants should be moved once with a large wheel-loader. Mining operations are encouraged to move transplants directly from new mining areas to the reclamation area.
2. Do not cut too far below the root zone, but make sure all of the root zone is acquired. Willow roots only grow to a depth of approximately one foot. So, a cut depth of 1 to 1.3 feet is typical. If the cut depth is too deep, then sand, gravel, and soil is transferred to the bank

site. The result is that the transplant is too high, and the erodible mixture of sediment is near the toe of the bank.

3. For banks that are more than 1-foot tall, transplants should be stacked in a shingle-like format to achieve the final bank elevation. Care should be taken to ensure that the design depth is not exceeded. This creates an incised channel.
4. The toe and top seams of the transplants should be covered with soil or sediment.

FIGURE 30: **Transplanting with a wheel- loader. After the transplants are placed, a track hoe is used to finalize their placement, cover the seams, and to meet grade requirements.**

Figure 31 shows a transplanted bank with a floodplain bench after a bankfull event. The transplants and bench reduce floodplain velocities, thereby creating deposition. This deposition further fills in the seams between transplants making them stronger for the next event.

FIGURE 31: **Transplanted vegetation and deposition after a bankfull event.**

Transplanted vegetation is a critical component of successful reclamation projects. It is strongly recommended that all projects, if possible, include transplants. Maintaining lateral stability in placer-mined valleys without the use of transplants will have a much higher risk of channel erosion.

6.6.2 Bioengineering

Bioengineering methods are useful additions to transplants. Methods used in the demonstration projects included brush mattresses, brush layers, and live staking. Design guidance is provided in the USDA-NRCS National Engineering Handbook, Part 654, Technical Supplement 14I: Streambank Soil Bioengineering. Example photos from the demonstration projects are shown in Figure 32 through 33.

FIGURE 32: **Brush mattress used to provide bank roughness and support faster re-growth of vegetation. The brush mattresses extend below the floodplain bench into the water table.**

FIGURE 33: **Live stakes. Live stakes are used to help secure transplants, but more importantly, to speed up the re-establishment of woody vegetation along the streambank.**

6.7 Techniques to Potentially Minimize Aufeis

One key component of this project was to investigate how *aufeis* can be managed on placer-mine reclamation projects. This was done by completing a literature review of *aufeis* and permafrost hydrology, assessing reference condition and mined streams in the Nome Creek Watershed, which is an area known to have *aufeis*, and evaluating results of past reclamation projects, including the demonstration projects in the Jack Wade Creek Watershed.

The literature review showed that *aufeis* is of greatest concern in disturbed landscapes, such as placer mines. The primary cause is the conversion of subsurface flow to overland flow by the removal of vegetation and excavation activities. Mines remove vegetation that can provide insulation to the underlying water and intercept springs along the toe of hillslopes. These springs bring water from the subsurface to the surface where it can freeze and build. Furthermore, river icings can exacerbate streambank erosion during breakup because the riparian vegetation has been removed. In addition, the reclaimed valley includes a mixture of unconsolidated sands, gravels, and cobble. Without riparian vegetation, this material is highly erodible.

The reference streams in the Nome Creek Watershed were vertically and laterally stable, even though icings were present. Stability is provided by intact cascade-step-pool sequences that provide vertical grade control and riparian vegetation communities along the streambanks and valley bottoms. The coarse streambeds and vegetated banks provide considerable resistance to erosional forces. In addition, based on the literature review, these reference streams probably experience less *aufeis* than the disturbed portions of Nome Creek; however, additional research would need to confirm this.

Lessons learned from touring past reclamation sites and monitoring the demonstration projects shows that instability is caused by a combination of *aufeis* breakup and summer rain events. In fact, it appears that some of the worst problems have resulted more from rain events than *aufeis* break up. This outcome was observed in the Karle and Densmore (1994) report and the monitoring from the Jack Wade Creek Demo 1 site. However, severe instability problems have been observed near Coldfoot from *aufeis* buildup. So, as recommendations are developed, it is important to consider that instability can be caused by both processes: *aufeis* buildup and breakup, and summer rain events.

Based on the literature review, assessments from Nome Creek, and observations and monitoring from past projects, the following ideas are proposed. These ideas should be considered experimental with the goal of trying to minimize the flow of ground water to the surface. Vertical and lateral stability will also help during ice and rain events, and they are discussed in the above section.

6.7.1 Talik Re-establishment

The number one priority in minimizing the development of *aufeis* is to restore a talik zone and thereby minimize the amount of groundwater that reaches the land surface where it can freeze. During the reclamation process, all springs and seeps should be identified. These features are often found along the toe of the hillslope, or the margin between mine excavation and an intact hillslope. If possible, an investigation of the hillslope/valley transition should be made prior to mining to map the presence of any springs with side channels delivering water to the main channel. These springs and channels may be perennial features that need to be re-established during reclamation. However, all new springs bringing subsurface flow to the surface created during the mining process should be buried. This reclamation process includes re-grading the floodplain to an approximate original contour that includes material along the hillslope/valley transition. The goal is to allow subsurface flow from the hillslope/uplands to remain as subsurface flow as it travels towards the channel. In many cases, this will mean filling the valley and mined channel so that the streambed elevation is above bedrock (if bedrock is present).

6.7.2 Toe of Hillslope Swales and Pools

In some cases, it may not be feasible to return created springs back to subsurface flow. An example is a spring and the attendant overland flow brought to the surface by an adjacent road cut. For those instances in mine reclamation where created springs cannot be buried, a different technique than re-establishing the talik zone is needed. One option might be creating toe of hillslope swales and pools. This technique would involve creating a shallow swale with perhaps a series of connected pools. The pools would provide a place for water and ice to be stored in a low-energy environment. A swale connecting the pools would provide summer drainage from the toe of slope to the main-stem channel. Obviously, this technique is only an option in valleys that are wide enough to fit the swales with pools, a vegetated riparian corridor, and the stream channel. It will not work in highly confined valleys. In these settings, it’s probably best to tie the springs into the main channel with a side channel.

6.7.3 Floodplain Vegetation and Roughness

Once the talik zone has been re-established, transplants should be used along the entire length of the stream channel to provide lateral stability. In addition, the valley bottom should be re-vegetated with transplants to the extent possible. In most cases, there will not be a large enough supply of transplants to cover the entire valley bottom. The next best alternative is to transplant rows across the valley, perpendicular to the flood flow. These rows should include buried spruce trees that extend from the bedrock or max cut depth to the bottom of the transplants. A few inches of sand/gravel/soil mix should be placed over the trees. The transplants are placed next and extend to the ground elevation. Care should be taken to ensure that the root mass of the transplants is below the ground elevation. The width of the transplanted row should be enough to prevent the transplants from being displaced during flood events.

To provide further floodplain roughness, whole black spruce trees should be placed in a zig zag pattern between the transplanted rows. The trees can be anchored with boulders. A riparian seed mix should be used to help re-establish vegetation between the transplant rows.

7.0 CONCLUSIONS AND RECOMMENDATIONS

The scope of this project was multi-pronged. A literature review was completed to summarize the processes governing hydrology in a sub-arctic environment, and to illustrate how *aufeis* formation may inhibit the success of placer-mine reclamation as required by BLM policy. A second, and more focused, component of the project was to develop design criteria that could be used to improve placer-mine reclamation in sub-Arctic Alaska. Design criteria development included the development of bankfull regional curves to assist with designing the appropriate channel size and reference reach surveys to help design the channel profile through a cascade-step-pool sequence. Together, the dimension and profile designs are critical natural channel design elements needed for successful placer-mine reclamation in confined valleys.

Key findings from this project are provided below and followed by recommendations for the BLM to consider as the evolution towards better reclamation continues.

7.1 KEY FINDINGS

- *Aufeis* is exacerbated in disturbed landscapes like placer mines. This was evident in the literature and shown on many placer mine sites on BLM-managed land.
- Many of the early natural channel design failures did not follow the design process. Most of the early projects did not use bankfull regional curves. Early projects also did not use transplants or develop design criteria for establishing an appropriate cascade-step-pool sequence.
- Fining of the bed material from mining processes may contribute to reclamation failure.
- Reference condition streams (un-mined) in the Nome Creek Watershed, which is known to have *aufeis*, were vertically and laterally stable with a well-established cascade-step-pool sequence. These streams, along with reference reaches from Denali and the Valdez Creek area, can be used as a design aid.
- Using transplants along streambanks is critical for providing lateral stability and long-term success. Projects that do not use transplants have a high risk of failure.
- Rainfall-runoff can be as problematic, and maybe more problematic than *aufeis* for long term stability.
- Reclamation projects using a meandering-design approach are less successful than those using a step-pool approach.
- Talik zones are important for minimizing the development of *aufeis*.
- Adaptive management will be required for most projects.

7.2 Recommendations

- Use the bankfull regional curves provided in Appendix A, or develop site-specific regional curves, for sizing the riffle dimension of the reclaimed channel.
- Use the design criteria outlined in this report to design the pool dimension and profile. Risk can be further reduced by performing sediment transport competency and capacity analyses.
- Avoid meandering designs in placer mine reclamation projects unless the valley is unconfined with less than 1% slope. Even then, the project will require experienced designers.
- Re-establish talik zones in areas susceptible to *aufeis*.
- Use transplanted vegetation along all streambanks. If possible, transplant the entire valley bottom. If the entire valley cannot be transplanted, create transplant rows with black spruce in between.
- Finally, create a dedicated BLM stream team to continue developing and refining design criteria and to assist miners with designs, channel and structure layout, and construction methods. This work is complicated and BLM hydrologists, fish biologists, and engineers are gaining valuable experience that can improve reclamation success.

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APPENDICES

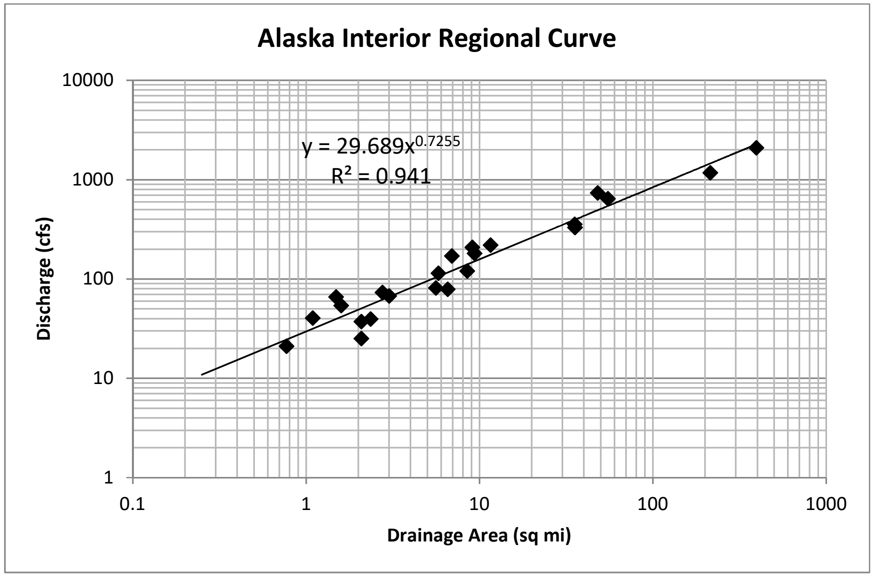
Bankfull Regional Curves

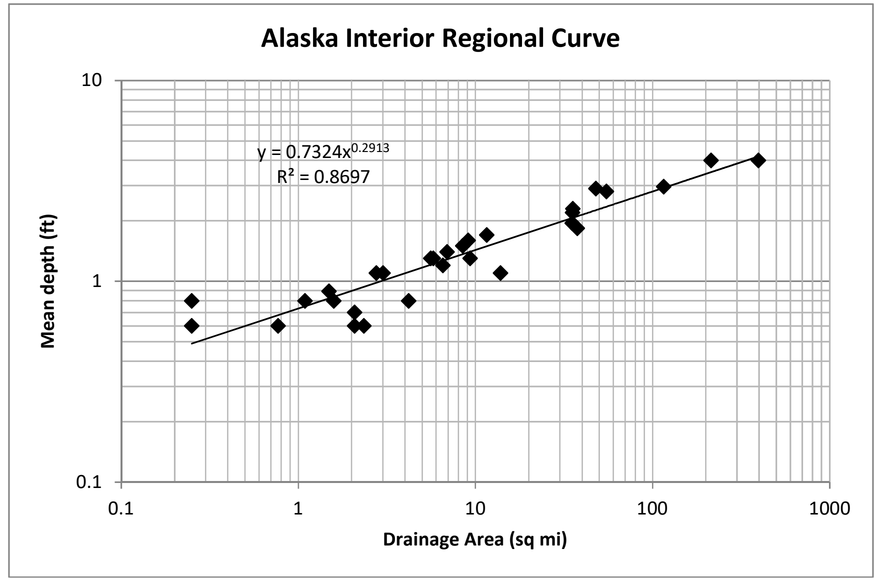
Reference Reach Data

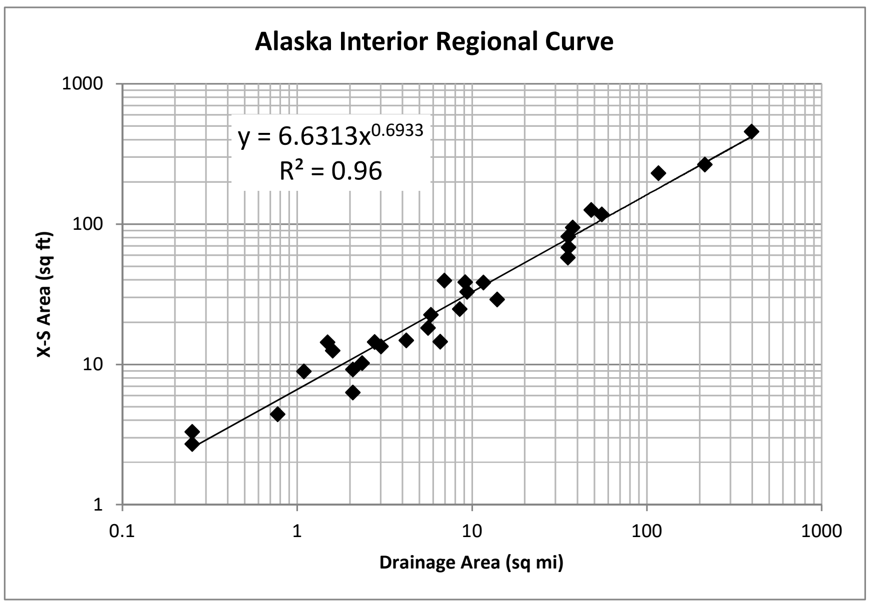
Results from Nome Creek Function-Based Assessment

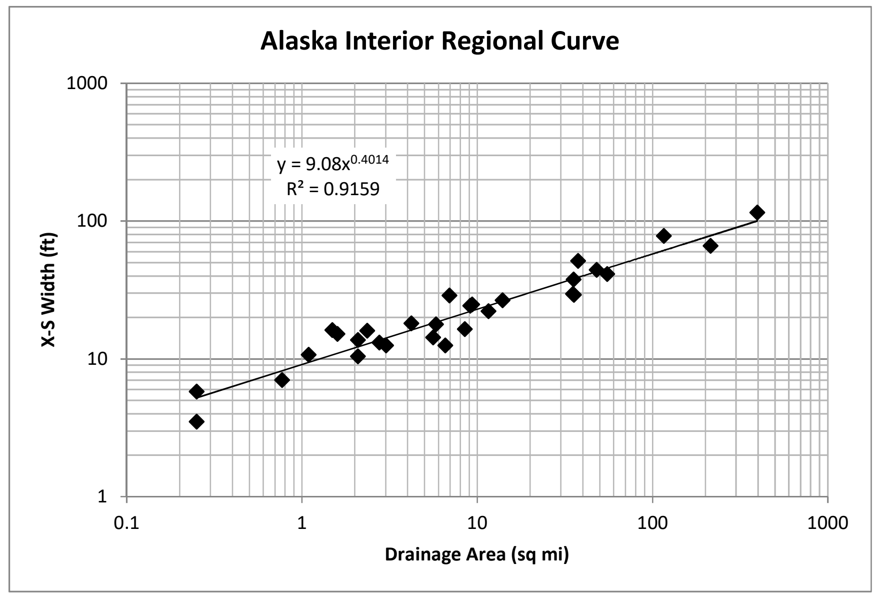
Appendix A

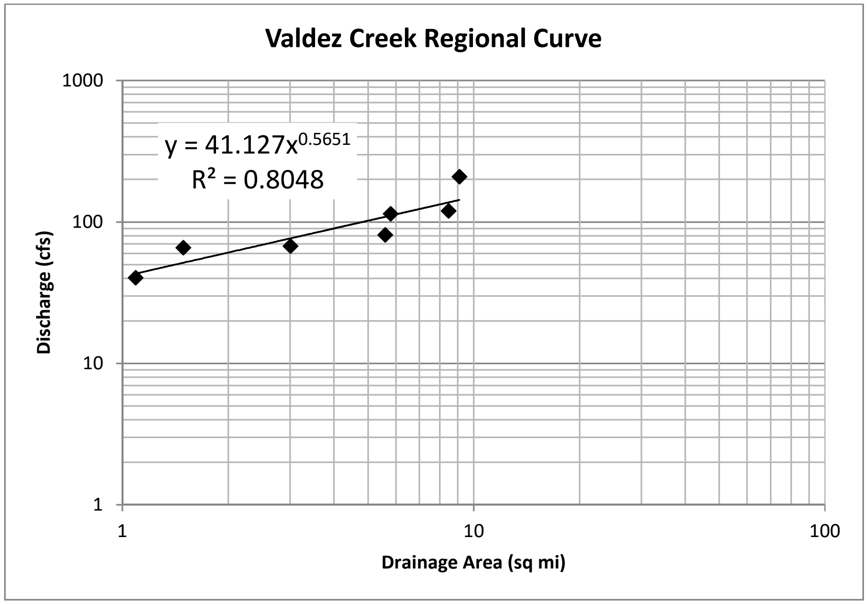
Bankfull Regional Curves

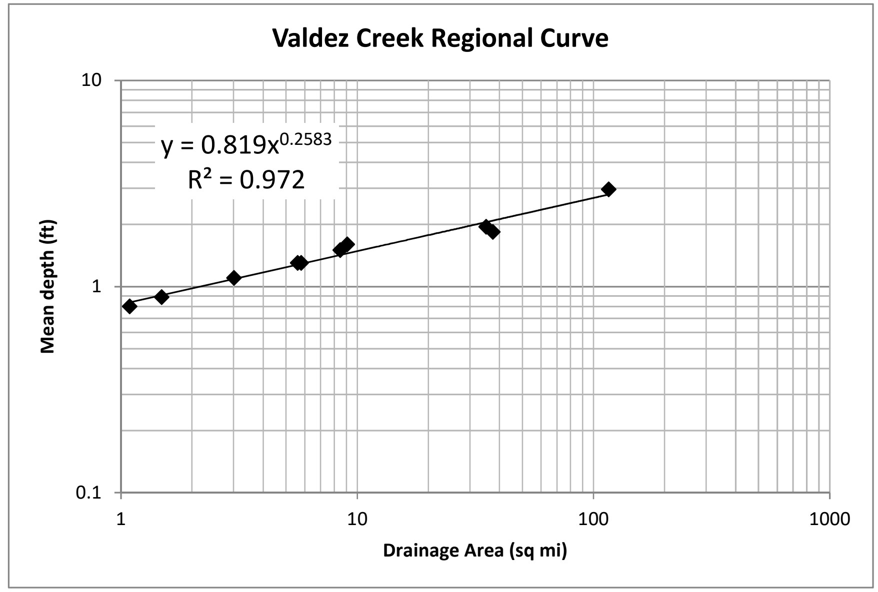

Alaska Interior Regional Curve
y = 29.689x^0.7255
R² = 0.941
Discharge (cfs)
Drainage Area (sq mi)
10000
1000
100
10
1
0.1
1
10
100
1000

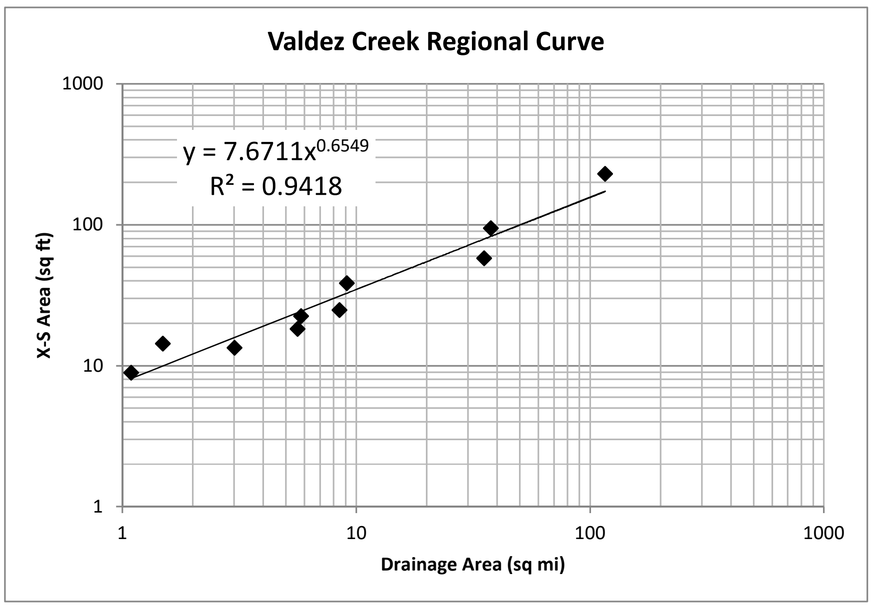

Alaska Interior Regional Curve
y = 0.7324x^0.2913
R² = 0.8697
Mean depth (ft)
Drainage Area (sq mi)
10
1
0.1
0.1
1
10
100
1000

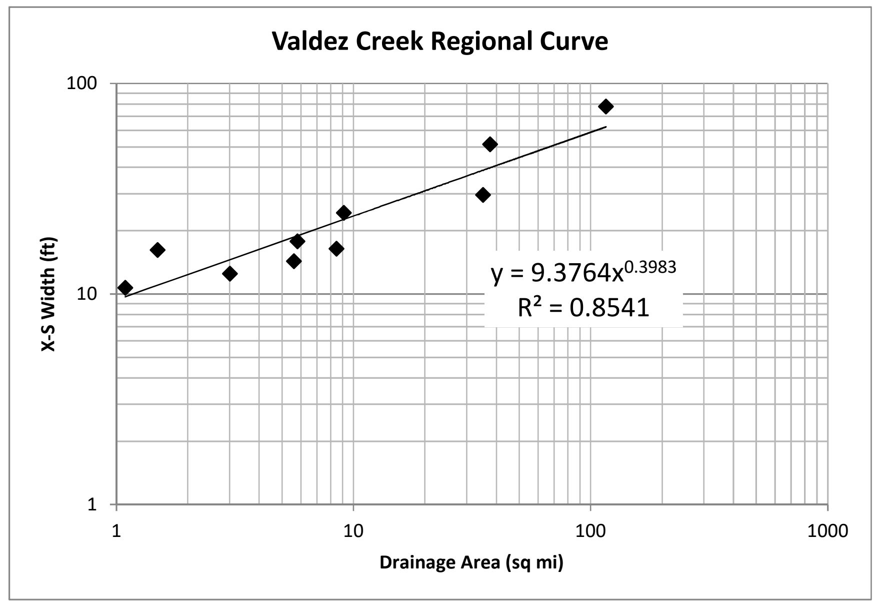

Alaska Interior Regional Curve
y = 6.6313x^0.6933
R² = 0.96
X-S Area (sq ft)
Drainage Area (sq mi)
1000
100
10
1
0.1
1
10
100
1000

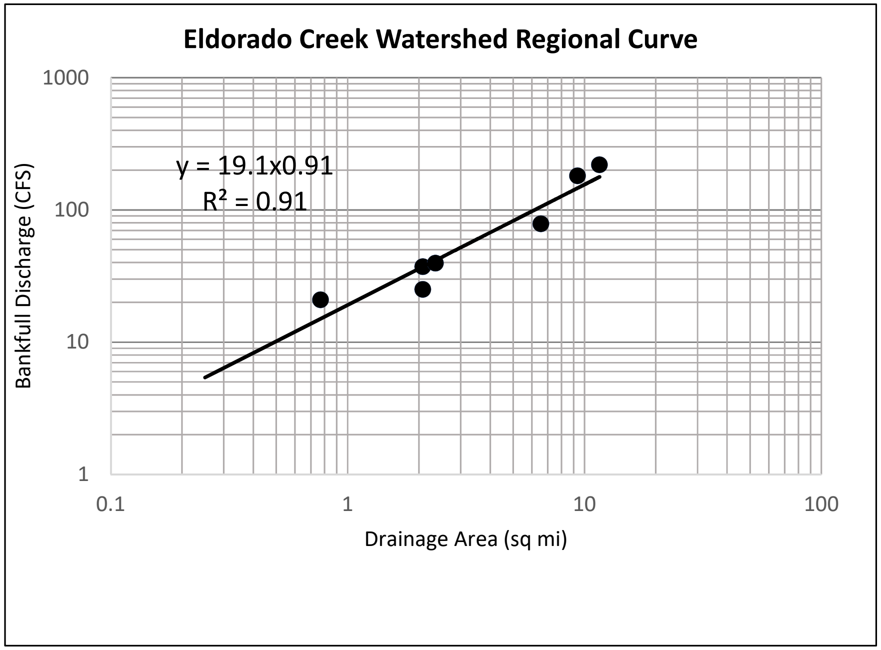

Alaska Interior Regional Curve
y = 9.08x^0.4014
R² = 0.9159
X-S Width (ft)
Drainage Area (sq mi)
1000
100
10
1
0.1
1
10
100
1000

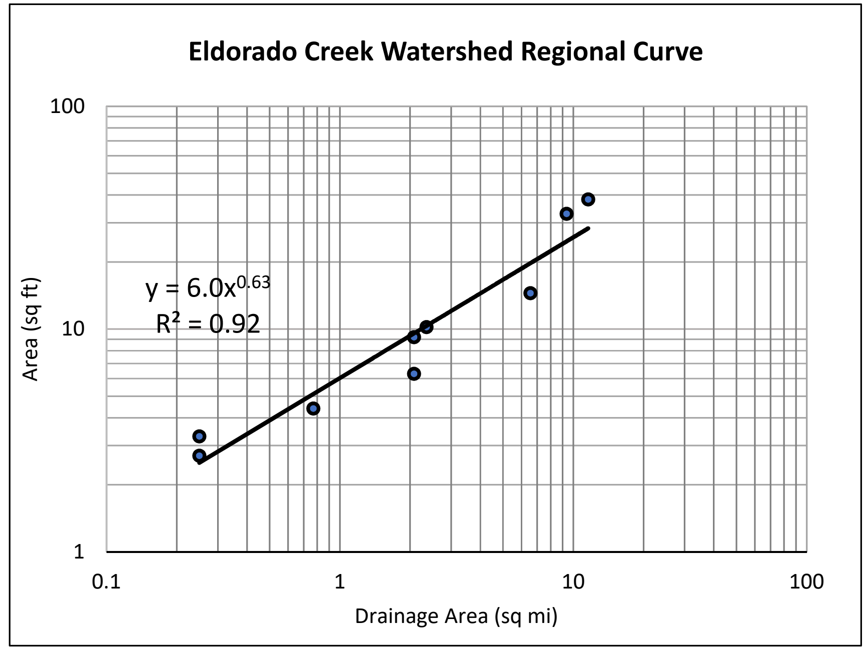

Valdez Creek Regional Curve
y = 41.127x^0.5651
R² = 0.8048
Discharge (cfs)
Drainage Area (sq mi)
1000
100
10
1
1
10
100

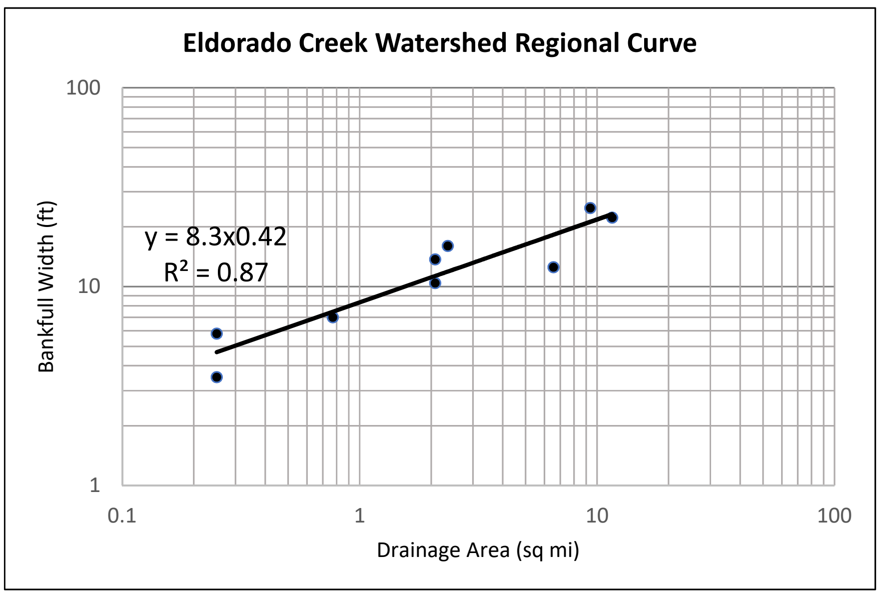

Valdez Creek Regional Curve
y = 0.819x^0.2583
R² = 0.972
Mean depth (ft)
Drainage Area (sq mi)
10
1
0.1
1
10
100
1000

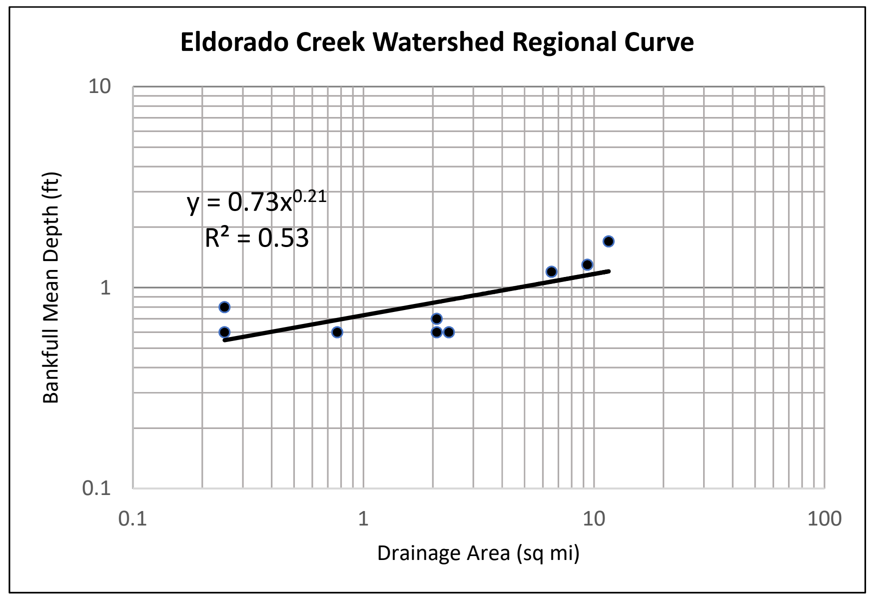

Valdez Creek Regional Curve
y = 7.6711x^0.6549
R² = 0.9418
X-S Area (sq ft)
Drainage Area (sq mi)
1000
100
10
1
1
10
100
1000

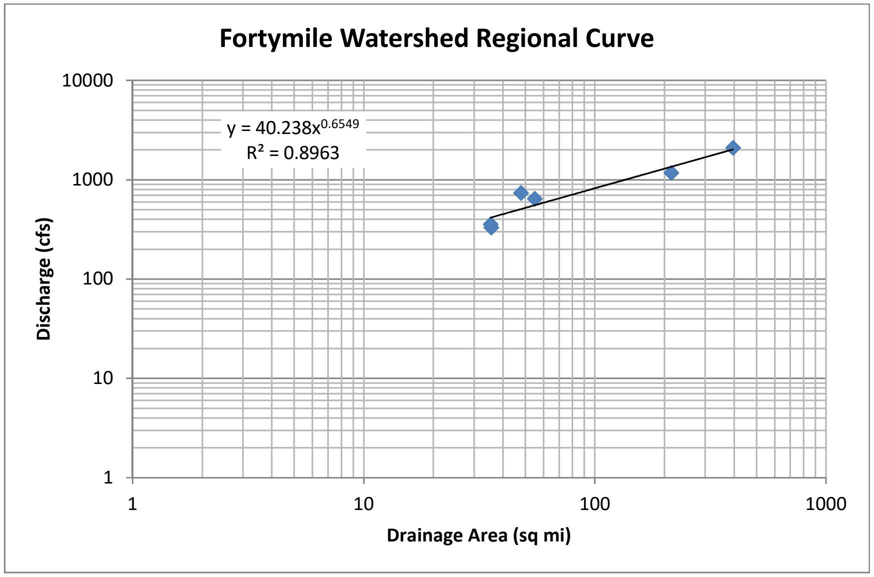

Valdez Creek Regional Curve
y = 9.3764x^0.3983
R² = 0.8541
X-S Width (ft)
Drainage Area (sq mi)
100
10
1
1
10
100
1000

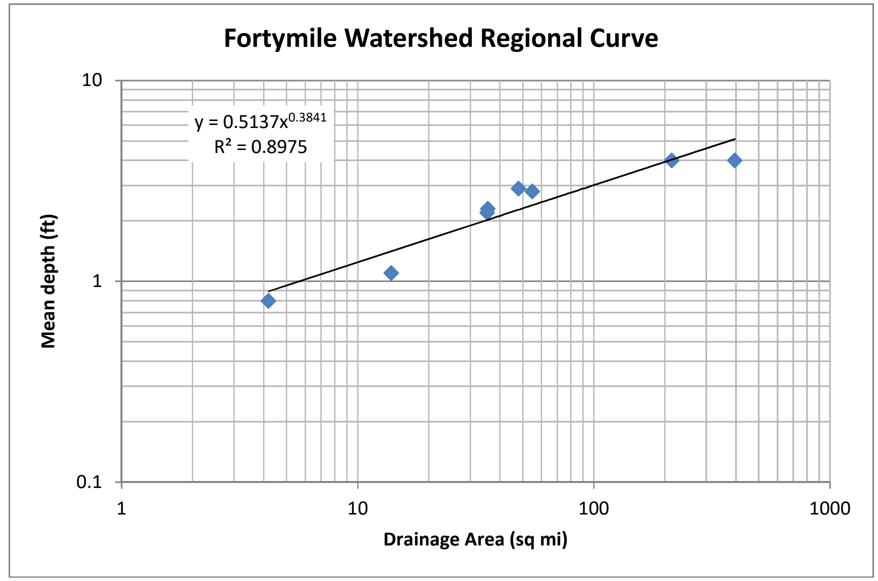

Eldorado Creek Watershed Regional Curve
y = 19.1x0.91
R² = 0.91
Bankfull Discharge (CFS)
1000
100
10
1
0.1
1
10
100
Drainage Area (sq mi)

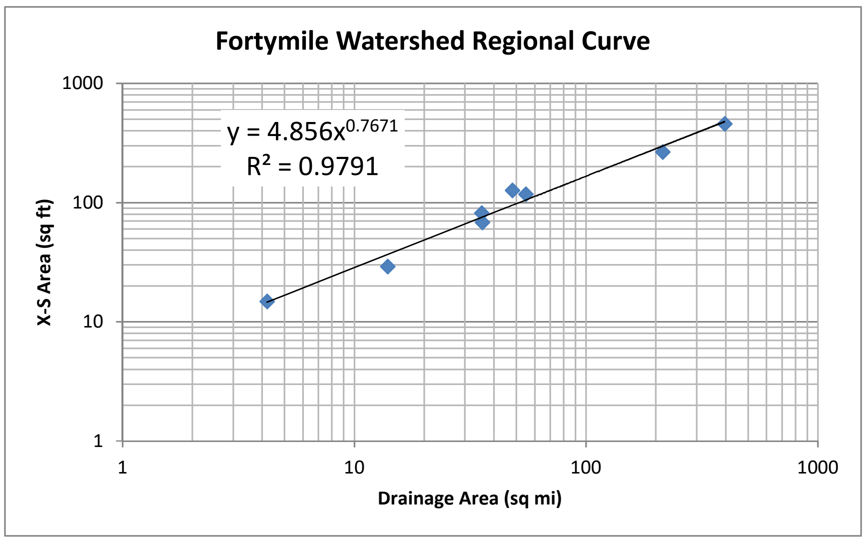

Eldorado Creek Watershed Regional Curve
y = 6.0x^0.63
R² = 0.92
Area (sq ft)
100
10
1
0.1
1
10
100
Drainage Area (sq mi)

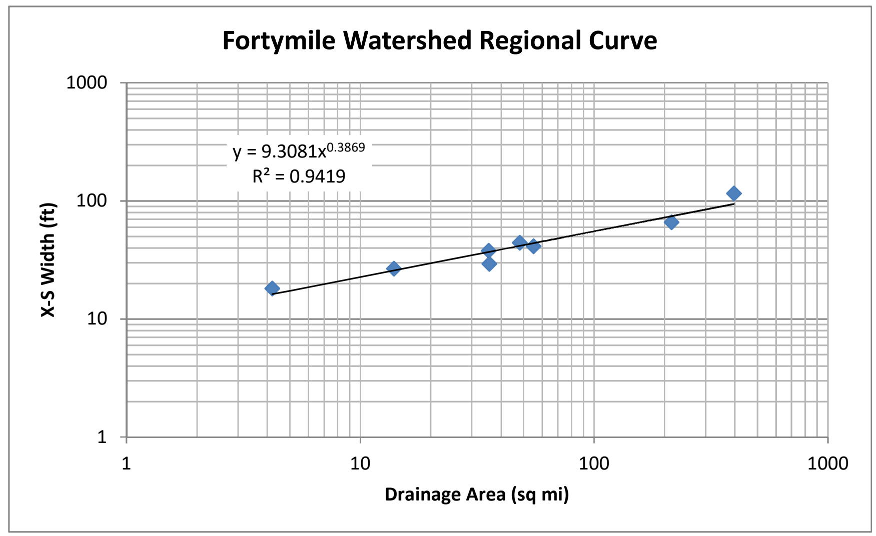

Eldorado Creek Watershed Regional Curve
y = 8.3x0.42
R² = 0.87
Bankfull Width (ft)
100
10
1
0.1
1
10
100
Drainage Area (sq mi)


Eldorado Creek Watershed Regional Curve
y = 0.73x^0.21
R² = 0.53
Bankfull Mean Depth (ft)
10
1
0.1
0.1
1
10
100
Drainage Area (sq mi)


Fortymile Watershed Regional Curve
y = 40.238x^0.6549
R² = 0.8963
Discharge (cfs)
Drainage Area (sq mi)
10000
1000
100
10
1
1
10
100
1000


Fortymile Watershed Regional Curve
y = 0.5137x^0.3841
R² = 0.8975
Mean depth (ft)
Drainage Area (sq mi)
10
1
0.1
1
10
100
1000


Fortymile Watershed Regional Curve
y = 4.856x^0.7671
R² = 0.9791
X-S Area (sq ft)
Drainage Area (sq mi)
1000
100
10
1
1
10
100
1000


Fortymile Watershed Regional Curve
y = 9.3081x^0.3869
R² = 0.9419
X-S Width (ft)
Drainage Area (sq mi)
1000
100
10
1
1
10
100
1000

Appendix B

Reference Reach Data

Mountain Streams Bedform Diversity Data							
Master Spreadsheet							
State	Stream	Region	Lat	Long	Stream	DA	Slope
	Name				Type	Sqmi	ft/ft
AK	Eldorado Above Canyon	Eldorado Creek Watershed	63.51347	-151.00345	B4	11.58	0.025
AK	Iron Creek Middle	Eldorado Creek Watershed	63.497133	-151.010133	C3b	2.08	0.073
AK	Iron Creek near confluence	Eldorado Creek Watershed	63.49891	-151.01909	B3	2.35	0.049
AK	Reinhart	Eldorado Creek Watershed	63.50341	-151.0219	B3a	0.77	0.101
AK	Little Champion	Nome Creek Watershed	65.44068	-146.59739	B3a	1.59	0.063
AK	Nome Creek Above Campground	Nome Creek Watershed	65.38548	-146.56815	B3	6.92	0.027
AK	Nome Creek Trib	Nome Creek Watershed	65.36995	-146.5763	B3a	2.76	0.044
AK	Eldorado Upper	Valdez Creek Watershed	63.14867	-147.21634	B3a	1.09	0.081
AK	Eldorado Lower	Valdez Creek Watershed	63.15166	-147.21587	B4a	1.49	0.069
AK	Lily Creek Upper	Valdez Creek Watershed	63.33443	-148.27249	B3a	5.8	0.054
AK	Rusty Creek	Valdez Creek Watershed	63.19318	-147.32391	B3a	3.01	0.062

Mountain Streams Bedform Diversity Data										
Master Spreadsheet										
		Riffle Bed Material				**Representative Riffle**				
State	Stream	D16	D50	D84	D95	Area	Width	Dmax	Mean D	Dmax
	Name	mm	mm	mm	mm	Sqft	Ft	Ft	Ft	Ratio
AK	Eldorado Above Canyon	7.1	29	90	210	38.2	22.2	2.6	1.7	1.5
AK	Iron Creek Middle	65	130	400	800	6.3	10.4	1.2	0.6	2.0
AK	Iron Creek near confluence	50	120	260	410	10.2	16	1.6	0.6	2.7
AK	Reinhart	15	89	260	360	4.4	7	1.1	0.6	1.8
AK	Little Champion	41	100	220	360	12.5	15.2	1.3	0.8	1.6
AK	Nome Creek Above Campground	80	160	280	510	39.6	28.8	1.8	1.4	1.3
AK	Nome Creek Trib	64	120	210	330	14.4	13.1	1.5	1.1	1.4
AK	Eldorado Upper	22	84	240	360	8.9	10.7	1.1	0.8	1.4
AK	Eldorado Lower	24	51	110	200	14.2	16.1	1.3	0.9	1.4
AK	Lily Creek Upper	40	87	290	570	22.5	17.8	2	1.3	1.5
AK	Rusty Creek	37	78	210	350	13.4	12.5	1.6	1.1	1.5

Mountain Streams Bedform Diversity Data			
Master Spreadsheet			
State	Stream	W/D	ER
	Name	Ratio	
AK	Eldorado Above Canyon	13	1.5
AK	Iron Creek Middle	17	2.8
AK	Iron Creek near confluence	26.7	2.2
AK	Reinhart	11.7	1.6
AK	Little Champion	19	2.2
AK	Nome Creek Above Campground	21	1.8
AK	Nome Creek Trib	12	2.2
AK	Eldorado Upper	13	2.3
AK	Eldorado Lower	18	1.4
AK	Lily Creek Upper	14	1.7
AK	Rusty Creek	11	4

Mountain Streams Bedform Diversity Data							
Master Spreadsheet							
		Bankfull Hydraulics from Representative Riffle					
State	Stream	Discharge	Velocity	Mannings	Froude	Shear	Unit Strm
	Name	cfs	ft/s	n	Number	Stress	Power
AK	Eldorado Above Canyon	219	5.7	0.055	0.81	2.42	15.4
AK	Iron Creek Middle	25.5	4	0.065	0.98	2.4	11.2
AK	Iron Creek near confluence	39.1	3.8	0.06	0.89	1.78	7.5
AK	Reinhart	20.9	4.8	0.068	1.12	3.55	18.8
AK	Little Champion	53.8	4.3	0.073	0.87	3.03	13.9
AK	Nome Creek Above Campground	170.2	4.3	0.068	0.66	2.22	9.9
AK	Nome Creek Trib	72.7	5.1	0.063	0.88	2.81	15.2
AK	Eldorado Upper	40.3	4.5	0.08	0.9	3.99	19
AK	Eldorado Lower	65.5	4.6	0.075	0.89	3.58	17.5
AK	Lily Creek Upper	114	5.1	0.075	0.83	3.88	22
AK	Rusty Creek	67.2	5	0.075	0.87	3.95	21
						lbs/sqft	lbs/ft/s

Mountain Streams Bedform Diversity Data										
Master Spreadsheet										
		Pool								
State	Stream	Pool Width Ratio			Pool Area	Pool Area Ratio		Pool Max Depth Ratio		
	Name	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
AK	Eldorado Above Canyon							1.8	2	1.9
AK	Iron Creek Middle							1.4	3	2.2
AK	Iron Creek near confluence	0.8	0.8	0.8	1.1	1.1	1.1	2.4	3.7	3
AK	Reinhart							0.9	2.7	1.6
AK	Little Champion	0.9	0.9	0.9	1.6	1.6	1.6	1.3	3.7	3
AK	Nome Creek Above Campground	0.8	0.8	0.8	1.2	1.2	1.2	1.8	3	2.1
AK	Nome Creek Trib	1.05	1.05	1.05	0.96	0.96	0.96	1.4	2.5	2
AK	Eldorado Upper							1.7	3.2	2.4
AK	Eldorado Lower	0.9	0.9	0.9	1	1	1	1.2	2.8	2.2
AK	Lily Creek Upper	0.6	0.6	0.6	0.8	0.8	0.8	1.1	2	1.6
AK	Rusty Creek	1.4	1.4	1.4	1.4	1.4	1.4	0.3	2.2	1.6

Mountain Streams Bedform Diversity Data										
Master Spreadsheet										
		Profile								
State	Stream	Bank Height Ratio			Step-Pool Spacing			Cascade-Pool Spacing		
	Name	Min	Max	Weighted	min	max	avg	min	max	avg
AK	Eldorado Above Canyon	1	1		0.8	0.8	0.8	2	4	3
AK	Iron Creek Middle	1	1					3.4	7.5	4.9
AK	Iron Creek near confluence	1	2	1.4	0.7	0.8	0.8	1.8	3.2	2.3
AK	Reinhart	1	1		1.1	1.1	1.1	1.9	3.4	2.5
AK	Little Champion	1	2.2	1.4	0.4	0.6	0.5	0.9	3	2
AK	Nome Creek Above Campground	1	2.2	1.5				2	4.1	3.4
AK	Nome Creek Trib	1.3	1.6	1.4	0.4	1.1	0.7	0.9	6.8	2.9
AK	Eldorado Upper	1	1		0.7	0.8	0.8	1.3	3.7	2.4
AK	Eldorado Lower	1.3	2	1.4	0.3	0.3	0.3	1.3	8	3.6
AK	Lily Creek Upper	1	1.3	1.1	0.3	0.6	0.4	2.1	3.7	2.9
AK	Rusty Creek	1.2	1.4	1.2				2.4	9.2	5.5
				Avg	Ratio	Ratio	Ratio	Ratio	Ratio	Ratio

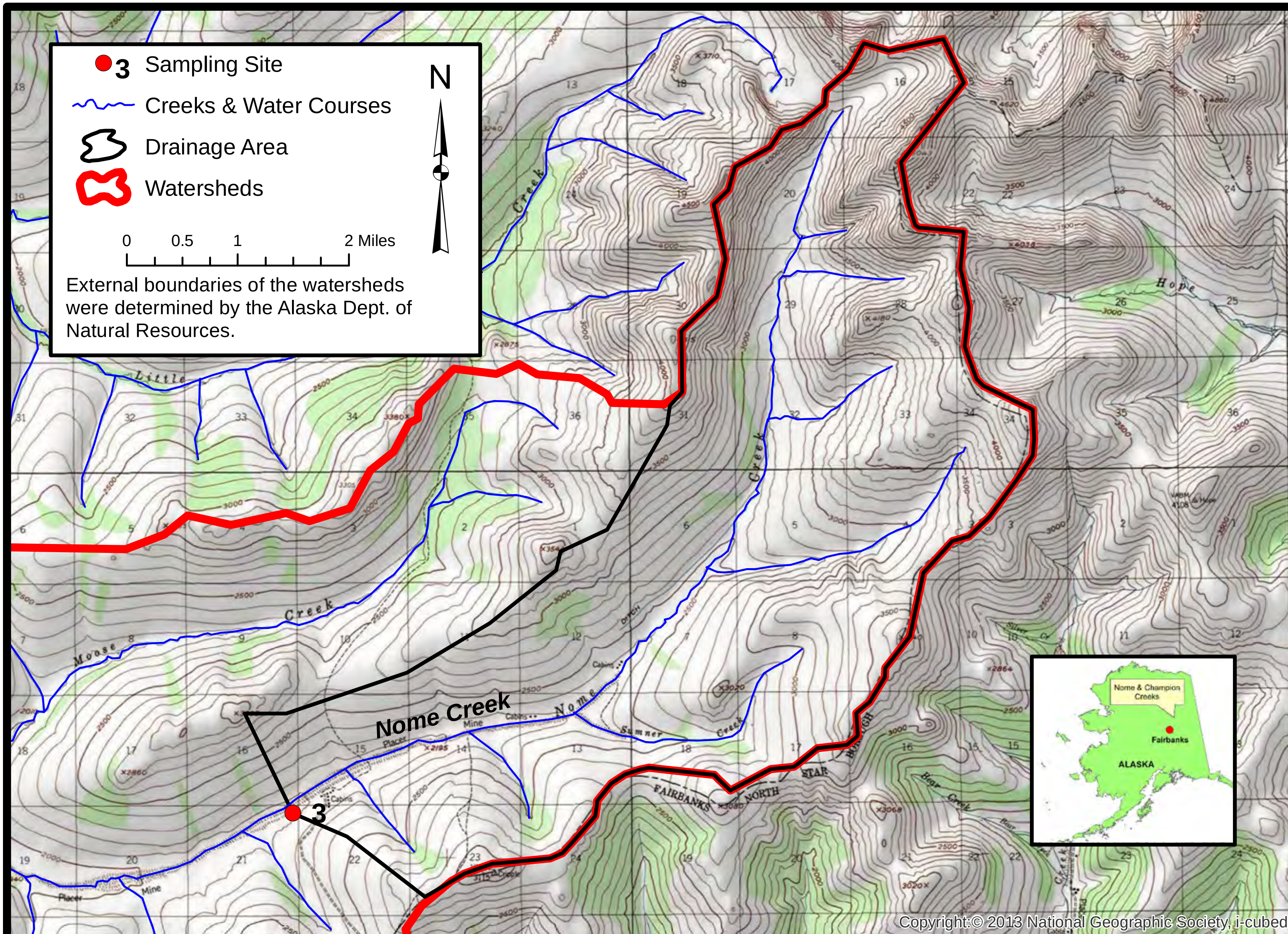
Mountain Streams Bedform Diversity Data									
Master Spreadsheet									
State	Stream	Step Height in Feet			Step Height Ratio			Cascade Slope Ratio	
	Name	Min	Max	Avg	Min	Max	Avg	Min	Max
AK	Eldorado Above Canyon	0.3	0.5	0.4	0.2	0.3	0.25	0.3	0.9
AK	Iron Creek Middle	0.7	1.96	1.4	1.2	3.3	2.3	0.6	1.1
AK	Iron Creek near confluence	0.3	0.8	0.5	0.6	1.3	0.9	0.9	1.9
AK	Reinhart	0.3	1.74	0.9	0.4	2.9	1.5	0.2	1.5
AK	Little Champion	0.4	1.3	0.8	0.5	1.6	1	0.3	2.1
AK	Nome Creek Above Campground	0.7	1.05	0.8	0.5	0.7	0.6	0.5	1.5
AK	Nome Creek Trib	0.4	0.92	0.7	0.3	0.8	0.6	0.7	1.5
AK	Eldorado Upper	0.6	1.5	0.9	0.7	1.9	1.1	0.7	1.5
AK	Eldorado Lower	0.3	0.98	0.6	0.3	1.2	0.7	0.2	1.5
AK	Lily Creek Upper	0.3	1.34	0.6	0.2	1	0.5	0.6	1.2
AK	Rusty Creek	0.4	1.1	0.8	0.4	1	0.7	1.11	1.15

Mountain Streams Bedform Diversity Data										
Master Spreadsheet										
State	Stream		Pool Slope Ratio			Cascade Length Ratio			Pool Length Ratio	
	Name	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max
AK	Eldorado Above Canyon	0.6	0.1	0.7	0.4	1.2	3.2	2.2	0.4	1
AK	Iron Creek Middle	0.8				2	6.3	3.7	0.4	1.1
AK	Iron Creek near confluence	1.5	0	2.6	0.9	0.8	2.3	1.5	0.4	1.4
AK	Reinhart	0.8	0.1	0.5	0.2	0.8	2.5	1.7	0.3	0.9
AK	Little Champion	1.1	0	0.6	0.1	0.4	2.3	1	0.1	1.1
AK	Nome Creek Above Campground	1.1	0	1.5	0.6	1	4.3	2.5	0.3	2.2
AK	Nome Creek Trib	1	0	0.7	0.3	0.5	4.9	2.1	0.4	1.7
AK	Eldorado Upper	1	0	0.4	0.3	0.6	2.5	1.5	0.4	1.1
AK	Eldorado Lower	0.9	0.1	0.9	0.4	0.8	7.4	2.8	0.2	0.6
AK	Lily Creek Upper	0.9	0.2	0.4	0.1	1.3	4.3	3	0.2	0.5
AK	Rusty Creek	1.13	0	1.2	0.4	0.8	8.8	4.4	0.4	1.5

Mountain Streams Bedform Diversity Data									
Master Spreadsheet									
State	Stream		Step Length Ratio			Cascade	Pool	Step	No. Pools
	Name	Avg	Min	Max	Avg	Length	Length	Length	Per
AK	Eldorado Above Canyon	0.7	0.1	0.2	0.2	65.95	29.46	4.59	0.054
AK	Iron Creek Middle	0.6	0.3	1	0.6	70.66	14.59	14.74	0.022
AK	Iron Creek near confluence	0.7	0.1	0.2	0.2	57.86	38.4	3.74	0.034
AK	Reinhart	0.6	0.3	0.6	0.5	55.36	29.67	14.98	0.066
AK	Little Champion	0.5	0.1	0.5	0.2	56.77	31.72	11.51	0.042
AK	Nome Creek Above Campground	1.1	0.3	0.8	0.5	63.43	28.8	7.77	0.009
AK	Nome Creek Trib	0.8	0.1	0.4	0.2	61.65	33.65	4.7	0.034
AK	Eldorado Upper	0.7	0.1	0.8	0.3	53.82	32.03	14.15	0.045
AK	Eldorado Lower	0.3	0	0.2	0.1	84.38	12.53	3.09	0.033
AK	Lily Creek Upper	0.3	0.1	0.3	0.1	80.6	14.25	5.15	0.025
AK	Rusty Creek	0.8	0.4	0.9	0.6	74.43	18.33	7.24	0.018
						%	%	%	Reach Lngt

Appendix C

Results from Nome Creek Function-Based Assessment



Date:

7 JULY 2017

Project Manager:

Greg DuBois

NATIONAL SYSTEM OF PUBLIC LANDS
U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF LAND MANAGEMENT

APC SERVICES LLC

A Subsidiary of Alaska Peninsula Corporation

Sample Site 3 Drainage Area
21.31 mi², Nome Creek,
Nome Creek Watershed

Figure:

Summary

Stream:	Nome Creek at Bridge
Watershed:	Nome Creek
Location:	---
Latitude:	---
Longitude:	---
State:	AK
County:	---
Date:	June 23, 2017
Observers:	Harman, Barrett, Dubois, Wassillie
Channel type:	C3
Drainage area (sq.mi.):	21.7
notes:	---

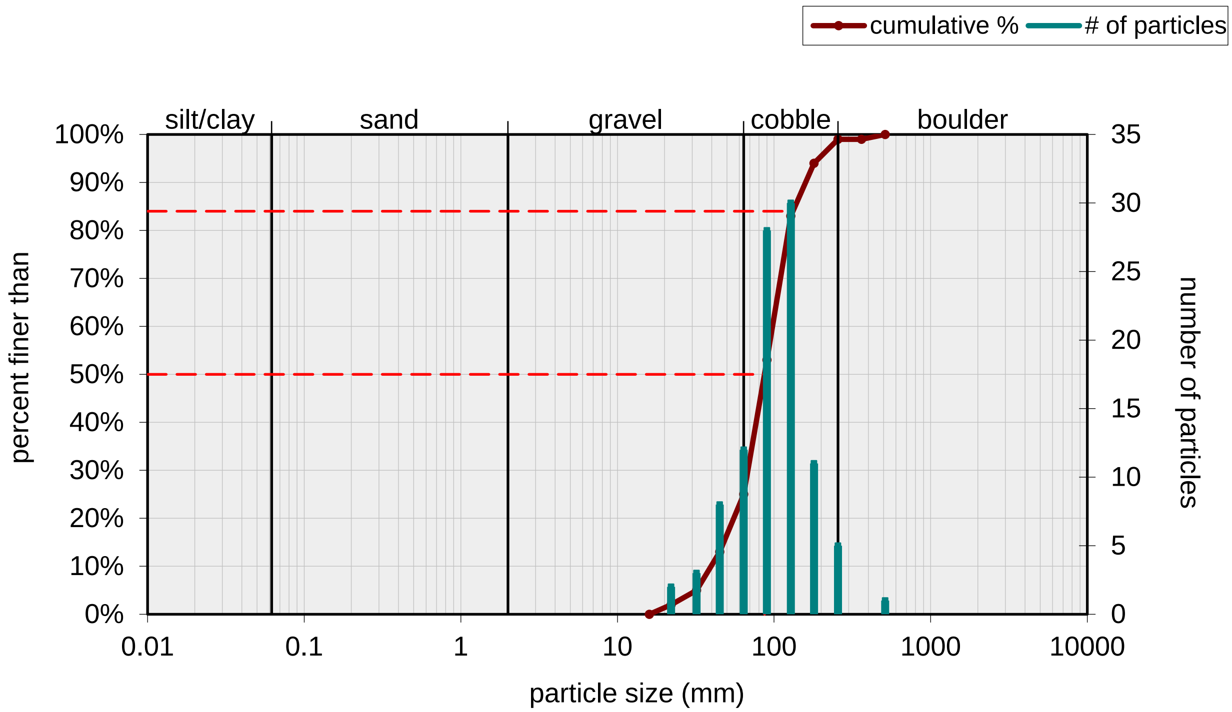
Dimension

		bankfull channel			
		typical	min	max	
floodplain:	width flood prone area (ft)	---	---	---	
	low bank height (ft)	2.5	---	---	
riffle-run:	x-area bankfull (sq.ft.)	81.3	79.2	83.4	
	width bankfull (ft)	49.6	42.1	57.1	
	mean depth (ft)	1.64	1.5	1.9	
	max depth (ft)	2.4	2.3	2.5	
	hydraulic radius (ft)	1.6			
pool:	x-area pool (sq.ft.)	53.3	53.3	53.3	
	width pool (ft)	42.6	42.6	42.6	
	max depth pool (ft)	2.4	2.4	2.4	
	hydraulic radius (ft)	1.2			
dimensionless ratios:		typical	min	max	
	width depth ratio	30.3	22.4	39.1	
	entrenchment ratio	---	---	---	
	riffle max depth ratio	1.5	1.4	1.5	
	bank height ratio	1.0	---	---	
	pool area ratio	0.7	0.7	0.7	
	pool width ratio	0.9	0.9	0.9	
	pool max depth ratio	1.5	1.5	1.5	
hydraulics:		typical	min	max	
	discharge rate (cfs)	403.7	377.9	429.4	
	channel slope (%)	1.1			
		riffle-run	min	max	pool
	velocity (ft/s)	5.0	4.5	5.4	7.6
	Froude number	0.68	0.66	0.71	1.48
	shear stress (lbs/sq.ft.)	1.123	0.998	1.249	0.824
	shear velocity (ft/s)	0.761	0.717	0.803	0.652
	stream power (lb/s)	277.1	259.4	294.8	
	unit stream power (lb/ft/s)	5.584	4.543	6.995	
	relative roughness	5.7	---	---	
	friction factor u/u*	6.5	6.3	6.8	
	threshold grain size (t*=0.06) (mm)	61.4	49.0	61.4	
	Shield's parameter	0.038			

Pattern

	typical	min	max
meander length (ft)	528.0	---	---
belt width (ft)	82.0	---	---
amplitude (ft)	---	---	---
radius (ft)	---	---	---
arc angle (degrees)	---	---	---
stream length (ft)	1200.0		
valley length (ft)	1023.0		
Sinuosity	1.2		
Meander Length Ratio	10.6	---	---
Meander Width Ratio	1.7	---	---
Radius Ratio	---	---	---

Riffle Surface Pebble Count, Nome Creek at Bridge

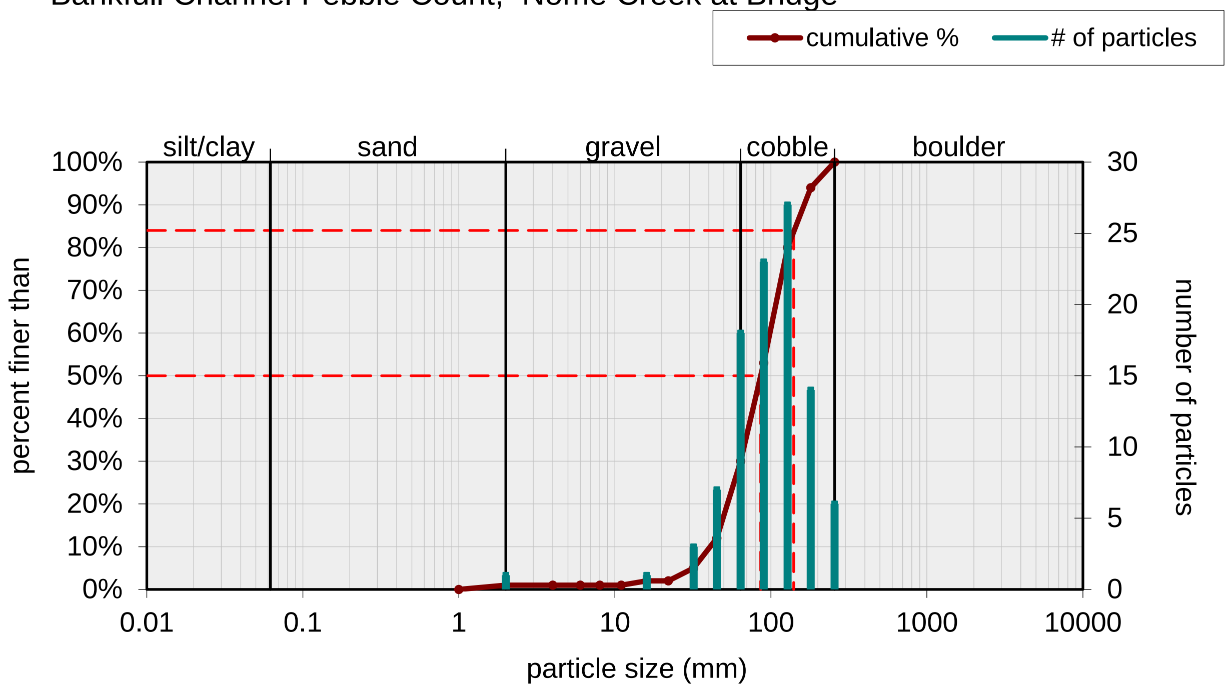


Size (mm)	
D16	49
D35	72
D50	87
D65	100
D84	130
D95	190

Size Distribution	
mean	79.8
dispersion	1.6
skewness	-0.06

Type	
silt/clay	0%
sand	0%
gravel	25%
cobble	74%
boulder	1%

Bankfull Channel Pebble Count, Nome Creek at Bridge

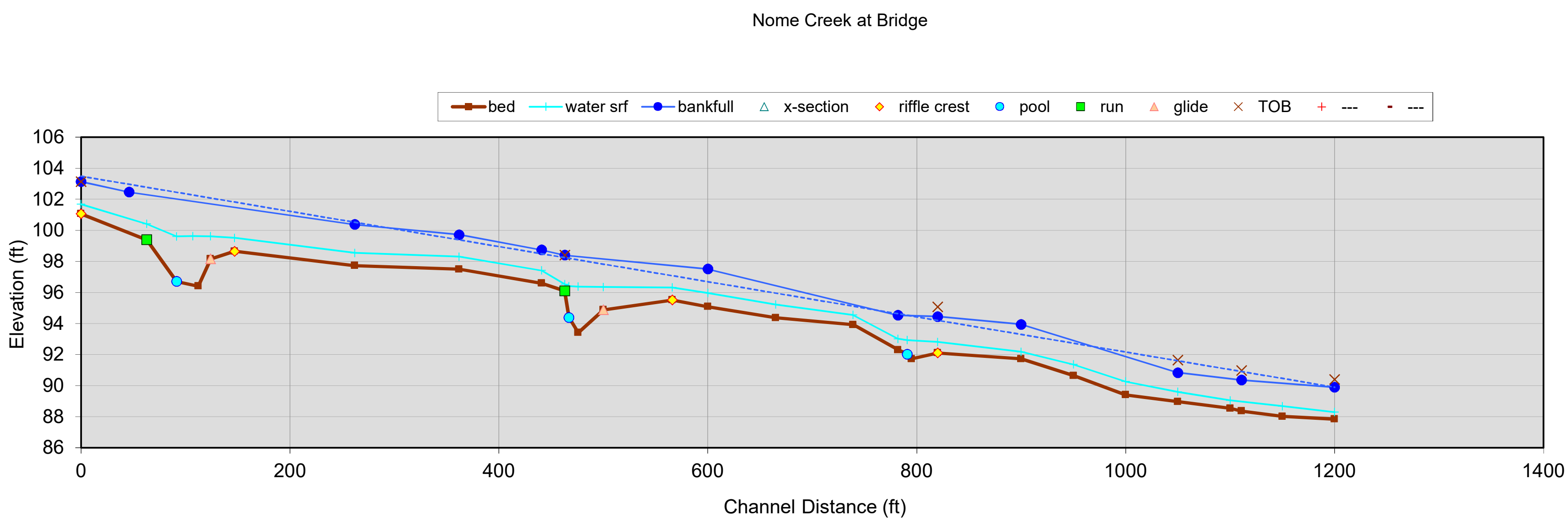


Size (mm)		
D16	49	3.4
D35	69	12
D50	86	17
D65	110	20
D84	140	29
D95	190	39

Size Distribution	
mean	82.8
dispersion	1.7
skewness	-0.02

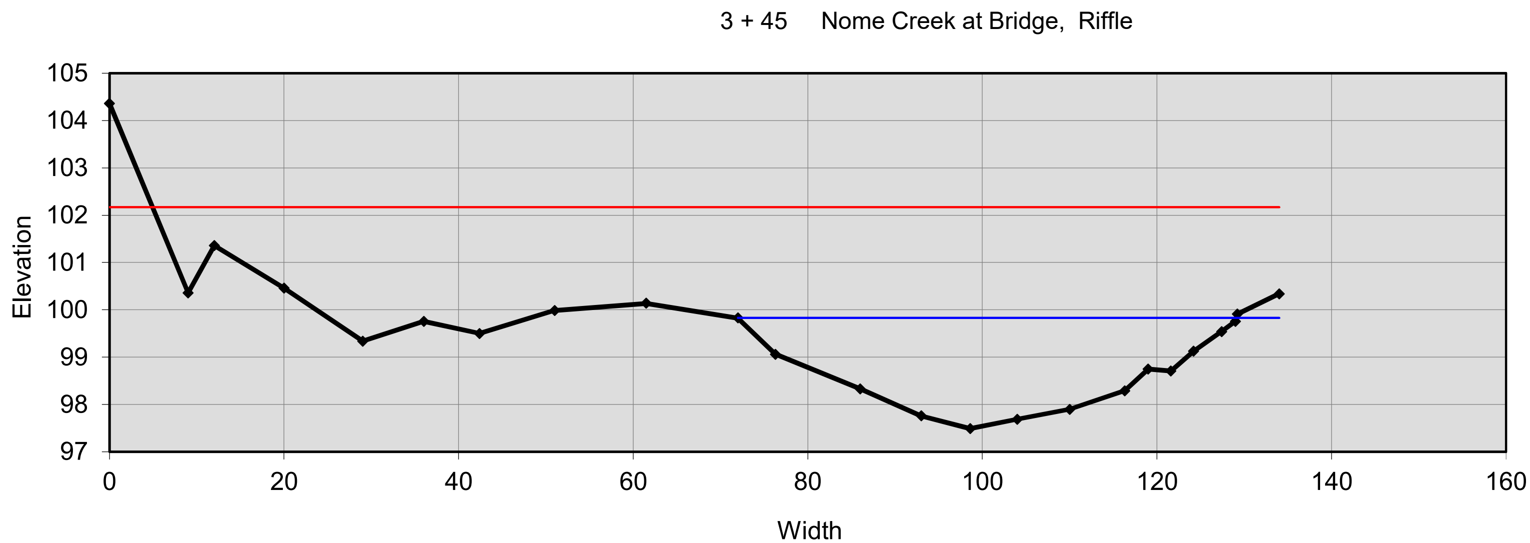
Type	
silt/clay	0%
sand	1%
gravel	29%
cobble	70%
boulder	0%

Longitudinal Slope Profile



	slope (%)		slope ratio		length (ft)		length ratio		pool-pool spacing (ft)		p-p ratio	
reach	1.1		---		1200.0 (24.2 channel widths)		---		---		---	
riffle	1.5	(0.94 - 2)	1.4	(0.9 - 1.8)	201.3	(63 - 316)	4.1	(1.3 - 6.4)	---		---	
pool	0.19	(0 - 0.41)	0.2	(0 - 0.4)	31.5	(29 - 33)	0.6	(0.6 - 0.7)	349.8	(324 - 375.5)	7	(6.5 - 7.6)
run	3	(2.8 - 3.3)	2.7	(2.5 - 3)	16.3	(4 - 28.5)	0.3	(0.1 - 0.6)	---		---	
glide	0.24	(0.045 - 0.43)	0.2	(0 - 0.4)	44.5	(23 - 66)	0.9	(0.5 - 1.3)	---		---	

Cross Section 1



Bankfull Dimensions	
83.4	x-section area (ft.sq.)
57.1	width (ft)
1.5	mean depth (ft)
2.3	max depth (ft)
57.4	wetted parimeter (ft)
1.5	hyd radi (ft)
39.1	width-depth ratio

Flood Dimensions	
---	W flood prone area (ft)
---	entrenchment ratio
---	low bank height (ft)
---	low bank height ratio

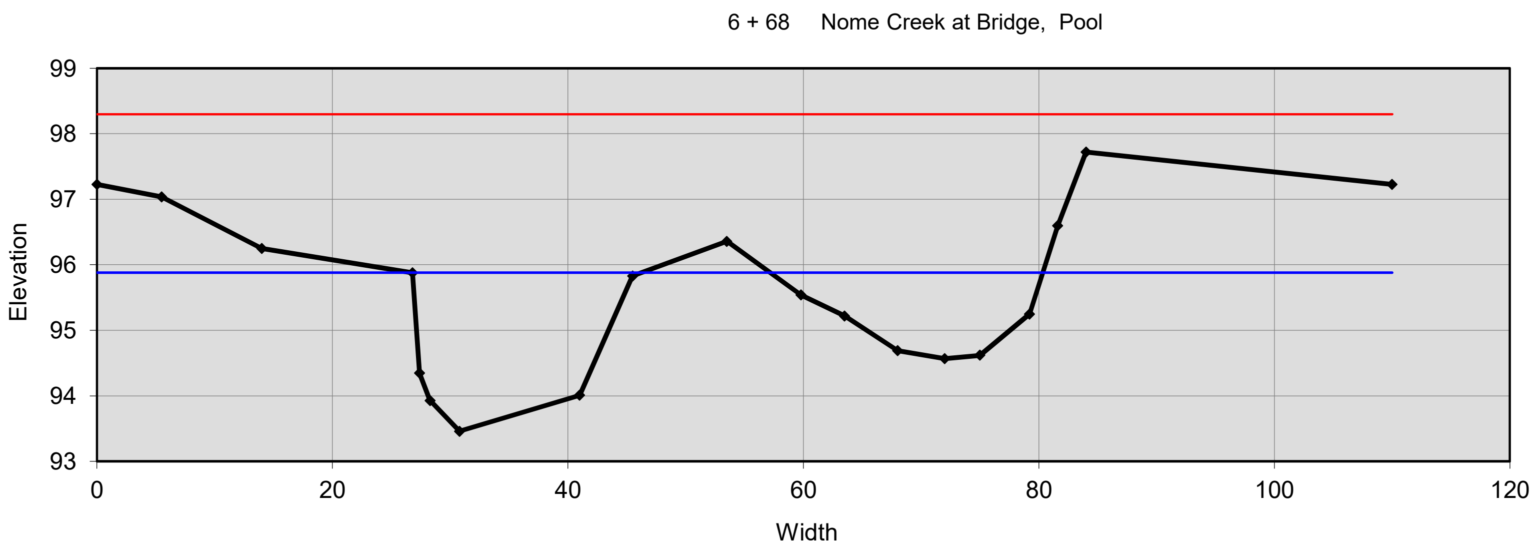
Materials	
87	D50 Riffle (mm)
130	D84 Riffle (mm)
49	threshold grain size (mm):

Bankfull Flow	
4.5	velocity (ft/s)
377.9	discharge rate (cfs)
0.66	Froude number

Flow Resistance	
0.044	Manning's roughness
0.20	D'Arcy-Weisbach fric.
6.3	resistance factor u/u*
3.4	relative roughness

Forces & Power	
1.1	channel slope (%)
1.00	shear stress (lb/sq.ft.)
0.72	shear velocity (ft/s)
4.5	unit strm power (lb/ft/s)

Cross Section 3



Bankfull Dimensions

53.3	x-section area (ft.sq.)
42.6	width (ft)
1.3	mean depth (ft)
2.4	max depth (ft)
44.4	wetted parimeter (ft)
1.2	hyd radi (ft)
34.0	width-depth ratio

Flood Dimensions

---	W flood prone area (ft)
---	entrenchment ratio
---	low bank height (ft)
---	low bank height ratio

Materials

87	D50 Riffle (mm)
130	D84 Riffle (mm)
41	threshold grain size (mm):

Bankfull Flow

3.9	velocity (ft/s)
209.3	discharge rate (cfs)
0.63	Froude number

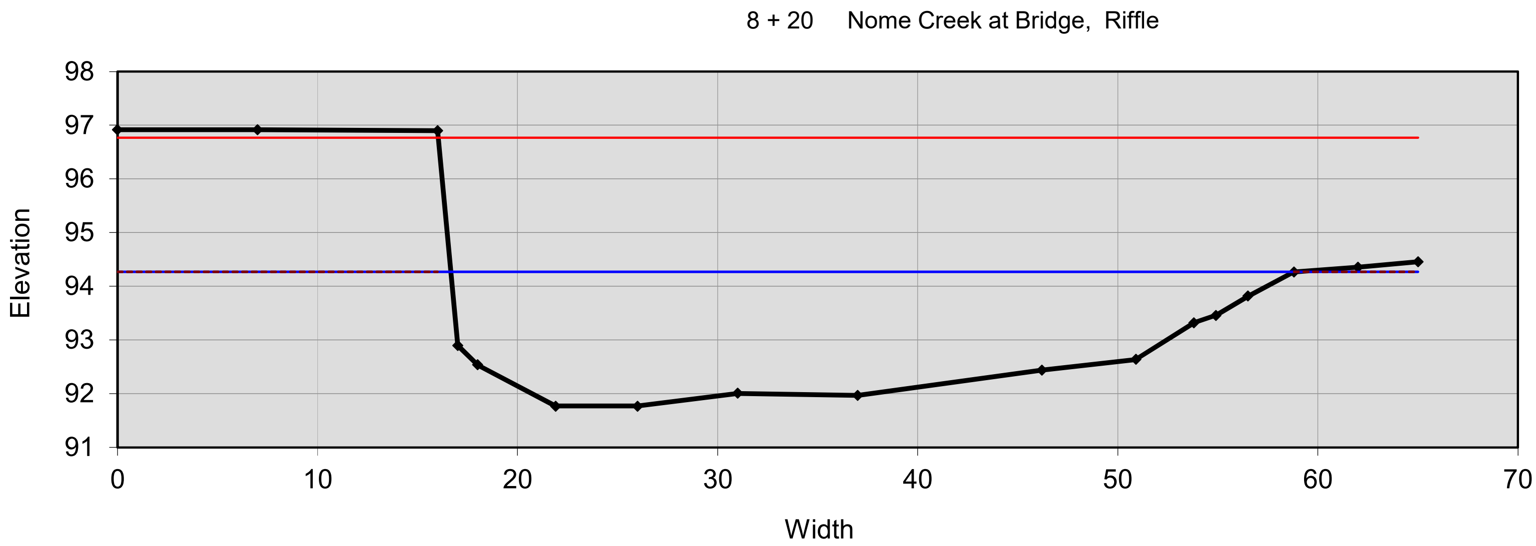
Flow Resistance

0.045	Manning's roughness
0.22	D'Arcy-Weisbach fric.
6.0	resistance factor u/u*
2.9	relative roughness

Forces & Power

1.1	channel slope (%)
0.82	shear stress (lb/sq.ft.)
0.65	shear velocity (ft/s)
3.4	unit strm power (lb/ft/s)

Cross Section 3



Bankfull Dimensions	
79.2	x-section area (ft.sq.)
42.1	width (ft)
1.9	mean depth (ft)
2.5	max depth (ft)
43.5	wetted parimeter (ft)
1.8	hyd radi (ft)
22.4	width-depth ratio

Flood Dimensions	
---	W flood prone area (ft)
---	entrenchment ratio
2.5	low bank height (ft)
1.0	low bank height ratio

Materials	
87	D50 Riffle (mm)
130	D84 Riffle (mm)
61	threshold grain size (mm):

Bankfull Flow	
5.4	velocity (ft/s)
429.4	discharge rate (cfs)
0.71	Froude number

Flow Resistance	
0.043	Manning's roughness
0.18	D'Arcy-Weisbach fric.
6.8	resistance factor u/u*
4.4	relative roughness

Forces & Power	
1.1	channel slope (%)
1.25	shear stress (lb/sq.ft.)
0.80	shear velocity (ft/s)
7	unit strm power (lb/ft/s)

Nome Creek (Area Surrounding Bridge and Downstream)

Common Botanical Species Noted During Field Surveys (June 23th, 2017)

STRATUM	SCIENTIFIC NAME	COMMON NAME
Trees/Shrubs		
	Alnus viridis ssp. sinuata	Sitka alder
	Dasiphora fruticosa	Shrubby cinquefoil
	Empetrum nigrum	Mossberry
	Picea mariana	Black spruce
	Rhodendron tomentosum	Northern Labrador tea
	Salix alaxensis	Felt-leaf willow
	Salix chamissonis	Chamisso's willow
	Salix glauca	Grey-leaf willow
	Spiraea stevenii	Alaska spiraea
Herbs/Wildflowers		
	Cornus canadensis	Dwarf dogwood
	Epilobium latifolium	Dwarf fireweed (River Beauty)
	Wilhelmsia physodes	Kaiser's sandwort
Ferns & Allies		
	Equisetum arvense	Common horsetail
	Equisetum scirpoides	Dwarf scouring rush