Appendix D

Channel Migration Study

Documentation of CMZ Modifications; Index-Galena Flood Repairs Memorandum, January 4, 2011

North Fork Skykomish Channel Migration Study, River Mile 1.8 to 11.0, Index Galena Flood Repairs Mile Post 6.4 to 6.9, by Anchor QEA, LLC, March 2009
MEMORANDUM

To: Dave Lucas and Steve Dolde, Snohomish County Public Works
   Bob Munchinski, HW Lochner
From: Tracy Drury and Marisa Lee, Anchor QEA, LLC
Re: Documentation of CMZ Modifications; Index-Galena Flood Repairs, Task 7.1
    Refine Channel Migration Zone

Date: January 4, 2011
Project: 080532-01.03

Anchor QEA, LLC (Anchor QEA) was retained by HW Lochner and Snohomish County (County) to refine the Channel Migration Zone (CMZ) for the Index-Galena Flood Repairs Project. Under a previous contract, the CMZ was defined through the project area at a coarse resolution as part of an approximately 11-mile CMZ analysis for the North Fork Skykomish River using geospatial data such as Light Detection and Ranging (LiDAR) and geologic maps, with limited field data. The original CMZ under this scope included a low-, moderate-, and high-risk zone. Task 7.1 of the current scope of work includes refining the high-risk CMZ line adjacent to the proposed realignment of Index-Galena Road along the south valley wall between approximately Mile Post (MP) 6.1 and 7.3. The refined CMZ line in digital format was provided to the County and HW Lochner on October 1, 2010. This memorandum documents the modifications made to the original CMZ to produce the refined line.

MODIFICATIONS TO ORIGINAL SCOPE

The original scope and contract for this task assumed that subsurface geologic data and analysis would be available for Anchor QEA’s use in the CMZ evaluation. These data include boring logs along the proposed road alignment, geophysical exploration of the slope, and a complete geotechnical site assessment throughout the site. Changes in scope for the geotechnical portion of the project have resulted in these data not being available for Anchor QEA’s use at this time. In addition, the hydraulic (HEC-RAS) model of the site was not modified per the original scope at the time of the CMZ analysis; the model output was expected to be available to evaluate expected flood levels and velocities. Therefore, refinement of the CMZ was primarily based on field observation of surface and near-surface...
materials, and best professional judgment of expected subsurface conditions, current and future channel dynamics, and hillslope processes. All modifications to the scope were described in a memorandum from Tracy Drury, P.E. dated July 23, 2010 and approved by Steve Dolde, P.E.

**METHODOLOGY**

Preliminary surface geology mapping and limited geophysical analysis for a portion of the site were available for the investigation. Analysis and mapping performed as part of Anchor QEA’s previous scope were used to create field maps and identify key areas of interest. Anchor QEA staff were on site the week of September 20, 2010, to perform site reconnaissance to characterize the river bank, floodplain, and valley wall materials. The site conditions were light to heavy rain with saturated ground and wet vegetation. Prior to the site visit, County staff staked the proposed road centerline at approximately 50-foot intervals.

Anchor QEA staff walked along the banks and floodplain and characterized soil conditions at approximately 100-foot intervals and noted where significant changes in bank or floodplain composition occurred. A 42-inch steel soil probe was used to evaluate near-surface soils. Conditions were noted, mapped, and tied into the proposed alignment by measuring perpendicular distances from the survey stakes using a 100- or 300-foot tape. Notes and measurements were later transferred into a Geographic Information System (GIS) map to refine the CMZ using the other available data layers, including the LiDAR.

**FIELD OBSERVATIONS**

The stationing shown on the figures and referred to within this memorandum is approximate and based on the most recent version of the road alignment provided to Anchor QEA by HW Lochner, dated August 22, 2010. The following list is a summary of field observations made by Anchor QEA staff affecting the position of the CMZ; these observations are also noted on Figures 1 through 3.

- **Station 77+20 to Station 69+00.** Several large boulders, up to approximately 6 feet in diameter, are located within the active channel and along the bank. There is an accumulation of approximately 1- to 2-foot diameter boulders along the surface of a bar in the active channel between Station 75+50 and 72+00. Boulders located at the
surface of the adjacent floodplain may be river alluvium or remnant alluvial fan deposits.

- **Station 69+00 to 63+50.** A low, sandy vegetated bar is located adjacent to the river bank which is steep and composed of stacked boulders of approximately 3- to 5-foot in diameter. The boulders appear to be placed historically as bank protection. The adjacent floodplain is composed of topsoil at the surface to approximately 2 to 3 feet in depth, underlain by what is likely river-deposited alluvium composed of sandy gravels with some cobble. An overbank flow path is located in the floodplain beginning at approximately Station 64+50. The surface material is loose, sandy soil to a depth greater than the maximum depth of soil probe. The valley wall is composed of alluvial fan deposits from approximately Station 67+00 to 60+00. At least two small drainages from the fan flow along the toe of the valley wall.

- **Station 63+50 to 60+00.** The top of bank is slightly lower in elevation with 3- to 4-foot diameter boulders at the toe. Overbank flow paths in the adjacent floodplain have sandy or mucky soils at surface up to the maximum depth of the soil probe, underlain by sands and gravels; standing water is present in the flow path near the valley wall. The flow path areas are vegetated with willow and other moisture-seeking plant species.

- **Station 60+00 to 56+50.** Many large boulders up to approximately 6 feet in diameter are located along the toe of bank and in the river bed. Overbank flow paths are present through the adjacent floodplain with mucky soils at the surface and standing water.

- **Station 56+50 to 53+00.** The river bank and floodplain are composed of erodible alluvium. An actively-eroding bank was observed near Station 55+00. A debris chute deposit is located between Station 54+00 and 53+00 with materials composed of angular rock ranging from approximately 6 inches to over 4 feet in diameter.

- **Station 53+00 to 49+50.** The prominent side channel that flows along the former (washed-out) road alignment is located along the toe of the valley slope. The toe of the side channel bank is lined with several large boulders up to approximately 6 feet in diameter. The valley slope is composed of bouldery colluvium at the surface.

- **Station 49+50 to 46+00.** The side channel bank is primarily composed of approximately 3- to 4-foot diameter bouldery colluvium. A narrow sandy bar is present in the active channel at the toe of the valley slope from approximately 49+50 to 47+50. Occasional very large (approximately 10-feet in diameter) boulders were
observed at or near the toe of the slope. Active landslide deposits are present at Station 46+50.

- **Station 46+00 to 35+00.** Between these stations, the side channel flows on the north side of an intact portion of Index-Galena Road, which separates the side channel alignment from the valley slope. A low trough with wet soils and standing water is present between the toe of the valley wall and the intact portion of the roadway. The valley slope through this area is typically composed of bouldery colluvium at the surface.

- **Station 35+00 to 31+00.** Occasional very large boulders (up to 12-feet in diameter) were observed along the toe of the slope. At Station 33+00, the valley slope steepens. A rib of bedrock was also observed at this location.

- **Station 31+00 to 25+00.** Bedrock outcrops are located approximately 20 feet above the elevation of the side channel in this location. The lower portion of the valley slope becomes shallower and is composed of gravels and cobbles from approximately Station 31+00 to 26+50. A low marshy area is present between the side channel alignment and the valley wall from approximately Station 26+50 to 25+00.

- **Station 25+00 19+50.** Bedrock outcrops are located at the toe of the slope.

- **Station 19+50 to 18+50.** Bedrock outcrops are located along the shoulder of the roadway (downslope of the proposed alignment).

- **Station 18+50 to 12+50.** A bench or terrace-like area is present between the side channel alignment and the roadway, up to an approximate elevation of 850 feet where the valley slope becomes much steeper. No bedrock, large boulders, or otherwise resistant materials were observed in this area downslope of the U.S. Forest Service road or along the toe of the Index-Galena Road prism. Consequently, without additional subsurface data this feature is assumed to be river alluvium/floodplain materials and; therefore, erodible.

- **Station 12+50 to 10+00.** There are large boulders present in the bank and in the bed of the side channel that appear to originate from the Trout Creek fan, many from 6 to 8 feet in diameter.

**LIMITATIONS**

The documentation provided in this memorandum has been developed for the County for use in feasibility analysis and design of the Index-Galena road realignment. Conditions
within the project site may change both spatially and with time, and additional scientific data may become available. Further, this task was not performed according to the original scope, which has been explained in this memorandum and agreed upon by Snohomish County staff. Significant changes in site conditions or available information may require re-evaluation of the CMZ. Within the limitations of the scope, schedule, and budget, our services have been executed in accordance with generally accepted scientific and engineering practices in this area at the time the memorandum was prepared.

Attachment: Figures
FIGURES
Figure 1
Refined CMZ and Field Observations
Documentation of CMZ Modifications Memorandum
Index-Galena Flood Repairs Task 7.1

NOTES:
Elevation map and 10-foot contours produced from 2006 LiDAR during previous scope of work. Proposed road alignment provided by HW Lochner on 7-22-10. All locations shown are approximate.
Large boulders

V. large boulders @ toe

4-5 ft diam. bouldery colluvium with narrow bar at toe

DS end of low bar at toe

Active portion of landslide 2-3 ft boulders in low area adj. to water

Accumulation of large boulders at surface

At 44+ colluvium slope, boulders get smaller in avg. diameter

Low area with mucky soils

Very lg. boulder

Bouldery colluvial slope between bedrock and 42+00

Depression - downed trees pointed downslope

Boulder slope 4-5 ft diam.
Figure 3
Refined CMZ and Field Observations
Documentation of CMZ Modifications Memorandum
Index-Galena Flood Repairs Task 7.1

NOTES:
Elevation map and 10-foot contours produced from 2006 LiDAR during previous scope of work. Proposed road alignment provided by HW Lochner on 7-22-10. All locations shown are approximate.

LEGEND
- Refined CMZ Line
- Proposed Road Alignment 7-22-10
- Approx. Bedrock Outcrops
- Other Hardpoints
- Existing Index-Galena Road Centerline
- 10-foot Contours

Elevation Relative to Main Channel
- High : 50 ft
- Low : 0 ft

Very lg. boulder at backwater area w/ old cedar on top

Very lg. boulder

Bedrock 18-20 feet above WSEL

Low marshy area

Bedrock to 18+55

Trout Creek fan

FS Road
NORTH FORK SKYKOMISH CHANNEL MIGRATION STUDY
RIVER MILE 1.8 TO 11.0

INDEX GALENA FLOOD REPAIRS
MILE POST 6.4 TO 6.9

Prepared for
Snohomish County Public Works

Prepared by
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March 2009
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EXECUTIVE SUMMARY

The purpose of this study is to determine a 50-year Channel Migration Zone (CMZ) for an approximately 9-mile-long length of the North Fork Skykomish River (NFS). The CMZ is defined as the spatial area of the existing channel, adjacent floodplain, or valley margins that the river may occupy over the course of the next 50 years.

This study was prompted by a large flood event in November of 2006 when multiple washouts occurred along the Index Galena Road, including two major washouts at mileposts (MPs) 6.4 and 6.9 that have permanently closed the road. The road has remained closed and the results of this report will be used to help identify a new roadway alignment.

The NFS is a steeply sloped, high relief basin that flows from bedrock-lined canyons in the high Cascades to the confluence with the South Fork Skykomish. The upper valley is steep and confined in bedrock through a significant length of river. The project site is lower gradient and many areas are unconfined. Deposition of wood and sediment transported from upstream is more likely to occur through these reaches, likely creating logjams and large gravel bar areas that are observed in upper reaches of the river.

The NFS basin was logged and the channel was cleared in the 1960s and 1970s, resulting in a straightened channel with increased hydraulic energy. These conditions promote the transport of wood and sediment downstream where much of these materials would likely be temporarily stored within the reach under more natural conditions. The river is currently in a stage of recovery—wood and sediment are being stored, creating logjams, and splitting the mainstem river into multiple channels. Logjams and multiple channel configurations reduce hydraulic energy and promote the deposition of additional wood and sediment. In this way, a feedback loop is created where logjams, sediment deposition, and split flow conditions leads to more logjams, sediment deposition, and split flow conditions. Therefore, we expect that the river will expand its active channel width and will occupy a broader range of the valley floor in the next 50 years than it has occupied in the last 50 years.

The historic meander zone (HMZ; the area of known historical occupation by the river) was delineated by evaluating historical aerial photos and LiDAR data. This area included all identifiable areas throughout the geologic history. However, many of the indentified features
were located on ancient alluvial fans or terraces that are no longer accessible to the river. This initial delineation allowed us to identify areas of confinement with little migration history as well as unconfined areas where channel migration has been very active.

Channel migration character was evaluated throughout the project area and three general migration patterns were evaluated. Steady migration of a meander bend occurs when the channel moves in a specific direction for an extended period of time. This type of migration can be in the lateral direction (across the valley floor) or in the downstream direction. Meander bends often move in both the lateral and downstream directions with one or the other being the “dominant” direction of migration. Hence, a dominant lateral or downstream migration pattern was indentified. The third dominant migration type indentified was avulsion, where the river abruptly moves from one location in the valley floor to another, leaving the former channel location dry or as an overflow channel.

In delineating the CMZ, only areas likely to be occupied by the river were considered. All historical features were removed from consideration. Once the likely channel migration area was determined, the CMZ was further delineated into areas of high, moderate, and low likelihood (hazard zones) of future occupation by the river. High hazard zones consist of existing active channel, recent and low floodplain areas, and all side channels located in the photographic record. The high hazard zone also includes additional areas of the floodplain susceptible to channel avulsion and lateral and downstream migration. Moderate hazard zones typically include areas susceptible to erosion in the event of channel avulsion or unidirectional channel migration over an extended period of time. These areas are typically located at a distance away from the active channel or in high bank or erosion resistant areas. The low hazard zone covers areas of the CMZ where channel occupation is possible under specific conditions, although not very likely. These areas are located where materials are highly erodible, but the location is a great distance away from the active channel or potential channel avulsion paths.

The project area was delineated into five reaches based upon geologic confinement and floodplain characteristics, dominant channel migration character, and the slope discharge product (gradient and hydrology). The parameters were evaluated and segments of like conditions were grouped together. Reach breaks were indentified where distinct changes in the
delineation criteria occurred. Reach 1 is the furthest upstream reach and Reach 5 is located downstream near the town of Index.

Reach 1 is a confined reach with a narrow CMZ. Little migration activity was identified in the historical record and future migration activity is likely to erode some portions of the adjacent floodplain while mostly maintaining the current orientation and meander patterns. Reach 2 is unconfined and migration activity has been active. We expect extensive channel movement through this reach and a transition of the dominant migration pattern from downstream to avulsive as logjams and gravel bars expand. Reach 3 is highly confined and the river currently occupies nearly the entire valley floor. We expect little change in the width of the valley floor that the river occupies in the future. Reach 4 is an avulsion dominated reach where the river has actively used most of the valley floor. We expect the river to continue to expand its active channel width and occupy much of the valley floor. Reach 5 has been a downstream migration dominated reach, although we expect that more avulsive behavior will be exhibited in the future as logjams, gravel bars, and split flow conditions expand in this reach.

In summary, the river is in a stage of natural recovery where wood and sediment are increasingly being temporarily stored in the project area in the form of logjams and large gravel bars. These features promote split flow conditions and help reduce hydraulic energy of the system. The presence of these features promotes additional wood and sediment deposition creating a feedback loop. The result of these processes is a wider active channel and a greater width of the valley floor being used by the river during floods. In addition, these features will lead to more active channel migration and a greater likelihood of channel avulsion. Increasing the frequency of channel avulsion also increases the width of the valley floor that is likely to be occupied by the river. Because of these distinct changes in river behavior, it is likely that the river will occupy a much wider portion of the valley floor in the future than it has in the past 50 years. In this way, the future is not likely to resemble the recent past and responsible river management actions should consider this likely change in river behavior.
1 INTRODUCTION

The purpose of this study is to determine a 50-year Channel Migration Zone (CMZ) for an approximately 9-mile-long length of the North Fork Skykomish River (NFS). The CMZ is defined as the spatial area of the existing channel, adjacent floodplain, or valley margins that the river may occupy over the course of the next 50 years. The NFS is located in southeast Snohomish County, near the town of Index (Figure A-1 in Appendix A). For this study, we conducted a reach assessment for the NFS from approximately river mile (RM) 1.8, just northwest of the town of Index at milepost (MP) 1.3, to RM 11.0 near the community of Galena at MP 10.3 (Figure A-2). We conducted site reconnaissance to assess ongoing geomorphic processes and identify ancient versus current geomorphic features, evaluate sediment and wood inputs, and evaluate the expected channel migration character within the system. We delineated the valley floor into locations outside the 50-year CMZ and further delineated the CMZ into areas of high, moderate, and low likelihood of occupation by the river within the next 50 years.

This study was prompted by a large flood event in November of 2006 when multiple washouts occurred along the Index Galena Road, including two major washouts at MPs 6.4 and 6.9 that have permanently closed the road (Figure A-2). During the 2006 flood, the river migrated into an area previously occupied by the road and developed an active side channel running down the road alignment through some areas, while flowing along and directly adjacent to the road in others (Figure 1).
Snohomish County Public Works (SCPW) is interested in re-establishing a direct connection between Index and Galena by rebuilding the Index Galena Road outside the CMZ and above the elevation of the 100-year flood. Historically, the NFS has occupied the entire valley floor as it migrated between valley walls. Logging activities, sediment extraction, and other river management actions in the 1900s straightened the river and removed much of the structure and complexity of the channel system and its floodplain. Changes in management policy and protection in the upper watershed have promoted more natural system recovery in the basin, and the NFS is in the process of recovering. In this context, recovery is defined as reverting back to a highly dynamic river system with multiple high flow paths and forested islands, as well as vast gravel bar development and widening of the active channel. Development of these features is coupled with dramatic channel migration and avulsion activity. Therefore, it can be expected that the NFS will occupy a wider segment of the valley floor than in past decades and that migration and avulsion activity will likely be more episodic and less predictable.

The products of this study will provide the tools to make educated decisions about an appropriate road relocation approach and specific alignments from a river management
standpoint. This document does not consider hill slope or geotechnical conditions along any potential road alignment.
2 REGIONAL GEOLOGY

The NFS is located in the greater Skykomish River basin to the west of Stevens Pass and drains to several sub-basins. A majority of the North Fork valley downstream of approximately RM 15/MP 14 is composed of Tertiary-aged granitic intrusions and volcanic igneous rock. Jurassic and Cretaceous-aged metamorphic rocks are present in the upper reaches of the basin with some igneous intrusions, Quaternary volcanics, and landslide deposits (Figure A-3; Table B-1 in Appendix B). Throughout the study area, the valley is filled with alluvium and flanked by Oligocene-aged granodiorite bedrock of the Index Batholith, with some areas of Quaternary alpine drift and interbedded Eocene volcanic and sedimentary rock (Figure A-4; Tabor et al. 1993). Recent (post-glaciation) alluvium is composed primarily of cobbles and boulders in the channel bed, with some sand and gravel accumulations on point bars and in the floodplain. Older alluvium exists on ancient terraces that are primarily composed of stratified glacial recessional sands and gravels. Several large, ancient alluvial fans are also a part of the mapped alluvium.

It is important to understand the glacial history of the region, as this period in geologic history explains many of the features that are present today. The most recent glaciation occurred from about 19,000 to 13,000 years ago during the Fraser Glaciation. Ice originating in the mountains formed glaciers throughout the valleys of the Cascades, carving out steep valleys like the one we see for the NFS. As the glaciers began to recede, an enormous volume of meltwater was flowing off the toes of the glaciers, so that rivers often occupied the entire width of their respective valley floors. With further retreat, the amount of meltwater decreased and the rivers were no longer able to carry the available supply of glacial sediment. Sediment was deposited within the valleys, and the size of the rivers decreased significantly. A period of incision followed as rivers began to erode through and incise into the thick deposits of glacial sediment filling the valley bottoms. Over the course of thousands of years, much of the glacial sediment was removed from the NFS, leaving recessional terraces along the margins of the valley walls. These glacial terraces are currently not a part of the floodplain; however, terrace materials are easily erodible thereby making it possible that the river could occupy these areas in the future.
3 SITE DESCRIPTION

3.1 Basin Description

The NFS is a steeply sloped, high relief basin that flows from bedrock-lined canyons in the high Cascades to the confluence with the South Fork Skykomish. Over an approximately 28-mile distance, the river loses more than 4,000 vertical feet (Chart 1). The granitic and metamorphic bedrock underlying the basin create steep valley walls, and several colluvial chutes were identified, most notably just upstream of the study reach. The basin drains an area of about 147 square miles (93,950 acres), a majority of which is covered by evergreen forest. Additional land cover types include scrub/grassland, bedrock outcrops, and deciduous trees.

Chart 1

Longitudinal Profile of North Fork Skykomish
Elevations extracted from U.S. Geological Survey 10-meter Digital Elevation Model

Typical river profiles in near-equilibrium state exhibit a relatively smooth concave-up profile with a gentler sloping lower section and steeper upper section. As such, sediment supply originates in the headwaters and is typically transported through the upper watershed, and temporary sediment storage in the floodplain increases in the downstream
direction as channel gradient decreases. In many river systems, the channel slope decreases to the point that a depositional environment is present in the furthest downstream extent of the river system.

The longitudinal profile for the NFS shows several distinct changes in gradient, alternating between a concave-up and concave-down curve throughout the profile. The variations in the NFS profile are highly correlated with the extent of bedrock that the river traverses as well as the distribution of ancient landslides and alluvial fans that confine the channel. These features play a significant role in defining the channel grade and constriction during large floods. This results in variations in the sediment transport capacity along the river profile, thereby affecting the volume and lateral extent of temporary sediment storage within a given river reach. In addition, sediment input to the system occurs throughout much of the profile of the river. In locations of significant sediment inputs, channel gradient and confinement is also impacted. Distinct changes in river gradient were calculated throughout the NFS and are shown in Table 1.

<table>
<thead>
<tr>
<th>Approximate River Miles</th>
<th>Gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 18</td>
<td>1.40%</td>
</tr>
<tr>
<td>18 to 20</td>
<td>7.67%</td>
</tr>
<tr>
<td>20 to 26</td>
<td>4.03%</td>
</tr>
<tr>
<td>26 to 28</td>
<td>8.43%</td>
</tr>
</tbody>
</table>

River miles are approximate and based on Washington State Department of Natural Resources channel trace.

The project site is located within the lower basin, thereby it is within the segment of the NFS with the lowest gradient. This would suggest that the project site would be within a depositional zone or at least within an area where significant temporary sediment storage occurs. Our evaluation confirmed this hypothesis; additional information about the characteristics of specific reaches is described in more detail in later sections of this report.

The riverbed and bank material is characterized by large cobbles and boulders. Very coarse sand, gravel, and pebbles were observed as accumulations on point bars and islands (Figure 2). Boulders are angular and sub-angular in the upper reaches of the site and tend to
become more rounded downstream. In several places, the banks are lined with ancient alluvial fan deposits; these features are discussed in more detail later in this report.

![Figure 2](image)

**Figure 2**
Typical Grainsize of Mainstem Bedload

### 3.2 Human Activity

Logging and mining operations that occurred from the 1920s through the 1960s have dramatically affected river and floodplain dynamics (Hook 2006). A majority of the valley from about RM 4/MP 4.7 to RM 12/MP 11 has been clearcut in the past, and the left bank above RM 6.5/MP 6 was logged by the U.S. Forest Service (USFS) from the 1950s through 1969 (Hook 2006). In the late 1970s, the channel was cleared of wood debris by the USFS, a process formerly believed to be beneficial for flood control and fish habitat. After the channel clearing, hydraulic complexity decreased dramatically in many reaches as the river became straighter, deeper, and more narrow—since this time, the river has been recovering and continuing to recruit new wood debris (Hook 2006).

### 3.3 Hydrology

Hydrology for the NFS was recorded by a U.S. Geological Survey (USGS) stream gauge between 1910 and 1948. During this period, there were 21 peak stream flows on record, the
highest of which occurred in December 1933 at 28,400 cubic feet per second (cfs). More recent stream flow data do not exist for the NFS, although a gauge on the mainstem Skykomish River near Gold Bar, Washington, has been in operation since 1928. The magnitude of discharge recorded at this gauge station is much higher than on the NFS; however, trends in the frequency and relative magnitude of discharge over time may be of interest in considering likely future hydrologic conditions in the NFS.

Annual peak discharge data on the mainstem Skykomish River show that the highest peak discharge events have occurred in recent years (Chart 2). In general, the Skykomish River has progressively experienced more frequent flood events with higher magnitudes of flow. This is a common trend in Pacific Northwest rivers, and the frequency and magnitude of rainfall events has also been increasing over the past several decades.

![Chart 2](image-url)

**Chart 2**

**Annual Peak Discharge at Skykomish River Gauge near Gold Bar, Washington**

*For water years 1929 to 2006, USGS Gauge Station No. 12134500*
4 GEOMORPHIC PROCESSES

Geomorphic processes within the NFS can be characterized as historical and more recent. Historical processes are primarily related to the advance and recession of the last glaciations that formed the valley and subsequent processes that occurred over the following thousands of years. These ancient processes formed the valley and set constraints to future channel movement. More recent processes are described in this document as to the human influences on the river during the 1900s and the subsequent responses. Processes described include the immediate response to human activities as well as the natural recovery of the system that has been occurring over the past few decades. The projected natural recovery of the system over the next 50 years has profound implications on the expected behavior of the river—hence, the channel migration activity.

4.1 Historical Context

As mentioned previously, the glacial history of the region is primarily responsible for shaping the present-day NFS valley. The steep, bedrock-flanked valley was carved out by the advance of the glaciers approximately 19,000 years ago. As the glaciers receded, an extensive volume of sediment was released to the system, overwhelming the river’s ability to transport these materials. As a result, the valley floor was infilled with sediment and the grade of the valley was raised. At that time, the river was at a higher elevation than at present and was able to sweep across the entire valley as it deposited sediment. As the glacier continued to recede, sediment supply was dramatically reduced and a series of geomorphic processes took place that formed the ancient features we see in the system today. These features are described in Sections 4.1.1 and 4.1.2.

4.1.1 Ancient Alluvial Terraces

Alluvial terraces were formed as glacial sediment loads decreased toward the end of the last glaciation. The reduction in sediment load resulted in the river having a greater ability to transport sediment present in the riverbed. A distinct river channel developed, occupying a fraction of the river valley. Over thousands of years, the river deeply incised into the floodplain and migrated about the river valley through easily erodible alluvial material. Much of the recessional glacial materials were transported downstream as the river migrated. However, some accumulations of these materials
were not eroded away and are present as alluvial terraces that remain in the valley today.

Ancient glacial terraces were indentified throughout the project reach (Figure A-5). The elevation of these terraces relative to the existing channel was found to be up to 100 feet. Chart 3 shows a stepped cross-section of a fluvial terrace where two former channels have been abandoned at a relatively high elevation above the existing channel. Evidence of recent channel migration is also present here, but large-scale incision processes are no longer in play, leaving the former channel at a similar elevation to the active channel.

![Chart 3](chart3.png)

**Chart 3**
Cross-Sectional View at Approximately RM 9.4/MP 8.8 of Ancient Terrace Features Relative to the Existing Channel

### 4.1.2 Ancient Alluvial Fans

As glacial retreat progressed, tributary channels to the NFS also began to deliver large volumes of sediment to the NFS within the project reach. The tributary channels are very steep and had the capacity to deliver very large material to the river. Much of the sediment delivered by tributary channels was much larger than materials transported by the mainstem NFS. While some of this delivery may have occurred through fluvial
processes, it is likely that some sediment delivery occurred through colluvial processes and debris flows. Once these materials were deposited in the river, the river was unable to transport the large clast size downstream. Therefore, alluvial fans were developed and grew through time. Some of these fans are extensive in size, presently confine the river channel, and are composed of large, boulder-sized materials that the river is unable to transport.

Alluvial fans are present throughout much of the project reach along the valley walls where active (or formerly active) stream channels or debris chutes meet the valley floor (Figure A-5). Most of the fans observed appear to be actively delivering sediment to the river, although at a vastly decreased delivery rate from historical conditions. Figure 3 displays a recent delivery of sediment through a glacial terrace adjacent to the active river. This terrace is located directly downstream from an ancient fan, indicating that the fan is still delivering material to the river and may be continuing to expand, although at a much smaller rate than during the glacial period.

![Image of a stream with alluvial fans](image-url)

**Figure 3**
Debris Flow Deposits from Alluvial Fan at RM 7.6/MP 7.2
Recent debris flow deposits delivered through a terrace adjacent to an alluvial fan; seepage and surface flow observed (far right) indicates additional sediment delivery in this area is likely.
4.2 Recent Geomorphic Processes

Recent geomorphic processes are defined as system impacts and adjustments that have occurred since the influence of human activity in the basin. Human activity in the last century, such as logging, mining, and channel straightening, has greatly impacted the otherwise natural condition of the river system. This has affected the natural cycle of sediment movement, large woody debris (LWD) recruitment and deposition, and floodplain roughness. Protection of the upper watershed has resulted in a more recent trend where the system has been moving toward recovery to a natural state.

4.2.1 Human Impacts to the River

Until the 1950s, the basin was owned by private logging and mining companies. Little is known about the early extraction of wood and minerals from the area, although channel clearing to allow for materials to be transported out by river was a common practice. It was also common to extract gravel for building materials directly from the river, and we assume that practice also occurred in the NFS. It has been reported that the entire floodplain and adjacent valley walls were clearcut between 1929 and 1940 by private timber companies (Hook 2006). After the USFS acquired the land in the 1950s, logging continued until 1969 and reports of channel clearing continued into the late 1970s (Hook 2006).

What we can surmise from these activities is that the river was cleared of wood debris and logjams and straightened, likely for navigation and transport of materials. This activity would have greatly simplified the complexity of the channel. Logging of the floodplain and adjacent valley walls removed LWD from the system, thereby eliminating the possibility of LWD recruitment. These activities resulted in a river system with increased transport capacity than the natural state. Therefore, the river was capable of transporting a greater size and volume of sediment and wood through the system than under historical conditions. This likely resulted in some channel incision, further increasing the transport capacity of the river.

4.2.2 Sediment Sources

This study identified numerous sediment sources to the river although no greater understanding of current versus pre-disturbance rates of sediment delivery was
attained. As expected, tributary channels deliver a significant volume of material to the river. In addition, mass wasting adds a significant amount of material, as evidenced by numerous rock chutes, active alluvial fans, debris flows, and landslides along the valley walls. Massive sediment contributions, such as the one displayed in Figure 4, were identified upstream of the project site. Several active fans and tributary channels, such as Silver Creek, contribute large volumes of sediment to the system within the project area.

![Figure 4
Recent Debris Flow along Index Galena Road near RM 13/MP 12](image)

Although the mechanism of delivery to the river was not always certain, these features contribute significantly to the sediment sources in the system. These materials could be delivered through fluvial processes during snow melt, in the form of a debris flow, or through colluvial processes. Several active landslides were also observed along Index Galena Road and along valley walls adjacent to river banks. Many of the slides appear to consist of unsorted glacial sediment and pieces of weathered bedrock. The landslide in Figure 5 is currently active and likely delivers a significant volume of sediment to the river annually.
While numerous sediment sources were identified, it is unclear how present sediment delivery rates compare to pre-human disturbance rates. However, it is clear that the river is currently processing large volumes of sediment based on the number of sediment sources identified and the magnitude of sediment being delivered by these sources. Sediment inputs can be relatively continuous (during flood events) through tributary flow, or episodic through landslides or debris flow that may or may not be correlated with high flows in the river. Therefore, the timing and volume of sediment delivery is likely stochastic and may result in variable rates of sediment transport and storage through the project site.

4.2.3 Large Woody Debris

LWD plays an important role in the geomorphology of Pacific Northwest rivers. Wood is recruited into the system during flood events and naturally accumulates as logjams, contributing to channel and floodplain roughness, and initiating split flows and active channel widening. These jams have been identified as the most important factor
influencing channel form and process in large alluvial rivers. In addition, logjams have a significant influence on sediment transport and patterns of deposition.

Since the channel was cleared and the adjacent areas logged, LWD was removed from the system and recruitment of additional LWD was reduced. Floodplains and valley walls have been regenerating, and many areas possess trees in the 30- to 40-year-old range. While these trees are not large enough to remain stable within the mainstem channel, some are large enough to deposit on gravel bars and, in conjunction with other LWD, may be capable of forming logjams that will remain stable during moderate flood events. As trees mature in the basin, the size of some LWD delivered to the river will increase. Increasing the size of some LWD in the system will increase the likelihood that logjams will form and retain additional LWD.

4.2.4 Identified Channel Dynamics

Review of the historical aerial photographic record and traces of active channel positions through time revealed notable trends in channel behavior. The character of channel movement, or migration, was identified as both relatively steady channel migration of a riverbend through a gravel bar or floodplain, and channel avulsion where the river suddenly changes course often through historical channels abandoned through a similar process. These two channel behaviors are detailed in the sections below.

Channel Migration

Channel migration typically occurs along the outside of a meander bend where erosive forces of the river cut into its banks or instream channel bars. This process is often coupled with gravel bar development along the interior of the bend. The rates of migration are influenced by the erodibility of the bank material, magnitude of the erosive force, and orientation of flow to the eroding bank. This type of channel movement can occur in a lateral direction moving perpendicular to the valley grade, as well as in a downstream direction moving down the valley grade. In fact, nearly all channel migration activity is composed of both lateral and downstream directional components.
Steady migration of the mainstem channel near RM 3.2/MP 3.0 has been taking place throughout the photographic record. As the main channel erodes away the left bank, it moves closer to Index Galena Road, and the gravel bar in the right portion of the channel has progressively grown in a south-southeast direction (Figure 6).

![Figure 6](image)

**Figure 6**

**Steady Migration Adjacent to Index Galena Road at RM 3.2/MP 3.0**

Steady migration at approximately RM 3.2/MP 3.0; blue lines represent 2006 mainstem prior to 2006 flooding; a gravel bar grows along the inside of the meander bend

The 2006 flood eroded more than 100 feet of the bank perpendicular to flow, leaving the existing mainstem directly adjacent to the road at MP 3.0. Continued migration in this direction will likely put the Index Galena Road at risk in the near future. In fact, flood events since our initial evaluation have continued to erode the bank in this location and protective measures at this location were being considered at the time of this publication.

**Channel Avulsion**

Channel avulsion typically occurs when overland flow or flow through a former or side channel attains a greater hydraulic energy grade than the existing flow path. This often occurs in the form of cutting off a large meander bend or reoccupying a former mainstem channel location. This results in an abrupt relocation of the mainstem channel.
and subsequent abandonment of the former mainstem position. Figure 7 displays one example of a past channel avulsion within the study area.

![Figure 7](image)

**Figure 7**
Typical Channel Avulsion Activities Identified in the Lower Study Area

**4.2.5 Expected Future Channel Evolution**

The NFS is in the process of recovering from human disturbance and re-establishing more natural conditions for the system. Since the channel was de-snagged and straightened, the river has been slowly recovering. The recovery process has begun, with channel migration and lengthening of the channel network. Some LWD would be recruited to the system, but likely would be transported through the system as all floodplain materials currently are much too small to be stable in the system. Through time, additional channel migration would further extend the length of the channel network and reduce in-channel velocities. In addition, LWD on floodplains had been maturing and some LWD materials have begun to deposit on gravel bars and shallow
areas. As LWD accumulates and forms logjams, sediment deposition would be promoted in the lee of the structures. In addition, logjams help promote split channel flow and side channel development. Split flows and side channels reduce the hydraulic energy of the mainstem, thereby promoting increased deposition of LWD and sediment. In this manner, the recovery of the system is a feedback loop where channel migration leads to LWD deposition on bars and shallow areas, which leads to logjams and split flow conditions, which reduces hydraulic energy in the mainstem and promotes additional channel migration and expansion, which leads to additional deposition of LWD and sediment, and the feedback loop continues. The result of the process is an overall widening of the active channel; better hydraulic connectivity between the river, side channels, and floodplains; and a greater area impacted by flooding and erosive energy.

This feedback loop of recovery was identified through most locations within the NFS. A comparison of aerial photographs from 2006 and 2007 provides an example of channel expansion at RM 9.0/MP 8.5 near the mouth of Salmon Creek (Figure 8).

Figure 8
Channel Expansion at RM 9.0/MP 8.5
Aerial photographs at RM 9.0/MP 8.5 from 2006 (left) and 2007 (right) where rapid downstream migration resulted in channel expansion during the November 2006 flood event

Figure 8 shows that the 2006 mainstem has migrated downstream and laterally through floodplain areas of maturing vegetation. The significantly wider active channel is now present, thereby dispersing flood flows over a broader area during future floods. This
will likely result in an increase in LWD and sediment deposition in this area, promoting the continuation of the feedback loop described above.

In summary, we expect that future evolution of the NFS will include expansion of the active channel and increased deposition of LWD and sediment. This will lead to increased side channel and floodplain connectivity, expanding the flood area and the area at risk to channel avulsion. In addition, hydrologic conditions (frequency and magnitude of flood events) have been increasing, and with a greater awareness of climate change, many have predicted that this trend will continue into the foreseeable future. For these reasons, we expect that the river will occupy a greater percentage of the valley floor over the next 50 years than it has done throughout the previous 50 years. In this way, the future of the NFS may not resemble the most recent past.
5 STUDY APPROACH/METHODOLOGY

The delineation of the CMZ was conducted using electronic data available for the project area, limited site reconnaissance and survey, and historical information compiled during previous investigations (see Section 5.1). In addition, we applied widely accepted principles in fluvial geomorphology and channel form and process and applied our professional judgment to delineate the CMZ and hazard zones within the CMZ. This study Included:

- Identify the HMZ (see Section 5.2)
- Identify ancient fluvial features (see Section 5.3)
- Characterize types of channel movement and migration patterns (see Section 5.4)
- Delineate reaches (see Section 5.5)
- Delineate the CMZ (see Section 5.6)
- Delineate the CMZ into high, moderate, and low hazard zones (see Section 5.7)

5.1 Data Sources

A variety of data sources were available for the study. Abigail Hook researched historical conditions for her thesis work and presented observations of trends in natural recovery (Hook 2006). Hook also produced traces of fluvial features along the NFS including active channel traces from multiple historical aerials. Geo-rectified photographs from several of the years covered by Hook’s thesis, as well as aerial photographs from 1991, 2006, and 2007 were provided by Snohomish County. Light Detection and Ranging (LiDAR) data collected in 2007 by Snohomish County were used to create hillshades and relative elevation maps (an elevation map relative to the lowest elevation in the river channel) and to identify additional fluvial features.

Field observation was also a key component in identifying important features and distinguishing between ancient versus recent landforms that could not be classified in the LiDAR imagery. In several cases, field observation was used to make the final decisions regarding erosion potential and hazard zone classifications. Information was gathered about the characteristics of alluvium in different parts of the floodplain (such as the channel bed, gravel bars, edge of alluvial fans, and terraces), and areas of ongoing erosion were identified where relevant.
5.2 Identify the Historic Meander Zone

Identifying the HMZ was a three-step process using available geographic information system (GIS) data, historical aerial photographs, and LiDAR data. Channel traces from historical photographs identified the active mainstem and side channels for those years where the aerial photographs were available. Historical aerial photographs were examined for historical channel locations that were not included in the channel traces, and these locations were mapped. Locations of historical channel occupation were also identified by observing changes in vegetation type and density where the youth of the forest was used as an indicator of recent channel occupation. Finally, LiDAR imagery was used to identify geomorphic features indicative of channel occupation prior to the earliest aerial photographs. A relative elevation map was generated relating the floodplain adjacent to the channel (perpendicular) to the low point along the channel profile. Using the relative elevation map, we were able to identify relict channels within the historical floodplain more easily (Figure 9). Additionally, the bare earth LiDAR hillshade image was used to help recognize features within the existing channel, such as locations of ongoing erosion.

![Figure 9](image)

**Figure 9**
**Historical Channel Locations in LiDAR Imagery**
Several historical channel locations (faint blue areas depicted with red arrows) near RM 9.0/MP 8.5 that pre-date channel traces (purple) available from aerial photographs.

The HMZ was delineated by tracing the outer extent of all historical channel locations identified through the above-described process, regardless of elevation (Figure A-6). This
boundary displays the known area of river occupation since and possibly during the recession of the last glaciation. The HMZ represents the area the river has been in the past; however, because of channel incision and geologic constraints, it is not likely to reoccupy some of these areas.

5.3 Identify Ancient Fluvial Features

Terraces and alluvial fans were delineated by reviewing GIS data, evaluating aerial photographs and LiDAR imagery, and conducting a field reconnaissance. The purpose of this evaluation was to remove areas of the HMZ where the channel is unlikely or otherwise incapable of reoccupying. Channel incision after the last glacial retreat has rendered large areas of the HMZ inaccessible, and alluvial fans at tributary junctions have delivered clasts larger in size than the river is capable of transporting.

Identified ancient terraces fall into two categories: 1) high terraces with elevations far above the existing channel that the river is incapable of occupying; and 2) low terraces where the composition of the terraces make them highly erodible.

High terraces are at very high elevations relative to the river and located up the valley slope. An example of these terraces is displayed on Chart 3 in Section 4.1.1. High terraces were excluded from the CMZ because the likelihood of channel occupation is very low to impossible.

Low terraces may be outside the existing floodplain, but they are susceptible to future channel occupation. The initial boundary of the CMZ was set at the edge of the low terraces, and migration through the terraces was evaluated using methods described in the next several sections.

The initial CMZ boundary was narrowed based on the location of alluvial fans. While the elevation difference between the existing floodplain and fan surface is appreciable, many of these fans are composed of boulders that are much larger than the material transported by the river. Boulders exposed along the boundaries of the fans have created a natural barrier that exceeds the hydraulic capacity of the river; hence, the river is very unlikely to erode through these materials (Figure 10).
5.4 Characterize Types of Channel Movement and Migration Patterns

As described previously, the NFS moves through both relatively steady channel migration of a riverbend through a gravel bar or floodplain, and channel avulsion where the river suddenly changes course, often through historical channels abandoned through a similar process. We characterized the dominant type of channel change in river segment as either a lateral or downstream dominated steady migration, or channel avulsion where steady migration occurs until a side or former mainstem channel is encountered and then the river significantly changes course. This characterization was conducted by evaluating successive years of aerial photographs and carefully documenting the specific behavior of meander bends and locations where significant change has occurred within the time period of the historical record.

5.5 Delineate Reaches

Distinct reaches within the NFS were delineated based on valley confinement, channel migration character, and channel gradient. Confinement was typically identified in the form of alluvial fans along the channel margins where large boulders have buttressed the
bank and prevented migration. The channel is also confined at the mouth of tributaries that contribute significant volumes of material to the river. These materials have a component larger in size than the bedload of the river. Migration character was evaluated throughout the project area, and areas of change between one dominant characteristic and another were used to aid in the delineation. For example, some areas were dominated by a relatively consistent downstream migration of meander bends, while other areas displayed a history of channel avulsion. River gradient was calculated every 1,000 feet to determine the gradient for 4,000-foot segments. These data were used to help identify grade breaks that would be significant from a river dynamics standpoint and hence, from a channel migration perspective.

5.6 Delineate the Channel Migration Zone

For the purposes of this report, the CMZ is defined as the area of the active channel, floodplain, and adjacent uplands that may be susceptible to erosion and/or occupation of the active channel. The time period evaluated for potential occupation was 50 years into the future. The CMZ delineation drew heavily from the physical features present in the valley, dominant channel migration character, and our technical expertise in river hydrodynamics. In addition, our understanding of ongoing geomorphic processes and expected future channel conditions (described previously in this report) were applied in delineating the CMZ. Collectively, these factors were used to delineate the outer extent of the CMZ.

Evaluating physical features was focused on the erosion resistance of the riverbank and floodplain materials. Some features were considered hard points in the system and the hydrodynamics associated with hard points were factored into expected erosion. Elevation of floodplains and upland areas was also considered, in that for low lying areas where erosion is possible from overland flow and avulsion (as opposed to bank erosion only), the likelihood of channel occupation is greater.

The dominant channel migration character for the reach was factored into the CMZ as an indicator of erosive potential or intent. Trends in historical patterns—essentially, how the river behaves and where the river wants to go—were factored in. This parameter changes through the reach and thus is an important consideration. In addition, this parameter can
help estimate the expected magnitude of future erosion through areas where erosion potential is high.

The expected future conditions of the river channel and floodplain are vitally important to the delineation, in that we do not expect the future to resemble the past through the project area. Trends indicate that LWD storage and logjam accumulations have been increasing over the past few decades. This has led to increased temporary sediment storage and an expansion in channel width within the active channel. We expect these trends to continue as this process creates a feedback loop that will promote additional LWD and sediment storage, forested island development, and additional widening of the active channel. This process will also likely lead to increased channel avulsion activity, thereby increasing the volatility, or unpredictability, of the system.

5.7 Delineate the CMZ into High, Moderate, and Low Hazard Zones

Within the outer boundary, the CMZ was further delineated into high, moderate, and low hazard zones. These hazard zones are a rough approximation of the relative risk of channel occupation within the 50-year time period of the CMZ based upon the criteria described in Section 5.6. It is important to note that the boundaries between zones are a rough approximation and represent the probability of channel occupation along a reach or sub-reach scale. In reality, it is likely that some areas may in fact be subject to channel occupation, while others are not based upon the typical geometry of migration. The following paragraphs further explain the delineation of zones.

5.7.1 High Hazard Zone

The high hazard zones consist of the existing active channel, recent and low floodplain areas, and all side channels located in the photographic record. The high hazard zone also includes additional areas of the floodplain susceptible to channel avulsion and lateral and downstream migration. Actively eroding banks in high or ancient areas of the valley were also included where migration character and hydraulic capacity make erosion likely. These bank areas were verified by field observation. Slope failure or landsliding directly adjacent to the channel caused by bank undercutting was accounted for where the possibility for mass wasting could be reasonably identified by field observation or with the available data.
5.7.2 Moderate Hazard Zone

Moderate hazard zones typically include areas susceptible to erosion in the event of channel avulsion or unidirectional channel migration over an extended period of time. These areas are typically located at a distance away from the active channel or in high bank or erosion resistant areas. The moderate hazard zone also frequently includes small portions of the toe of alluvial fans to account for potential erosion by the river. This would likely occur only if the river approached the toe of the fan directly, resulting in the river abruptly changing course when impacting the fan. This scenario would likely result in only slight erosion in terms of linear distance based on material composition of the fans. In general, the moderate zone accounts for channel avulsion that requires a significant amount of channel migration before an avulsion may occur, or unidirectional channel migration that is relatively less probable than channel migration in the high hazard zone.

5.7.3 Low Hazard Zone

Low hazard zones cover areas of the CMZ where channel occupation is possible under specific conditions although not very likely. These areas are located where materials are highly erodible, but the location is a great distance away from the active channel or potential channel avulsion paths. In addition, some areas delineated as low hazard zones are in places where bank materials are resistant to erosion, but hydraulic energy has the potential to be great and migration character suggests that it possible that the river may work this area for a significant time.
6 REACH DELINEATION

Distinct reaches were delineated to assist in describing the reach scale existing conditions and location specific channel dynamics. The reach delineation also aided in describing locations of similar channel migration potential and hazard zone delineation. Reach delineation was based on the criteria described in Section 5. The resultant reach boundaries are presented in Figure A-7 and Table 2.

<table>
<thead>
<tr>
<th>Reach</th>
<th>River Miles</th>
<th>Mile Posts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.7 to 11.0</td>
<td>9.1 to 10.3</td>
</tr>
<tr>
<td>2</td>
<td>8.0 to 9.7</td>
<td>7.5 to 9.1</td>
</tr>
<tr>
<td>3</td>
<td>7.5 to 8.0</td>
<td>7.1 to 7.5</td>
</tr>
<tr>
<td>4</td>
<td>5.6 to 7.5</td>
<td>5.1 to 7.1</td>
</tr>
<tr>
<td>5</td>
<td>1.8 to 5.6</td>
<td>1.3 to 5.1</td>
</tr>
</tbody>
</table>

### 6.1 Geologic Confinement and Floodplain Characteristics

The geologic features of the river valley have a significant impact on its migration potential. Within the NFS valley, confinement by bedrock or boulder-sized alluvial fan material exists in several places throughout the study area. Confined reaches are commonly areas of increased hydraulic capacity; most sediment is moved through the reach and therefore temporary storage is minimal. Conversely, reaches with wider floodplains have a higher possibility for temporary sediment storage, and the river has a greater ability to migrate throughout the floodplain. Table 3 describes the physical conditions within each reach.

### Table 3

Confinement and Floodplain Characteristics

<table>
<thead>
<tr>
<th>Reach</th>
<th>Extent</th>
<th>Degree of Confinement</th>
<th>Floodplain and Bank Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Right Bank</td>
</tr>
<tr>
<td>1</td>
<td>RM 9.7 to 11.0</td>
<td>High</td>
<td>Moderately erosive</td>
</tr>
<tr>
<td></td>
<td>MP 9.1 to 10.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>RM 8.0 to 9.7</td>
<td>Low</td>
<td>Highly erosive</td>
</tr>
<tr>
<td></td>
<td>MP 7.5 to 9.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>RM 7.5 to 8.0</td>
<td>High</td>
<td>Erosion resistant</td>
</tr>
<tr>
<td></td>
<td>MP 7.1 to 7.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>RM 5.6 to 7.5</td>
<td>Low</td>
<td>Highly erosive; erosion resistant at fan</td>
</tr>
<tr>
<td></td>
<td>MP 5.1 to 7.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>RM 1.8 to 5.6</td>
<td>Moderate</td>
<td>Erosion resistant</td>
</tr>
<tr>
<td></td>
<td>MP 1.3 to 5.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6.2 Migration Types

Dominant migration type was used as an indicator of where to locate reach boundaries. Historical channel traces, aerial photographs, and LiDAR were utilized to determine dominant and secondary types of migration, as described previously in this report. Table 4 displays the dominant and secondary migration type within each reach.

<table>
<thead>
<tr>
<th>Reach</th>
<th>Extent</th>
<th>Dominant Migration</th>
<th>Secondary Migration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RM 9.7 to 11.0</td>
<td>Downstream</td>
<td>Lateral</td>
</tr>
<tr>
<td></td>
<td>MP 9.1 to 10.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>RM 8.0 to 9.7</td>
<td>Downstream</td>
<td>Avulsive</td>
</tr>
<tr>
<td></td>
<td>MP 7.5 to 9.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>RM 7.5 to 8.0</td>
<td>Downstream</td>
<td>Lateral</td>
</tr>
<tr>
<td></td>
<td>MP 7.1 to 7.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>RM 5.6 to 7.5</td>
<td>Avulsive</td>
<td>Lateral</td>
</tr>
<tr>
<td></td>
<td>MP 5.1 to 7.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>RM 1.8 to 5.6</td>
<td>Downstream</td>
<td>Avulsive</td>
</tr>
<tr>
<td></td>
<td>MP 1.3 to 5.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Steady downstream migration appears to be the dominant migration type taking place through much of the study area. This is likely because of the steepness of the valley grade and the fact that the river was cleared in the past. However, we expect that future conditions will be such that the river will become avulsive and as such, there will likely be greater lateral components to channel migration as well.

6.3 Gradient and Hydrologic Inputs

The valley gradient throughout the study area was examined for prominent increases or decreases in slope that may indicate important changes in channel behavior, such as a transition point between a transport and a depositional zone. The gradient was measured along the thalweg at 1,000-foot intervals by averaging the gradient 2,000 feet upstream and downstream from each point (Table B-2). Chart 4 shows the averaged gradient at 1,000-foot intervals from the South Fork Skykomish confluence to RM 11.0/MP 10.3. Gradient values were used to help delineate reach boundaries, which are displayed in Chart 4 as vertical black lines. Once reaches were delineated, the reach scale gradient for each reach was calculated, for use in calculating reach scale slope discharge products.
Gradient throughout the Study Area

Gradient averaged over a length of 4,000 feet of the thalweg, measured at 1,000-foot intervals; measurements were taken from the South Fork Skykomish confluence (Station 0.00) to approximately RM 11.0/MP 10.3

Hydrologic inputs with discharge values more than 200 cfs during a 100-year flood event were identified using the USGS Streamstats tool for Washington State (2007). Using known discharge values for the NFS and tributary discharge values from Streamstats, a slope-discharge product was calculated for each reach during a 100-year event (Table 5). The slope-discharge product is an indicator of hydraulic energy and hence, sediment transport capacity within a reach.
### Table 5
Average Gradient and Slope-Discharge Product for Project Reaches

<table>
<thead>
<tr>
<th>Reach</th>
<th>Average Gradient (percent)</th>
<th>Slope-Discharge Product (cubic feet per second)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.57%</td>
<td>529.38</td>
</tr>
<tr>
<td>2</td>
<td>1.45%</td>
<td>539.38</td>
</tr>
<tr>
<td>3</td>
<td>1.43%</td>
<td>531.88</td>
</tr>
<tr>
<td>4</td>
<td>1.21%</td>
<td>510.21</td>
</tr>
<tr>
<td>5</td>
<td>0.90%</td>
<td>433.61</td>
</tr>
</tbody>
</table>

See Tables B-2 and B-3 in Appendix B for gradient and slope-discharge calculations. The slope discharge product is a product of the average gradient of the reach and the total mainstem flow within the reach.
7 CHANNEL MIGRATION AND HAZARD ZONE DELINEATION

7.1 Reach 1 (RM 9.7 to 11.0, MP 9.1 to 10.3)

7.1.1 Description

Reach 1 is the furthest upstream reach with the largest mid-reach hydrologic input within the project area, an approximately 17 percent increase at the Silver Creek confluence (Figure A-8). The floodplain area is narrowly confined by bedrock on both sides of the valley, and only a few glacial terraces are present (Figure A-9). Silver Creek has developed a large fan that contributes a large volume of sediment, including some large material. The fan itself appears to provide enough sediment to inhibit migration through the fan, as evidenced by a gravel bar at the mouth of the creek in all historical aerial photographs. Although there are post-glaciation floodplain deposits in this reach, the channel has not moved into the floodplain within the historical record. The steep gradient of this reach allows for a narrow, deep main channel with a high hydraulic capacity and a relatively low amount of temporary sediment storage (Figure 11). Reach 1 appears to display steady downstream and lateral migration, but the lack of channel movement within the historical record suggests that the rate of migration is slower than in other reaches.

Figure 11
Mainstem Channel at Reach 1
The channel looking upstream from the Index Galena Bridge at the upstream extent of the study area
7.1.2 Channel Migration Zone Delineation

The solid confinement and relatively slow rate of migration, as well as the 50-year study period, suggest that the CMZ boundary and high risk zone are narrow throughout the reach (Figure A-10). Migration in this reach within the historical record has been minimal, although some migration in the future is expected. Migration in this area is caused by bank erosion, rather than avulsion, although an avulsion could occur where historical channels are present if a significant bed elevation increase were to occur over time. The moderate hazard zone throughout this reach is also narrow; the boundary between the high and moderate zones is dictated by proximity to the channel and expected migration rates, except near RM 10/MP 9.4 where the moderate boundary lies along a historical channel on the left side of the existing channel that is at a higher elevation. Although Index Galena Road lies outside of the CMZ boundary throughout a majority of the reach, the area with the highest risk of erosion is on the north side of the Index Galena Bridge where avulsion risks are well known; a portion of the road embankment was eroded by high flows in 2006 (Figure 12).

Figure 12
Washout North of Index Galena Bridge
This portion of the road is in the high hazard zone—the river is located directly adjacent to the opposite side of the road
7.2 Reach 2 (RM 8.0 to 9.7, MP 7.5 to 9.1)

7.2.1 Description

Reach 2 begins where the river exits the narrow, confined valley in Reach 1 and enters a broader, more accessible floodplain area (Figure A-11). Hydrologic inputs are minor and include Howard Creek, Lost Creek, and Salmon Creek. Reach 2 is unconfined relative to upstream and downstream reaches, and a majority of the floodplain is low post-glaciation alluvium (Figure A-12). Moderately erosive alpine glacial drift is located near the left, upstream boundary of the reach; weathered glacial drift is actively being deposited at the mouth of Howard Creek, creating a fan of gravelly material that is much smaller in size than typical alluvial fans in the study area. Ancient terraces are present at the upstream boundary. While these fans are high in elevation relative to the channel, they are highly erosive. Ancient terrace material downstream of the Salmon Creek outlet is currently being eroded away by the river and wasted by overland flow (Figure 13).

Figure 13
Eroding Terrace near Salmon Creek
The remains of a glacial terrace on the right bank near the mouth of Salmon Creek; the bank is being actively eroded by the river as well as by overland flow (far left)
Reach 2 is naturally a depositional area where the gradient drops from the bedrock canyon into a wider, flatter floodplain. Due to the high rate of deposition and frequent reworking of material during high flow events, the channel appears to migrate across the valley floor frequently through this reach. In recent decades, this has led to overall channel expansion. Within the photographic record, there are several places where rapid channel expansion has occurred, particularly during the 2006 flood event. Avulsions are also possible because many abandoned channels exist in the floodplain that could be reoccupied during a large event or when a steadily migrating bend erodes in a unilateral direction toward the low channel (Figure A-12).

### 7.2.2 Channel Migration Zone Delineation

Since a majority of the floodplain is composed of highly erodible material and has an elevation within 10 to 20 feet of the mainstem channel, the high hazard zone is extensive in Reach 2 and widens considerably from the hazard zone width of Reach 1 (Figure A-13). Several past avulsions have been identified within this zone, and avulsion activity will likely increase over the next 50 years as the channel expands and stores additional LWD and sediment. The moderate zone is very narrow in the upper portion of Reach 2 and generally is distinguished from the high hazard zone by an abrupt change in elevation and a perceived increase in erosion resistance (based upon available information). Index Galena Road lies outside of the CMZ boundary or in the low hazard zone throughout most of the reach except for a short segment near RM 8.3/MP 7.9, where the roadway is within the high hazard zone of the CMZ (Figure A-13).

### 7.3 Reach 3 – RM 7.5 to 8.0/MP 7.1 to 7.5

#### 7.3.1 Description

Reach 3 has no major hydrologic inputs and is unlike other reaches in that it is tightly confined on both sides of the valley by large alluvial fans (Figure A-14). The alluvial fan on the left side appears to be ancient, as no evidence of recent deposits was observed. Finer sediments overlying large boulders and an old growth cedar stump suggest the energy of the fan diminished over time and that the material has not been moved in the last few hundred years (Figure 14). The fan on the right bank is actively depositing debris flow material and eroding the ancient terrace deposit (see Figure 3). Sediment inputs from these debris flows are likely episodic and may or may not be associated
with flood events on the main river. The channel position has not migrated from its current position since the 1960s, despite channel clearing and high flow events that have altered other portions of the river. Hence, this reach is relatively stable and is not likely to change dramatically in the future.

Figure 14  
Toe of Ancient Alluvial Fan near RM 8.0/MP 7.5  
The toe of the large, inactive ancient alluvial fan near RM 8.0/MP 7.5 with large boulders at the toe

7.3.2  Channel Migration Zone Delineation

Large toe material in the left fan and debris flow deposits from the right fan constrict the high hazard zone to a relatively narrow width (Figures A-15 and A-16). The high hazard zone includes the remaining glacial terrace in front of the right fan that is actively eroding and will likely continue to do so. Along the fan and terrace boundaries, the moderate hazard limit accounts for continued erosion of the terrace and minor erosion into the right fan beyond the HMZ. The floodplain in the lower left portion of the reach is more erosive than the confined portion of the reach where the moderate zone boundary is related to the proximity of the floodplain to the existing channel and the angle that the channel may flow around the downstream end of the fan under potential future channel orientations. Index Galena Road is outside the CMZ boundary.
as it traverses a large alluvial fan. Through the downstream portion of the reach, the roadway is within the high hazard zone of the CMZ.

7.4 Reach 4 (RM 5.6 to 7.5, MP 5.1 to 7.1)

7.4.1 Description
Reach 4 includes the confluences of Excelsior Creek and Trout Creek—large tributaries that increase the discharge of the river by approximately 15 percent—and the upper and lower roadway washouts at MP 6.4 and 6.9 (Figure A-17). Alluvial fan deposits along the right side of the valley form the boundary of the CMZ through much of this reach (Figure A-18). Bedrock near RM 6.2 constricts the CMZ through a short portion of this reach. Despite these constriction points, the majority of the floodplain is low, wide, and highly erosive. Thin remnants of ancient glacial terraces are present along the right side of the valley that are composed of highly erodible material (Figure A-18).

The active channel is highly mobile and is capable of movement throughout the width of the low lying floodplain. A significant drop in gradient and sediment transport capacity coming out of Reach 3 allows for increased deposition of LWD and sediment in Reach 4. Review of aerial photographs indicates that the channel has moved throughout the floodplain, and the active channel has expanded during recent decades (Figure A-18). Most recently, logjam formation, sediment deposition, and channel migration to the south resulted in the washouts of the Index Galena Road and the development of an active side channel along and adjacent to the roadway alignment.

7.4.2 Channel Migration Zone Delineation
The CMZ on the left side of the valley is bounded by bedrock and alluvial fan materials, primarily the Trout Creek fan. This fan is composed of boulders that are much larger in diameter than the bedload of the present-day river (see Figure 10). For this reason, the fan acts as a hard point and a buffer limiting the CMZ through this area. Although portions of the floodplain in this reach have re-vegetated, these areas are highly susceptible to future erosion, and the channel will likely migrate through much of the forested area within the next 50 years.
The high hazard zone in Reach 4 encompasses the active floodplain, as well as portions of highly erosive terraces on the right side of the valley (Figure A-19). Rapid steady migration, numerous historical channels, and a history of avulsion in this reach imply that there is a high risk for movement throughout much of the floodplain, including through the forested area northwest of the road. We expect that the side channel flowing through the washout areas will continue to expand, and an avulsion of the mainstem through this area is certainly possible. The side channel is currently steeper than the mainstem, so it is possible that the river will migrate to this path of least resistance (Figure 15). A large logjam between the two channels may factor into future channel positions as well future LWD accumulation and the location of sediment deposition during large flood events. Index Galena Road is located within the high hazard zone through much of the reach, with the exception of the Trout Creek fan and the bedrock knob near RM 6.2/MP 5.7. Through the downstream reach, the road traverses a mix of the high and moderate hazard zones.

Figure 15
Relative Elevation of Mainstem versus Side Channel near Upper Washout
The side channel (foreground) that leads to the MP 6.4 and 6.9 washouts follows a steeper path than the mainstem channel (background behind instream bar)
7.5 Reach 5 (RM 1.8 to 5.6, MP 1.3 to 5.1)

7.5.1 Description

Reach 5 extends from the upstream limit of the town of Index at RM 1.8, to RM 5.6. This portion of the river receives flow from Lewis Creek, Canyon Creek, Bitter Creek, North Star Creek, and Boss Creek, although the overall hydrologic increase is insignificant (Figures A-20 and A-21). The existing channel is located on the right side of the valley and bordered by alluvial fan deposits along the right bank. Similar alluvial fan deposits are located along the left side of the valley from approximately RM 4.5/MP 4.2 to RM 3.4/MP 3.1 (Figures A-22 and A-23). The floodplain throughout a majority of the reach is composed of highly erosive post-glaciation deposits and several historical channels and terraces are present. Some homes in the Skyko community are located on the lowest of these terraces about 10 feet higher than the existing channel near RM 2.0/MP 1.4 (Figure A-23).

This reach primarily displays steady downstream migration but also has a history of avulsion. In the upper part of the reach, steady migration has been occurring within the period of record, and historical channels in the floodplain suggest that avulsion is likely in the future (Figure A-22). A meander bend near RM 5.2/MP 4.8 is actively eroding floodplain deposits as it migrates in a southwesterly direction, and historical channels lie to the south in the path of erosion (Figure 16).
Figure 16
Steady Downstream Migration near RM 5.2/MP 4.8

In the lower reach, the active channel moves about freely, frequently changing channel positions and orientations of bar deposits. A meander bend that currently parallels the Skyko community has moved several hundred feet downstream since 1992, steadily eroding the low terrace mentioned previously (Figure 17). Currently, multiple residences are located in the path of erosion and may be at risk of future channel occupation.
Figure 17
Downstream Channel Migration at RM 2.3/MP 1.8
Downstream channel migration at approximately RM 2.3/MP 1.8 from 1992 through 2007; the black arrow indicates the average direction of migration

7.5.2 Channel Migration Zone Delineation

The CMZ for Reach 5 includes all terraces in the upstream part of the reach and a portion of the terraces in the lower reach (Figures A-22 and A-23). A bedrock knob at the upstream reach boundary confines the channel, but erosion is still possible around the downstream side of the knob. Because the valley bottom is mostly composed of terrace and overbank material in this reach, the floodplain is highly erodible. Avulsions were identified in the photographic record, and it is expected that avulsion activity will occur in the future, particularly where a migrating bend erodes into an historical channel.

The high hazard zone for Reach 5 includes a majority of the left floodplain in the upper reach and a portion of the floodplain in the lower reach (Figures A-24 and A-25). The high hazard zone maintains a similar width throughout the reach (except where it is confined by bedrock or alluvial fan material).

The moderate hazard zone is narrow on the right side of the valley and is often located on the downstream side of confining features. On the right side, the moderate hazard
zone is located at elevation changes such as on a terrace that is located slightly higher than the rest of the floodplain, or was determined by proximity to the current channel and expected migration rates. Index Galena Road is not within the CMZ through much of Reach 5. The road is located through the low hazard zone near RM 5.0/MP 4.7 and through the high hazard zone near RM 3.2/MP 3.0 where the river is actively eroding into the road prism.
8 LIMITATIONS

We have prepared this report for use by Snohomish County Public Works Engineering Services Division for use in evaluating appropriate locations for relocating the Index Galena Road. Channel Migration and Hazard Zones are approximate and based on available data and limited site reconnaissance. Further refinement of boundaries displayed in this report will require additional evaluation and exploration of floodplain and upland materials. Conditions within the subject reach may change both spatially and with time, and additional scientific data may become available. Significant changes in site conditions or the available information may require re-evaluation. Within the limitations of scope, schedule, and budget, our services have been executed in accordance with generally accepted scientific and engineering practices in this area at the time this report was prepared.
9 REFERENCES


Source: Streams layer from WA DNR. Roads from ESRI. Parks, state, city and county boundaries from WSDOT. NFS watershed boundary from USGS Streamstats (2007).

Note: This figure has been created and utilized in support of the NFS Channel Migration Study. The figure is intended for use in the scope of the referenced report and should not be used outside of this context. All locations are approximate and have been created using available data. If additional data become available, further analysis may be necessary.
Source: Aerial image taken in 2006 prior to MP 6.4 and 6.9 washouts. Stream layer from WA DNR.
Note: This figure has been created and utilized in support of the NFS Channel Migration Study. The figure is intended for use in the scope of the referenced report and should not be used outside of this context. All locations are approximate and have been created using available data. If additional data become available, further analyses may be necessary.
Source: Geologic data and streams from WA DNR (2005). See Table B-1 for geologic unit names and descriptions. Geologic contacts are approximate. Basin delineation from USGS Streamstats (2007). Note: This figure has been created and utilized in support of the NFS Channel Migration Study. The figure is intended for use in the scope of the referenced report and should not be used outside of this context.
Surficial Geology of Project Area

Index Galena Flood Repairs MP 6.4 to 6.9

Source: Surficial geology data were collected by observation WA DNR geology data (2005), LiDAR imagery and field mapping. All contacts are approximate. Aerial photo taken in 2006 prior to MP 6.4 and 6.9 washouts.

Note: This figure has been created and utilized in support of the NFS Channel Migration Study. The figure is intended for use in the scope of the referenced report and should not be used outside of this context. All locations are approximate and have been created using available data. If additional data become available, further analyses may be necessary.
Figure A-5

Ancient Fluvial Terraces and Alluvial Fans Within the Project Area

North Fork Skykomish Channel Migration Study
Index Galena Flood Repairs MP 6.4 to 6.9

Source: Surficial geology data were collected by observation of LiDAR imagery and field mapping. All contacts are approximate. Aerial image taken in 2006 prior to MP 6.4 and 6.9 washouts.

Note: This figure has been created and utilized in support of the NFS Channel Migration Study. The figure is intended for use in the context of this report and should not be used outside of this context. All locations are approximate and have been created using available data. If additional data become available, further analysis may be necessary.
Figure A-6
Historic Channel Locations 1965-2007 and Historic Migration Zone
North Fork Skykomish Channel Migration Study
Index Galena Flood Repairs MP 6.4 to 6.9

Source: Channel traces from Hook (2006) and 2007 aerial photo provided by Snohomish County. Relative elevation map produced from 2007 LiDAR provided by Snohomish County.

Note: This figure has been created and utilized in support of the NFS Channel Migration Study. The figure is intended for use in the scope of the referenced report and should not be used outside of this context. All locations are approximate and have been created using available data. If additional data become available, further analyses may be necessary.
Figure A-7
Delineation of Reaches in Project Area
North Fork Skykomish Channel Migration Study
Index Galena Flood Repairs MP 6.4 to 6.9

Source: Aerial image taken in 2006 prior to MP 6.4 and 6.9 washouts.
Note: This figure has been created and utilized in support of the NFS Channel Migration Study. The figure is intended for use in the scope of the referenced report and should not be used outside of this context. All locations are approximate and have been created using available data. If additional data become available, further analyses may be necessary.
Figure A-8
2007 Aerial Photo, Reach 1
North Fork Skykomish Channel Migration Study
Index Galena Flood Repairs MP 6.4 to 6.9

Source: 2007 aerial photo provided by Snohomish County. Streams from WA DNR.
Note: This figure has been created and utilized in support of the NFS Channel Migration Study. The figure is intended for use in the scope of the referenced report and should not be used outside of this context. All locations are approximate and have been created using available data. If additional data become available, further analyses may be necessary.
Figure A-9
Geomorphic Features, HMZ and CMZ, Reach 1
North Fork Skykomish Channel Migration Study
Index Galena Flood Repairs MP 6.4 to 6.9

Source: Relative elevation map produced from 2007 LiDAR provided by Snohomish County. Water surface from 2007 aerial photo provided by Snohomish County.

Note: This figure has been created and utilized in support of the NFS Channel Migration Study. The figure is intended for use in the scope of the referenced report and should not be used outside of this context. All locations are approximate and have been created using available data. If additional data become available, further analysis may be necessary.

Relative Elevations
- Less than -5
- -5 to 5
- 5 to 10
- 10 to 20
- 20 to 30
- 30 to 40
- 40 to 50
- 50 to 100
- 100 to 200
- 200 to 300
- 300 to 400
- 400 to 500
- 500 to 1,000

River Miles
Road Mileposts
Index-Galena Road
2007 Water Surface
Reach Boundaries
Fluvial Terraces
Alluvial Fan Deposits
Glacial Alpine Drift
Bedrock

Source: B:\Projects\0532_Lochner\080532-01_IndexGalena\GIS\Maps\CMZ_Report\Fig9_CMZ_r1.mxd  mlee  02/26/2009  11:48 AM
Source: Water surface from 2007 aerial photo provided by Snohomish County.
Note: This figure has been created and utilized in support of the NFS Channel Migration Study. The figure is intended for use in the scope of the referenced report and should not be used outside of this context. All locations are approximate and have been created using available data. If additional data become available, further analyses may be necessary.
Figure A-11

2007 Aerial Photo, Reach 2
North Fork Skykomish Channel Migration Study
Index Galena Flood Repairs MP 6.4 to 6.9

Source: 2007 aerial photo provided by Snohomish County. Streams from WA DNR.
Note: This figure has been created and utilized in support of the NFS Channel Migration Study. The figure is intended for use in the scope of the referenced report and should not be used outside of this context. All locations are approximate and have been created using available data. If additional data become available, further analyses may be necessary.
Figure A-12
Geomorphic Features, HMZ and CMZ, Reach 2
North Fork Skykomish Channel Migration Study
Index Galena Flood Repairs MP 6.4 to 6.9

Source: Relative elevation map produced from 2007 LiDAR provided by Snohomish County. Water surface from 2007 aerial photo provided by Snohomish County.

Note: This figure has been created and utilized in support of the NFS Channel Migration Study. The figure is intended for use in the scope of the referenced report and should not be used outside of this context. All locations are approximate and have been created using available data. If additional data become available, further analysis may be necessary.
Low Hazard Zone  Moderate Hazard Zone  High Hazard Zone  Bedrock

River Miles  Road Mileposts  Index-Galena Road  2007 Water Surface  Reach Boundaries  Historic Migration Zone  Channel Migration Zone  Road and CMZ Intersection

Source: Water surface from 2007 aerial photo provided by Snohomish County.

Note: This figure has been created and utilized in support of the NFS Channel Migration Study. The figure is intended for use in the scope of the referenced report and should not be used outside of this context. All locations are approximate and have been created using available data. If additional data become available, further analyses may be necessary.
Figure A-14
2007 Aerial Photo, Reach 3
North Fork Skykomish Channel Migration Study
Index Galena Flood Repairs MP 6.4 to 6.9

Source: 2007 aerial photo provided by Snohomish County. Streams from WA DNR.
Note: This figure has been created and utilized in support of the NFS Channel Migration Study. The figure is intended for use in the scope of the referenced report and should not be used outside of this context. All locations are approximate and have been created using available data. If additional data become available, further analyses may be necessary.
Figure A-15
Geomorphic Features, HMZ and CMZ, Reach 3
North Fork Skykomish Channel Migration Study
Index Galena Flood Repairs MP 6.4 to 6.9

Source: Relative elevation map produced from 2007 LIDAR provided by Snohomish County. Water surface from 2007 aerial photo provided by Snohomish County.

Note: This figure has been created and utilized in support of the NFS Channel Migration Study. The figure is intended for use in the scope of the referenced report and should not be used outside of this context. All locations are approximate and have been created using available data. If additional data become available, further analysis may be necessary.
Low Hazard Zone  Moderate Hazard Zone  High Hazard Zone  Bedrock

Source: Water surface from 2007 aerial photo provided by Snohomish County.

Note: This figure has been created and utilized in support of the NFS Channel Migration Study. The figure is intended for use in the scope of the referenced report and should not be used outside of this context. All locations are approximate and have been created using available data. If additional data become available, further analyses may be necessary.
Figure A-17
2007 Aerial Photo, Reach 4
North Fork Skykomish Channel Migration Study
Index Galena Flood Repairs MP 6.4 to 6.9

Source: 2007 aerial photo provided by Snohomish County. Streams from WA DNR.
Note: This figure has been created and utilized in support of the NFS Channel Migration Study. The figure is intended for use in the scope of the referenced report and should not be used outside of this context. All locations are approximate and have been created using available data. If additional data become available, further analyses may be necessary.
Figure A-18
Geomorphic Features, HMZ and CMZ, Reach 4
North Fork Skykomish Channel Migration Study
Index Galena Flood Repairs MP 6.4 to 6.9

Source: Relative elevation map produced from 2007 LiDAR provided by Snohomish County. Water surface from 2007 aerial photo provided by Snohomish County.

Note: This figure has been created and utilized in support of the NFS Channel Migration Study. The figure is intended for use in the scope of the referenced report and should not be used outside of this context. All locations are approximate and have been created using available data. If additional data become available, further analysis may be necessary.

Relative Elevations
- Less than -5
-5 to 5
5 to 10
10 to 20
20 to 30
30 to 40
40 to 50
50 to 100
100 to 200
200 to 300
300 to 400
400 to 500
100 to 200
200 to 300
300 to 400
400 to 500
500 to 1000

Legend:
- Fluvial Terraces
- Alluvial Fan Deposits
- Glacial Alpine Drift
- Bedrock
- River Miles
- Road Mileposts
- Index-Galena Road
- 2007 Water Surface
- Reach Boundaries
- Historic Migration Zone
- Channel Migration Zone
- Road and CMZ Intersection

0 1,000 Feet
0 1,000 Meters

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2007 Water Surface
Reach Boundaries
Road and CMZ Intersection
Fluvial Terraces
Alluvial Fan Deposits
Glacial Alpine Drift
Bedrock
Low Hazard Zone  Moderate Hazard Zone  High Hazard Zone  Bedrock

River Miles  Road Mileposts  2007 Water Surface

Reach Boundaries  Historic Migration Zone  Channel Migration Zone  Road and CMZ Intersection

Source: Water surface from 2007 aerial photo provided by Snohomish County.
Note: This figure has been created and utilized in support of the NFS Channel Migration Study. The figure is intended for use in the scope of the referenced report and should not be used outside of this context. All locations are approximate and have been created using available data. If additional data become available, further analyses may be necessary.
Source: 2007 aerial photo provided by Snohomish County. Streams from WA DNR.

Note: This figure has been created and utilized in support of the NFS Channel Migration Study. The figure is intended for use in the scope of the referenced report and should not be used outside of this context. All locations are approximate and have been created using available data. If additional data become available, further analyses may be necessary.
Figure A-21
2007 Aerial Photo, Lower Reach 5
North Fork Skykomish Channel Migration Study
Index Galena Flood Repairs MP 6.4 to 6.9

Index-Galena Rd.

RM 2
RM 3
RM 4

0 1,000 Feet

River Miles
Road Mileposts
Index-Galena Road
Major Tributaries

Reach Boundaries
Historic Migration Zone
Channel Migration Zone

Source: 2007 aerial photo provided by Snohomish County. Streams from WA DNR.
Note: This figure has been created and utilized in support of the NFS Channel Migration Study. The figure is intended for use in the scope of the referenced report and should not be used outside of this context. All locations are approximate and have been created using available data. If additional data become available, further analyses may be necessary.
Source: Relative elevation map produced from 2007 LIDAR provided by Snohomish County. Water surface from 2007 aerial photo provided by Snohomish County.

Note: This figure has been created and utilized in support of the NFS Channel Migration Study. The figure is intended for use in the scope of the referenced report and should not be used outside of this context. All locations are approximate and have been created using available data. If additional data become available, further analysis may be necessary.
Figure A-23
Geomorphie Features, HMZ and CMZ, Lower Reach 5
North Fork Skykomish Channel Migration Study
Index Galena Flood Repairs MP 6.4 to 6.9

Source: Relative elevation map produced from 2007 LiDAR provided by Snohomish County. Water surface from 2007 aerial photo provided by Snohomish County.

Note: This figure has been created and utilized in support of the NFS Channel Migration Study. The figure is intended for use in the scope of the referenced report and should not be used outside of this context. All locations are approximate and have been created using available data. If additional data become available, further analysis may be necessary.
Figure A-24
CMZ Hazard Zones, Upper Reach 5
North Fork Skykomish Channel Migration Study
Index Galena Flood Repairs MP 6.4 to 6.9

Source: Water surface from 2007 aerial photo provided by Snohomish County.
Note: This figure has been created and utilized in support of the NFS Channel Migration Study. The figure is intended for use in the scope of the referenced report and should not be used outside of this context. All locations are approximate and have been created using available data. If additional data become available, further analyses may be necessary.
Figure A-25
CMZ Hazard Zones, Lower Reach 5
North Fork Skykomish Channel Migration Study
Index Galena Flood Repairs MP 6.4 to 6.9

Source: Water surface from 2007 aerial photo provided by Snohomish County.
Note: This figure has been created and utilized in support of the NFS Channel Migration Study. The figure is intended for use in the scope of the referenced report and should not be used outside of this context. All locations are approximate and have been created using available data. If additional data become available, further analyses may be necessary.
### Table B-1
Geologic Unit Names and Descriptions for the North Fork Skykomish Basin in the Skykomish River Quadrant

<table>
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<th>Age</th>
<th>Lithology</th>
<th>Named Unit or Note</th>
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</tr>
<tr>
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<td>mostly Vashon Stade in western WA; unnamed in eastern WA</td>
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</tr>
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### Table B-2

**Gradient Calculations at 1,000-foot Intervals along 2007 Thalweg used in Reach Delineation**

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- Horizontal datum is NAD 83 State Plane Washington North Zone
- Vertical datum is NAVD88
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<th>Total Discharge of Mainstem at Input (cfs)</th>
<th>Percent Increase in Discharge</th>
<th>Slope Discharge Product</th>
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Notes:
cfs = cubic feet per second
Total discharge of mainstem North Fork Skykomish at upstream extent of study area is 28,800 cfs (USGS 2007)