Lower Skykomish River Geomorphic Assessment

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APPENDIX A: Habitat Expansion Opportunities

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Executive Summary

Purpose

The purpose of this report is to define the relationships in the Lower Skykomish River between the primary fluvial processes active in this river (predominately lateral channel migration and avulsion, sediment transport and deposition, and floodplain engagement), factors that currently limit key fish habitat, and anthropogenic influences (gravel mining, levees and other bank stabilization, and transportation infrastructure). Through a description and analysis of the existing geomorphic condition of the river, intended outcomes for this report include the characterization and locations of the dominant fluvial processes and their constraining infrastructure; guidance on beneficial restoration practices, highlighting of those areas with the greatest flood and/or geomorphic risk; and an evaluation of the future trajectory of the river. This work will contribute to establishing a comprehensive technical basis for evaluating multi-benefit projects throughout the Lower Skykomish River valley, specifically those that reduce flood hazards, restore salmon habitat, and improve agricultural viability.

Study Area Characteristics

Along the Lower Skykomish River between River Miles (RMs) 23.5–0.0 (henceforth the "study area," extending from above Gold Bar to the Snoqualmie River confluence), both the natural geologic setting and constructed structures strongly influence channel characteristics and fluvial processes. The Skykomish River occupies a valley shaped by multiple advances of glaciers, some of which flowed down-valley out of the Cascade Mountains and others that were part of the great continental ice sheets that originated much farther north and advanced down the axis of the Puget Lowland. Today, the valley bottom is largely underlain by gravelly sediment, deposited by the rivers issuing forth from the margin of the most recent ice sheet as it retreated back to the north (about 16,000 years ago) or from the modern-day Skykomish River, and less commonly by clay or bedrock (Booth 1990).

The Skykomish River is a free-flowing, largely unregulated system with only a few tributaries feeding the mainstem along the 23.5 miles of the study area. Riverbank armoring as well as the armored embankments of the BNSF Railroad and US Highway 2 have both isolated swaths of the historic floodplain from river connection and restricted channel migration across portions of the river's floodplain. However, active channel migration is common today in many locations and has been recorded by maps and aerial photographs dating back to the late-nineteenth and early twentieth centuries.

For purposes of both analysis and discussion, the study area was divided into seven subreaches, varying from 1.2 to 5.2 river miles in length. Subreach boundaries were drawn on the basis of observed changes in geomorphic form or riverine behavior. The boundaries of the lowermost four subreaches (from the confluence with the Sultan River to the confluence with the Snoqualmie River) are identical to those defined by Snohomish County (2018) for this same 13.5 miles of the Lower Skykomish River.

Approach

The interpretations and findings regarding the past and future conditions of the Lower Skykomish River have been based on multiple sources, particularly prior published studies of the river, extensive review of maps and aerial photographs dating back to the late nineteenth century, analysis of LiDAR-generated topography, field observations and measurements made along the river over 10 days in the summers of 2019 and 2020, and discussions with multiple individuals having long experience with the river. All spatial data sources were compiled in a Geographic Information System for easy reference and comparison. The overall approach has been to develop a spatially hierarchical description of the river—its overall watershed context, the dominant reach-scale processes and conditions, and more site-specific constraints and/or opportunities—to guide river corridor planning and restoration. Under such an approach, restoration is primarily an effort to reestablish natural rates and magnitudes of the processes that create and sustain aquatic ecosystems, targeting root causes of degradation rather than simply correcting symptomatic expressions of that degradation.

Key Findings

1. The Lower Skykomish River expresses three distinct geomorphic zones: the “braided reach” (subreaches 7, 6, and 5), a confined zone (subreaches 4, 3, and 2), and a deltaic zone (subreach 1, at the confluence with the Snoqualmie River).
2. Zones of channel activity and floodplain occupation have generally shrunk in area over the last century, likely an expression of early twentieth-century gravel mining and early/mid-century construction of levees and revetments.
3. Subreaches 7–5 downstream of RM 19.6 provide the most promising opportunities for ecological restoration and/or protection, through the reestablishment or protection of the critical fluvial processes responsible for creating and maintaining aquatic habitats.
4. Zones of both potential habitat creation and risk to upland human activity commonly coincide, making the need to balance these potentially competing needs particularly important along the Lower Skykomish River.

1 Introduction

1.1 Report Purpose

The purpose of this report is to define the relationships in the Lower Skykomish River (the "study area," RMs 23.5–0.0) between the primary fluvial processes active in this river (predominately lateral channel migration and avulsion, sediment transport and deposition, and floodplain engagement), factors that currently limit key fish habitat, and anthropogenic influences (gravel mining, levees and other bank stabilization, and transportation infrastructure). Through a description and analysis of the existing geomorphic condition of the river, intended outcomes include the characterization and locations of the dominant fluvial processes and their constraining infrastructure; guidance on beneficial restoration practices, highlighting of those areas with the greatest flood and/or geomorphic risk; and an evaluation of the future trajectory of the river. This work is intended to establish a comprehensive technical basis for evaluating multi-benefit projects throughout the Lower Skykomish River valley, specifically those that reduce flood hazards, restore salmon habitat, and improve agricultural viability.

This report could not have been prepared without the assistance of multiple scientists and engineers who contributed to its content. Particular thanks for data, analysis, insights, and guidance are due Aaron Kopp, Frank Leonetti, Brett Gaddis, Kit Crump, Mike Rustay, and Gi-Choul Ahn (Snohomish County); Peter Verhey (Washington Department of Fish and Wildlife); Spenser Easton (ESA Associates); and Daniel Elefant and Sky Miller (Cardno, Inc.).

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1.2 Approach— Applying the Lens of Fluvial Processes

This study emphasizes the characterization and analysis of fluvial processes to guide restoration planning, applying a hierarchical understanding of the river in its watershed context to guide river corridor planning and restoration. Beechie et al. (2008) grouped these watershed-scale processes under the categories of hydrology, sediment, riparian, channel, floodplain connectivity, and water quality (Table 1-1). Subsequently, Beechie et al. (2010) recommended "…reestablish[ing] normative rates and magnitudes of physical, chemical, and biological processes that sustain river and floodplain ecosystems," emphasizing that "restoration actions should address the root causes of degradation…" (p. 209).

Table 1-1 Examples of watershed-scale and reach-scale processes that control riverine ecosystem dynamics (reproduced from Beechie et al. 2010, their Table 1)

Ecosystem feature	Driving processes
Watershed scale *(these processes control delivery of sediment, water, organic matter, nutrients and chemicals, light and heat, and biota from the surrounding environment into river channels and floodplains)*	
Sediment	Sediment delivered to river systems through landsliding, surface erosion, and soil creep.
Hydrology	Runoff delivered to streams through surface and subsurface flow paths.
Organic matter	Tree fall, leaf litter fall.
Light and heat	Solar insolation and advective heat transfer to the water column.
Nutrients	Delivery of dissolved nutrients via groundwater flow.
Chemicals	Delivery of contaminants, pesticides from agricultural or industrial sites through surface runoff or shallow subsurface flow.
Biota	Migration of aquatic organisms, seed transport.
Reach scale *(these processes rework inputs to channels to determine local habitat structure, water quality, and biotic assemblages)*	
Channel morphology and habitat structure	Channel migration, bank erosion, bar formation, and floodplain sediment deposition create a dynamic mosaic of main-channel, secondary-channel, and floodplain environments. Wood recruitment results in part from bank erosion and channel migration, and wood accumulations reduce bank erosion rates or enhance island formation. Sediment and wood transport and storage processes drive channel cross-section shape, formation of pools, and locations of sediment accumulation. Bank reinforcement by roots reduces bank erosion rates and may force narrowing and deepening of channels. Animals such as beaver physically modify the environment and create new habitats.
Thermal regime	Local stream shading and exchange of water between surface and hyporheic flows regulates stream temperature at the scale of habitat units and reaches.
Water chemistry	Delivery of dissolved nutrients through groundwater and hyporheic exchange; uptake of nutrients by aquatic and riparian plants. Delivery of pesticides and other pollutants at point sources damage health and survival of biota.
Riparian species assemblages	Seedling establishment, tree growth, succession drive reach-scale riparian plant assemblages.
Aquatic species assemblages	Photosynthesis drives primary production of algae and aquatic plants. Leaf-litter inputs drive detritus- based food web strands. Habitat selection, predation, feeding, growth, and competition drive species composition of invertebrate, amphibian, and fish assemblages.

A restoration program guided by these principles, particularly one with multiple ecological and social objectives and an intention for its works to persist long-term without subsequent human intervention, needs to identify (1) areas with a disproportionate influence on the key watershed processes that sustain the downstream river channels (in particular, the delivery of water and sediment), (2) valley segments that express dynamic habitat-forming processes (e.g., zones of active sediment deposition and channel migration) and sustain channel–floodplain interactions, and (3) reaches with component features that hold particularly high actual or potential for biological use in both the channel and the riparian zone. This is a multi-scalar approach (Figure 1-1), placing a higher priority on protecting the natural functions of key watershed, valley, and riverine zones than on efforts to rebuild those structures at single, site-specific locations. This approach was anticipated by Roni et al. (2002), who recommended a ranked priority for restoration comprising first the reconnection of isolated high-quality fish habitats, followed by restoration of hydrologic, sedimentologic, and riparian processes. They advised construction of instream habitat enhancement (e.g., additions of wood, boulders, or nutrients) only after restoring natural processes or where short-term improvements in habitat are desired.

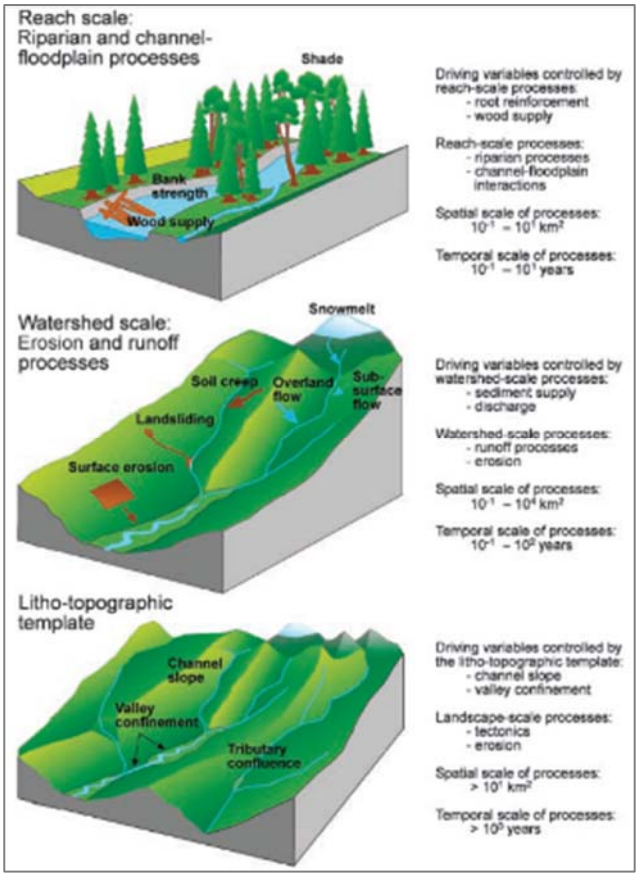


Figure 1-1 Illustration of the hierarchy of processes that control dynamics of habitat features and species assemblages.
(Reproduced from Beechie et al. 2010, their Figure 2.)

A classic example of using a process-based approach to design restoration projects is illustrated by addressing the depleted quantities of large woody debris (LWD) in channels. Low amounts of instream LWD, well-documented in Pacific Northwest rivers and streams (Fox and Bolton 2007, including the Lower Skykomish River) can directly impact one or more of the critical life stages of salmonids. From a purely symptomatic perspective the solution is obvious—if low LWD loads are identified as the overriding problem of degraded habitat then adding wood to rivers is the logical solution, and around which a mature practice has developed for the placement of individual logs and engineered log jams. Process-based restoration, however, would look to the ultimate source of that wood, replanting riparian forests and allowing lateral migration of the active channel to provide a sustainable source of logs over the long term and the geomorphic mechanism needed to bring them into the river (Latterell and Naiman 2007, Booth et al. 2016). Providing the understanding and data to implement this latter approach is the goal of this geomorphic assessment.

The range of relevant time frames for regulatory and planning applications, however, typically are shorter than the period needed to grow a mature riparian corridor of trees, and they commonly differ even from one another. For example, Snohomish County Planning and Development Services (PDS) assumes 100 years for purposes of applying Snohomish County Code 30.62B.330 Erosion Hazard Areas – Channel Migration Zones. Snohomish County Planning and Development Services assumes a design life of 100 years for projects along the river adjacent to public infrastructure. Over such a period, however, channel positions cannot be anticipated with any confidence and so the area of potential 100-year channel migration is a broad zone, determined by any/all past locations of the channel and broad reach-averaged rates of migration (see Cardno 2020). For purposes of multi-benefit project planning and integrated floodplain management, a narrower horizon of 50 years is appropriate, aligning with the current research endeavors of the University of Washington Climate Impacts Group and typical assumed design lifespans

for proposed projects on the mainstem rivers of Snohomish County adjacent to private property. Even this period is too long, however, to predict future channel positions with any confidence. It is also more than twice as long as the scope of Snohomish County's current General Policy Plan (extending only to 2035) or the 20-year projection of the County's Future Land Use. Application of the findings of this Geomorphic Assessment emphasize the likely behavior and restoration opportunities over the next one to two decades, a period over which channel behavior is more predictable and updated guidance from future planning efforts is unlikely to supersede the present effort.

1.3 Sources of Data

Given the multidimensional elements that constitute a comprehensive "geomorphic assessment," multiple sources of information have been used to describe and to analyze conditions along the river. These include prior studies and historical airphotos (enumerated in the next section), observations and insights from agency staff, recent field observations and data collected expressly for this report, hydraulic modeling and analytical assessment of sediment movement and channel patterns, and a variety of both quantitative analyses and geomorphic inferences using this collective body of information about the river.

1.3.1 Historical and current information used in report

Information from several existing studies of the geology, geomorphology, hydrology, hydraulics, land use, and other aspects of the condition and behavior of the Lower Skykomish River forms the foundation of this study. These existing studies include:

- A USGS-published geologic map at 1:50,000 scale that includes nearly the entire the study area down to RM 2 (Booth 1990);
- Early geomorphic studies in response to gravel mining (Dunne 1979, Dunne et al. 1980, Collins and Dunne 1990) and the November 1990 flood (at the time, the flood of record) (nhc 1992);
- A geomorphic study of the lower 13.5 miles of the Skykomish River (De Vries 2010);
- An assessment of conditions and conceptual project opportunities between RMs 10 and 13 (Kopp 2017);
- A prior CMZ study of the South Fork Skykomish River, with its downstream end just a few miles upstream of the present study area (King County 2017);
- A plan for land uses and other actions in the Lower Skykomish River (RMs 0–13.5) (Snohomish County 2018);
- Spreadsheets summarizing the locations and numbers of redds and adult Chinook and steelhead in the Lower Skykomish River from RM 13.5 downstream to the mouth (Peter Verhey, WDFW, written commun. 2020); and
- The recently completed Channel Migration Zone study for the Lower Skykomish River (RMs 0–23.5) (Cardno 2020).

Historical channel positions of the Lower Skykomish River, also used for the Channel Migration Zone study (Cardno 2020), were digitized primarily from historical aerial photography, supplemented with historical maps and Light Detection and Ranging (LiDAR) topographic data. Most of the aerial images used in this study were acquired and digitized by Snohomish County staff prior to the initiation of this study. Historical channel locations were digitized in GIS from georectified aerial photos dated 1938 through 2003; orthorectified digital aerials from 2007 to 2018; and georectified maps published by the USGS, one in 1897 (for only the downstream-most 1.8 river miles) and the other in 1921 (covering the remainder of the study area) (Table 1-2). The digitization process included mapping of what is termed here the "active channel" for each photo year, which included a composite of the low-flow channel, bare gravel bars, and patches of apparently young, sparse shrubby vegetation (Collins and Montgomery 2002; O'Connor et al. 2003). The 1897 and 1921 maps could not be sufficiently well-registered with the later

airphotos to be useful in quantitative analyses, but they were invaluable in characterizing the historical extent of channel occupation across the floodplain.

Table 1-2 Imagery Used in the Delineation of Channel Positions

Year	Source	Type	Scale or Resolution
1897	US Geological Survey	Map	1:125,000
1921	US Geological Survey	Map	1:125,000
1938	US Army Corps of Engineers	Aerial photo	1:4,800
1965	HG Chickering Jr. Inc.	Aerial photo	1:4,800
1969	S.A. Newman Forest Engineers Inc.	Aerial photo	1:4,800
1978	S.A. Newman Forest Engineers Inc.	Aerial Photo	1:4,800
1984	S.A. Newman Forest Engineers Inc.	Aerial photo	1:4,800
1991	Sound Aerial Surveys	Aerial photo	1:4,800
1998	WA Department of Natural Resources	Aerial photo	1:4,800
2001	WA Department of Natural Resources	Aerial photo	1:4,800
2003	Triathalon	Aerial photo	1:4,800
2007	Snohomish County	Digital aerial	1 ft/pixel (1:610)
2011	National Agriculture Imagery Program	Digital aerial	1 m/pixel (1:2,000)
2015	National Agriculture Imagery Program	Digital aerial	1 m/pixel (1:2,000)
2018	National Agriculture Imagery Program	Digital aerial	0.5 ft/pixel (1:305)

The georectification tolerance for the photos was 25 feet as compared to the location of features in the 2015 aerials. The channel tracings, delineated at 1:5,000, fell within anticipated tolerances of 20 feet from the vegetation line, wherever zoomed in to verify.

In addition, a LiDAR-based digital elevation model (DEM) was used to image channels across the floodplain and to generate the Height Above Water Surface (HAWS) map. The aerial survey for the LiDAR was flown during low-water conditions in 2014 below RM 6.35 and in 2017 above that point. Flows during the 2014 survey were approximately 2,000 cfs, a moderately low discharge exceeded by 67% of daily average flows in the gage record. The 2017 survey was flown during multiple, indeterminate periods, but the small difference in the two surveys' water-surface elevations (0.7 foot at their junction) suggests that the integrated surface is broadly representative of low-flow conditions with any differences too small to make noticeable differences in the subsequent HAWS mapping that was derived from these data.

All geographical information was integrated into a GIS using ArcGIS Desktop 10.8. Determinations of the contributing watershed areas to each subreach was obtained from https://streamstats.usgs.gov.

1.3.2 New field data collection

The primary field effort conducted specifically for this study included eight field visits, covering overlapping segments of the study area by raft, from late August through early October 2019. Field data collection included identifying bank materials, mapping the extent of bank armoring, identifying the extent of bedrock

outcrops on channel banks, conducting pebble counts, assessing the potential for river reoccupation of existing avulsion pathways, documenting bank and bar conditions, and assessing slope instability and associated mass-wasting deposits. Field notes, georeferenced photographs, and various locations obtained using a handheld global positioning system (GPS) unit (with a typical positional accuracy of 15–20 feet) were recorded during these visits. A follow-up raft traverse of the entire study reach was conducted over two days on September 2–3, 2020 to confirm prior observations and to make additional observations following the large flows of winter 2019–2020.

Sediment sizes were characterized by measuring the intermediate diameter of at least 100 clasts on gravel bars using the "first-touch" technique of Wolman (1954). All sampling sites were at consistent morphologic locations along the river—on the upstream side of well-developed point bars in unconstrained reaches, about half-way between the upstream end and the apex of the bar, near the low-water edge. Clasts deposited here are most likely to reflect the active bedload during transport events (Kondolf et al. 2003). Accumulations of large wood, approximately located during the river traverses, were noted as observed. Large jams comprised at least 10 individual pieces, generally at least 50 cm in diameter and 10 m in length. No formal “wood survey” was conducted for this project, although even those surveys have a limited period of relevance (i.e., until the next large flood).

1.3.3 Hydraulic modeling

A two-dimensional hydraulic model has been prepared as a companion study to this geomorphic assessment for the Lower Skykomish River (Watershed Science and Engineering 2020). It is based on the current LiDAR topography and updated flow-recurrence discharges, providing the best current representation of existing flood flows along the river. For purposes of geomorphic analysis, conditions at the 2-year and 10-year recurrence were judged to be most useful—the former because this flow typically represents the “dominant” channel-forming discharge in alluvial rivers such as the Skykomish; and the latter because it is not only large enough but also frequent enough to exert its influence over channel form within the decadal-scale planning horizon of this study.

1.4 Introduction to the Study Area

1.4.1 Geology

The geology of the study area has been the subject of both regional mapping (Tabor et al 1993; Pessl et al. 1989; Booth 1990) (Figure 1-2) and more recent and detailed investigations (Dragovich et al. 2011, 2013; Allen et al. 2017). These reports have emphasized the geology associated with bedrock and glacial-age deposits and more recent tectonic activity, and so they do not provide much direct insight into the present-day process and landforms of the Skykomish River itself. However, they do set the context for those modern processes, and they also characterize the geologic materials that define the lateral boundaries of the river's active and historical floodplain.

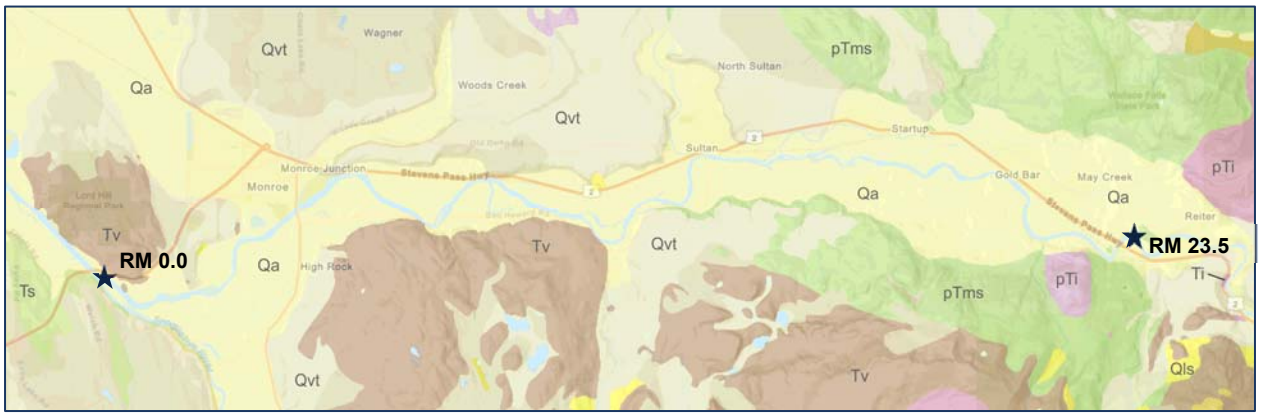


Figure 1-2 **Generalized geologic map, extracted from Washington Department of Natural Resources.** Qa = modern river alluvium, Qls = modern landslide deposits, Qvt = glacial till and associated outwash deposits, Ts = Tertiary sedimentary rocks, Tv = Tertiary volcanic rocks, Ti = Tertiary intrusive rocks, pTms = pre-Tertiary metasedimentary rocks, pTi = pre-Tertiary intrusive rocks. The study area extends from river mile (RM) 0.0 to RM 23.5. West-to-east (left-to-right) map extent ≈ 20 miles. Accessed from https://geologyportal.dnr.wa.gov/.

Glacier ice originating in the mountains of British Columbia has invaded the Puget Lowland at least several times in the last million years (Armstrong and others 1965; Easterbrook and others 1967; Troost 2016), leaving an imprint of glacial and glacio-fluvial activity that continues to affect the Skykomish River to the present day. This ice was part of the Cordilleran ice sheet of northwestern North, referred to as the "Puget lobe" since Bretz (1913) (Figure 1-3). The extent of this lobe was limited by the net flux of ice from British Columbia, melting of the ice in the lowland, and the mountainous topography surrounding the lowland itself. Over the Lower Skykomish River valley during the last glacier advance, ice was at least 3,000 feet thick at its maximum stage, with an upper surface that sloped down to the east as the lateral margin of the ice expanded upvalley. The maximum upvalley ice margin in the Skykomish River valley was likely around the town of Index, about 5 miles east of the upstream end of the study area (Booth 1986).

Today, the valley bottom is largely underlain by gravelly sediment, deposited by the rivers issuing forth from the margin of the most recent ice sheet as it retreated back to the north (about 16,000 years ago) or from the modern-day Skykomish River, and less commonly by clay or bedrock (Booth 1990). Both Allen et al. (2017) and Dragovich et al. (2013) report thicknesses of this valley-bottom alluvium of up to 80 feet in the western and central part of the study area; these thicknesses likely decrease farther upvalley as bedrock valley narrows in width.

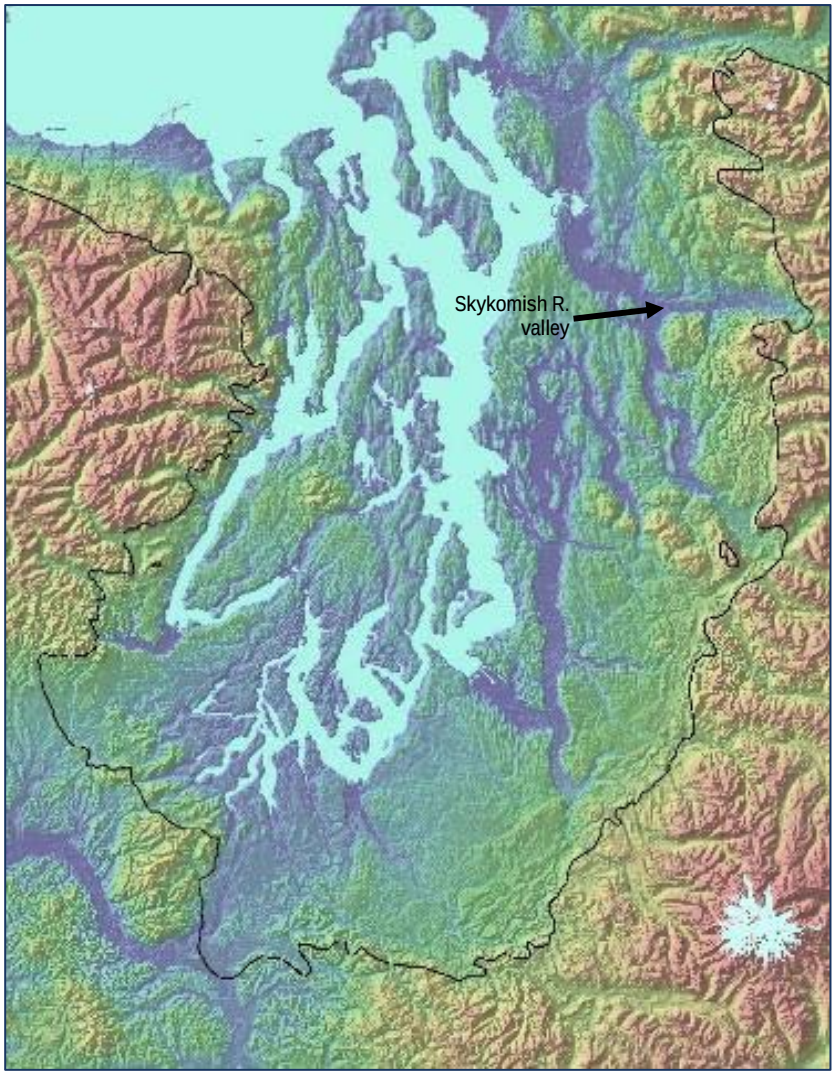


Figure 1-3 Outline (thin black line) of the maximum extent of the Puget lobe during the last ice-sheet advance (about 16,000 years ago).

Because of the great thickness of ice, lakes were impounded in each of the mountain valleys blocked at their mouths by the Puget lobe. During ice retreat, each lake surface would have dropped as progressively lower spillways in the underlying bedrock topography were exposed. In the Skykomish River valley, the high bedrock divide just south of the river permitted relatively few drainage routes across it (Figure 1-4). The most easterly of these spillways (and thus the one that would have been exposed earliest during the ice retreat), lying due south of the upstream end of the study area, is today the broad trough now occupied by Proctor Creek (which drains north and joins the Skykomish River at RM 24.1) and Lake Cavenaugh. The top of Deer Creek Flat, the broad embankment north of the river and above the town of Index, and the upper limit of lake deposits found even farther east of the map area, are roughly graded to the subaerial altitude of this trough (1,600 ft).

Continued ice thinning and ice-margin retreat eventually would have opened a lower spillway at Youngs Creek, south of Sultan, with an impounded lake behind that resulted in the upvalley deposition of lacustrine deposits, terraces, and outwash plains graded to the 600-ft elevation of this spillway. Subsequent exposure of a lower spillway at Elwell Creek (430 ft, 1.2 miles west of the Youngs Creek spillway), which joins the Skykomish River at RM 10.8 just downstream and opposite the town of Sultan, brought about another drop in the altitude of the ice-impounded lake. Extensive deposits graded to this base level cover several square miles to the west, east, and south-southeast of Sultan.

The next (and final) spillway traversed the west end of the bedrock ridge near High Rock, south of the town of Monroe. Although the eastern side of this lake-draining channel was bedrock-walled, its western side was likely formed by the edge of the now-rapidly retreating ice sheet, and so this condition undoubtedly was quite ephemeral. Once this last blockage of the Skykomish River valley was removed, however, the river still was not free-flowing into Puget Sound. Instead, a Puget Sound-wide lake (Lake Bretz, so named by Thorson 1981) filled the central lowland for an indeterminate period of likely several centuries.

The ultimate retreat of the ice sheet back into British Columbia, coupled with the rebounding of the previously ice-depressed crust of the Puget Lowland, finally allowed a modern subaerial drainage network to reestablish in the Skykomish River (and throughout the lowland). The legacy of these glacial-age lakes, however, remains on the landscape to the present day.

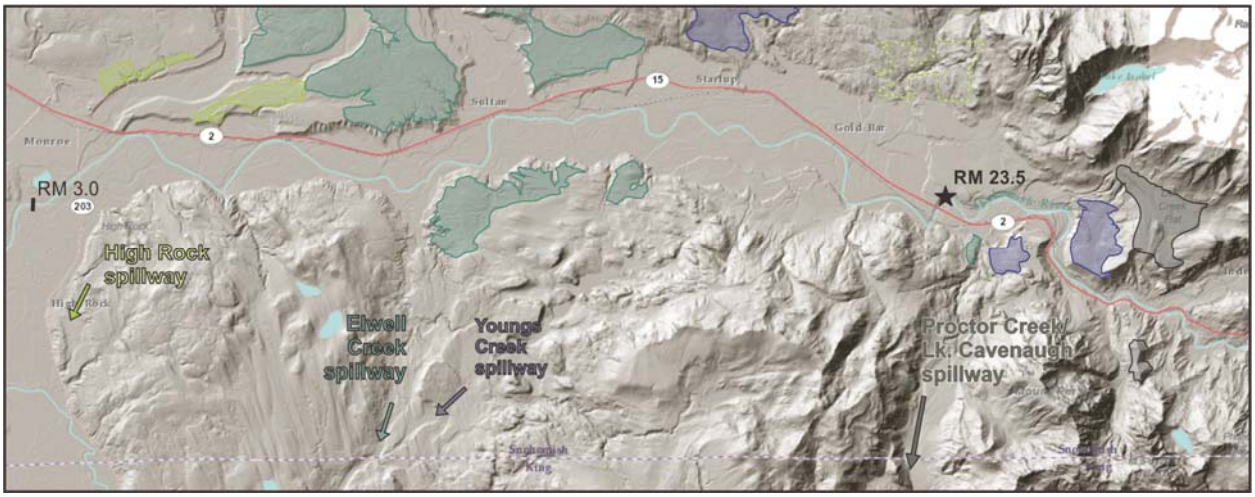


Figure 1-4 Map of glacial-age spillways out of the Skykomish R. valley during ice recession.
The four major spillways of the valley are marked by arrows; colored polygons mark major outwash deposits associated with each spillway (keyed by color). Data from Booth (1986, 1990).

1.4.2 History of human occupation

The peopling of western North America, particularly along the Pacific Coast, was likely initiated by crossing of a land bridge between Siberia and Alaska during the last glacial age (or, potentially, during earlier glacial advances) when sea level was low. This crossing was followed by migration into Canada and the lower United States shortly after 16,000 years ago as the last continental ice sheet retreated back into the upper mountains of British Columbia (e.g., Goebel et al. 2008). As summarized by Snohomish County (2018), native people settled and lived throughout the region, including the Skykomish River valley, managing local natural resources for use and trade. The first non-native settlers arrived in the 1850s, and the Government Land Office survey maps from the 1860s–1870s depict homesteading and limited road development. Significant increases in population and development in the early 1900s followed construction of the Great Northern Railway and US Highway 2. The highway appears as State Road No. 15, extending from Leavenworth to Everett, on a 1931 map showing the "State Roads as Established by the Legislature of 1893 to 1935" (https://www.wsdot.wa.gov/sites/default/files/2005/04/26/State-roads-as-established-by-Legislature-1893-1935.pdf; accessed 31 July 2020). However, it is only shown extending east from Everett as far as the town of Index, still well west of Stevens Pass, on a state highway map from 1912 (https://www.sos.wa.gov/legacy/maps/maps_detail.aspx?m=33; accessed 31 July 2020); on a map from 1909 there is no road shown up the Skykomish River valley at all (although the railroad is shown) (https://www.sos.wa.gov/legacy/maps/maps_dl.aspx?f=AR_DOTStateHighways1909.jpg; accessed 31 July 2020).

As people settled areas along the valley over the last century, agriculture became a prominent activity in the floodplain; agriculture continues to be the primary land use in the Lower Skykomish floodplain today

(Snohomish County 2018). The history of bank armoring and other channel modifications surely followed close behind the initial transportation routes and early settlers, given the dynamic nature of the river, the valley's favorable low-lying topography for roads and the railroad into the Cascade Range, and the agricultural value of floodplain soils. With homesteading and increasing use of the floodplain for agriculture, railroading, logging, roads and bridges, river training became more prominent. The General Land Office (GLO) maps depict the approximate locations of the Skykomish mainstem, large tributaries, some smaller side channel sloughs, and minor tributaries. By the 1870s, large meander bends of the Skykomish River north of Gold Bar were isolated from the mainstem. Farther downstream the mainstem channel shifted from a GLO-era location to the north instead to a side channel slough by 1938. A string of large concrete pylons, still observed today, are present in the 1938 aerial photo and cut off the GLO alignment, straightening the mainstem through a side-channel slough depicted in the GLO map.

Snohomish County (2018) summarized the history of such actions, beginning with the Work Projects Administration in the 1920s and 1930s, who built dikes and installed riprap along sections of the river and construction of dikes, levees, and shoreline armoring. This work continued into the 1940s through 1960s, largely by the U.S. Army Corps of Engineers. Gravel mining was active in the lower several miles of the river in the 1960s through the 1980s, and a variety of formal and informal river-training and bank-hardening installations have been constructed throughout the recent decades.

1.4.3 Present-day issues and concerns

Two geomorphic conditions, both related to episodically high discharges in the Skykomish River, constitute severe flood-related hazards to people, infrastructure, and agricultural activity in the Lower Skykomish River valley. The first is simply flood inundation, widespread here because of the extensive areas of low-elevation land that is bounded, commonly quite abruptly, by steep terraces faces or bedrock ridges. There are only modest amounts of "transitional" terrain—high enough to stand above most or all floodwaters, but low enough to be accessible and flat enough to be habitable (Figure 1-5).

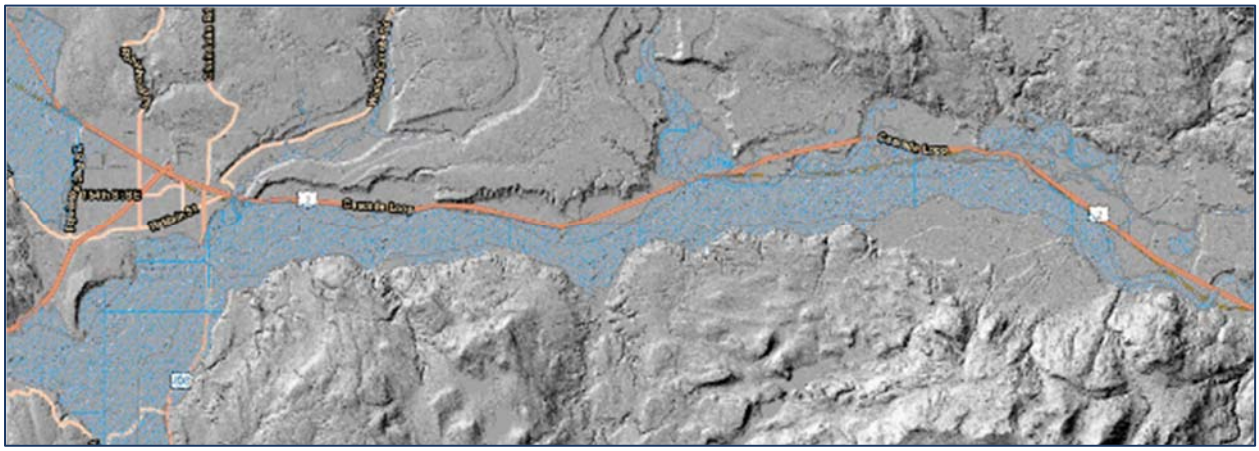


Figure 1-5 FEMA-designated 100-year floodplain of the Lower Skykomish River.
Note the limited area of the valley bottom that is *not* within the floodplain area. Available from http://gismaps.snoco.org/slsmaps.

The second such hazard is the interrelated processes of avulsion, bank erosion, and channel migration (Cardno 2020), also driven by sufficiently large flows to erode and transport sediment from the adjacent floodplain and terrace surfaces. Unlike flood inundation, however, this geomorphic hazard can result in severe, long-term alterations to the land. Roads, residential areas, and agricultural fields can be simply washed away in a single flood event. What is commonly seen as the geomorphically "balanced" response to bank erosion—namely, the creation of a new floodplain surfaces elsewhere in along the river—is typically irrelevant to the continuity of a road, to static property boundaries, or to continued access to fields by farm equipment.

The common (and commonly effective, at least over the short- to medium-term) solution to these flood-related hazards is the construction and regular maintenance of river training works to confine floodwaters

and resist channel migration. However, these actions have been specifically identified as primary impacts to populations of Endangered Species Act-listed species: threatened Chinook (*Oncorhynchus tshawytscha*) and Steelhead (*Oncorhynchus mykiss*). SBSRF (2005) identified the availability of off-channel rearing habitat as the primary factors limiting these populations, with the main causes being channelization of the river from gravel extraction and levee/revetment construction. These actions limit channel–floodplain interactions, isolate off-channel habitats from the main channel, and dampen the processes that create and sustain rearing habitats (Snohomish County 2018).

1.5 Document Organization and Conventions Used in this Report

In the following sections, characteristics of each of the seven subreaches of the Lower Skykomish River (Figure 1-6 and Table 1-3) are described individually, from upstream (subreach 7) to downstream (subreach 1). These descriptions are followed by syntheses of the entire study from the perspectives of both space (i.e., how do river conditions and processes change downvalley?) and time (i.e., what are the past and projected future evolutionary trajectories of the river?). The boundaries of the lower four subreaches are identical to those already defined in Lower Skykomish River Reach-Scale Plan (Snohomish County 2018) to facilitate comparison between that document and the present report. The upper three subreaches were previously defined in Cardno (2020) on the basis of geomorphic conditions, and those divisions for the upper 10 miles of the Lower Skykomish River are maintained here as well.

The primary units of measurement in this report are United States customary units, but International System of Units (SI units) are also included where convenient. Elevations are based on the NAVD88 vertical datum. Elevations from USGS topographic mapping are corrected to the NAVD88 datum.

Locations along the river are generally identified using river miles. For this report RM 0.0 is located at the confluence of the Skykomish River and the Snoqualmie River as of 2018 (about 4 miles downstream of the City of Monroe) with the mileage increasing upstream. River miles are established along a channel centerline, and river miles used in this report were developed by Snohomish County using orthophotography flown in 2018. Note that river miles used in other reports may have different starting points or may be based on a centerline developed from other map sources from different years, and therefore may not coincide precisely with the river miles used here.

Where the discussion refers to features on one side of the river (or river valley), the features are referred to as being either on the “right” or “left” bank (RB or LB) of the river. In this report (and, typically, all such reports), this refers to the right or left hand of an observer looking downstream along the channel or valley.

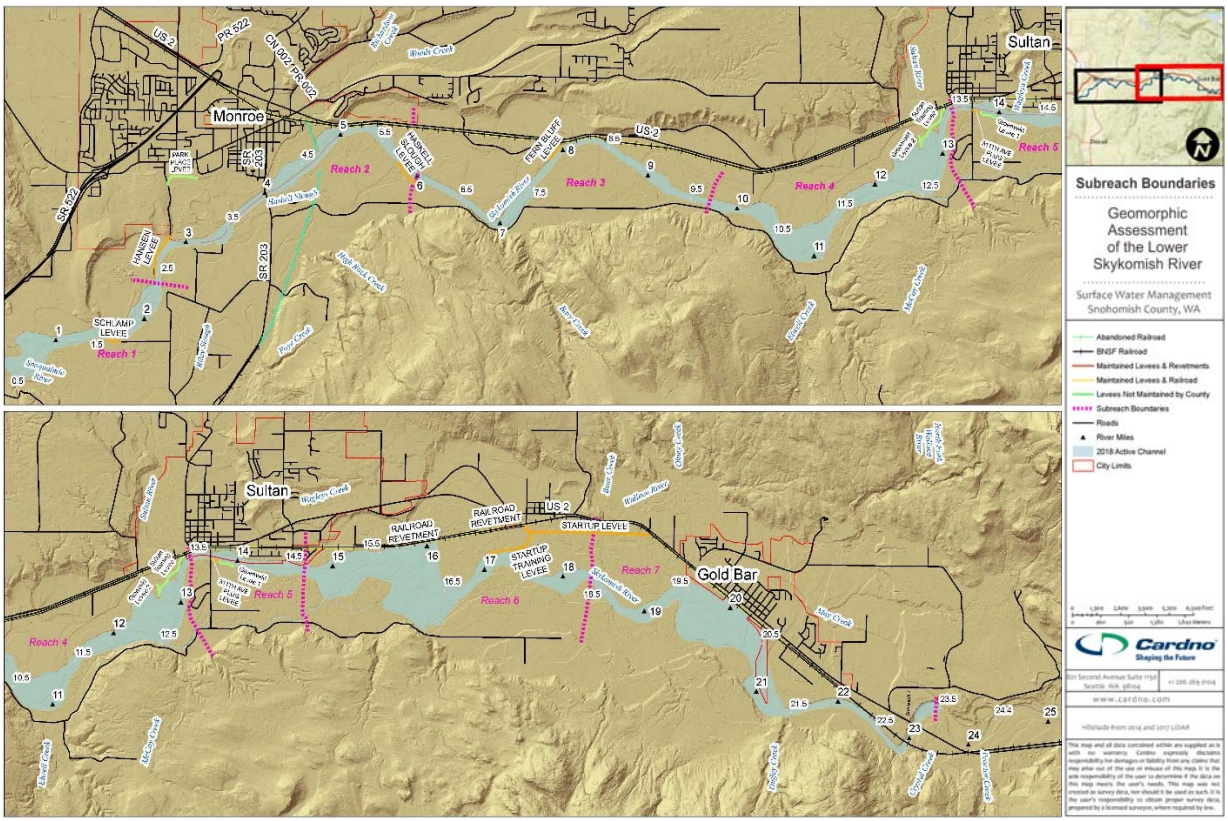


Figure 1-6 Index map of the study area, subreach boundaries, and river miles.

Table 1-3 Basic attributes of the seven subreaches.

Subreach # and length (mi)	Upstream RM	Downstream RM	Length (mi)	Gradient (from LiDAR DEM)	Major features (upstream to downstream)
7	23.5	18.3	5.2	0.0032	• US Hwy 2 bridge • BNSF Railroad bridge and revetment • USGS gage (12134500) • Duffey Creek alluvial fan • Left bank deep-seated landslide • Town of Gold Bar • Startup levee (upper part)
6	18.3	14.7	3.6	0.0023	• Town of Startup • BNSF Railroad revetment • Startup levee (lower part) • Startup training levee • Wallace R. confluence
5	14.7	13.5	1.2	0.0013	• Town of Sultan • Groeneveld levee 1 • 311th Ave plug levee • Mann Road berm and bridge
4	13.5	9.7	3.8	0.0012	• Sultan River confluence • Groeneveld levee 2 • McCoy Creek confluence • Mid-channel forested island • Elwell Creek confluence
3	9.7	6.0	3.7	0.0011	• BNSF Railroad revetment • Fern Bluff levee • Barr Creek confluence

Subreach # and length (mi)	Upstream RM	Downstream RM	Length (mi)	Gradient (from LiDAR DEM)	Major features (upstream to downstream)
2	6.0	2.4	3.6	0.0011	• BNSF Railroad revetment • Haskell Slough and levee • Riley Slough • Historical railroad crossing and prism • Woods Creek confluence • Lewis Street bridge • Town of Monroe • S Lewis Street bridge • Hansen levee
1	2.4	0.0	2.4	0.00080	• Schlamp levee • Riley Slough outlet • Snohomish River confluence

2 Geomorphology by Subreach

2.1 Subreach 7

Subreach # and length (mi)	Upstream RM	Downstream RM	Length (mi)	Gradient (from LiDAR DEM)	Pebble count RMs (D_{50})	Major features (upstream to downstream)
7	23.5	18.3	5.2	0.0032	19.6 (188 mm) 19.2 (105 mm)	• US Hwy 2 bridge • BNSF Railroad bridge • USGS gage (12134500) • Town of Gold Bar • Startup levee (upper part)

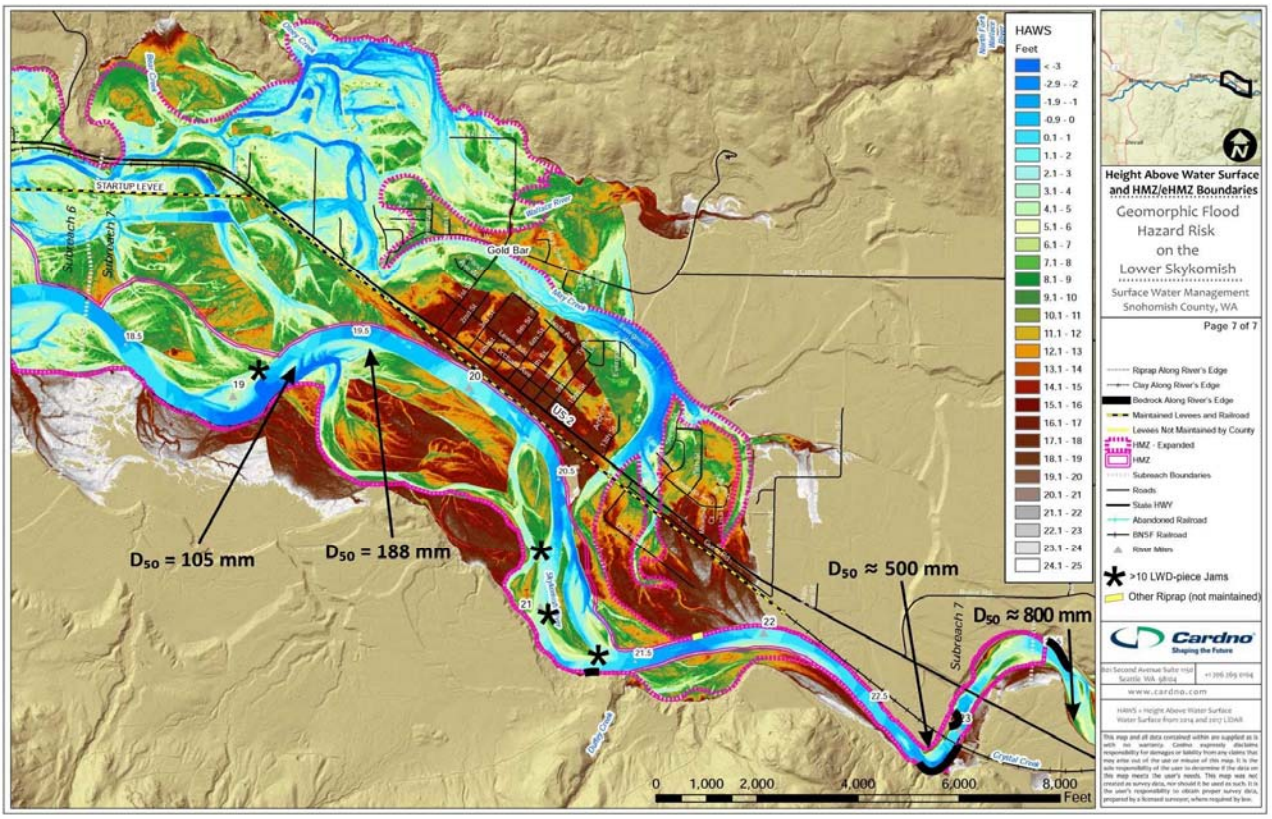


Figure 2-1 HAWS (Height Above Water Surface) map of subreach 7, highlighting the locations of pebble counts and median diameters (D_{50}), significant Large Woody Debris jams, bedrock outcrops along the river, and riprap.
Base map from the Cardno (2020) Channel Migration Zone study.

2.1.1 Channel features

As the Skykomish River enters the study area at RM 23.5, it flows in a static, single-thread planform that has persisted for at least the last century down to RM 21.4. The channel is encased along the right bank by postglacial alluvial terraces that stand more than 100 feet above the modern floodplain at RM 23.5, descending to within 15–20 feet of the low-flow river level through these first two miles of the study area. Presently, but more so historically, these terraces would have contributed a large quantity of bedload and

spawning size gravels to the river due to erosion exposure and the thickness of these terraces as the river eroded down through these layers. The contribution of sediment from these terraces is limited today by the armored alignment of the railroad that abuts the river in places. Along the left bank, the channel is bounded by the bedrock-cored ridge that forms the southern boundary of the Skykomish River valley and extends west for more than 15 miles, nearly to the confluence with the Snoqualmie River. Zones of prior channel occupation lie along both banks of the river between RM 22.0 and 21.4, but there is no photo-documented period of riverine occupation in these areas since the first record in 1938. LiDAR mapping, however, shows an extensive channel network along the right bank that obviously predates the construction of the BNSF Railroad and the town of Gold Bar. A near-perfect clone of the modern-day channel, at relatively similar elevation, is evident in the HAWS mapping (see Figure 2-1) northeast of the railroad, encircling Gold Bar but now completely isolated from the modern river. The relatively intact channel form and similar elevation of this isolated meander suggests it was abandoned or cut-off relatively rapidly and within the era of modern colonization, although is not shown as connected in the GLO map.

The channel first develops a modern anabranching planform at RM 21.4, where a channel avulsion created the modern split during or shortly after the 1990 flood (visible in the 1991 airphoto) and where low flows have shifted between two near-equant channels since 1921. At present a large jam anchors the head of the forested island between these channels. The present jam formed sometime between 2003 and 2005 but lost some logs between 2015 and 2017. Neither the split channel nor the stability of the island between them depends on this jam, however, since this channel configuration has persisted throughout the photographic record independent of the presence or absence of logs at the island's apex.

Not far downstream at RM 21, another channel division has persisted at least since 1921. The western branch is confined between relatively high bounding terraces, with little indication in the topography of significant lateral movement and only a single bifurcation (also with a large log jam at the apex of the split). The eastern branch, which carries the modern low-flow channel, occupies a zone with significantly lower floodplain elevations and topographic indicators of channel migration. Recent (2018–2020) erosion along the right bank at RM 20.69 has occurred, but the river's engagement with the BNSF Railroad revetment from RM 20.3 to 19.6 has effectively suppressed further migration in this zone.

Once the main thread of the river turns west away from the revetment, a large low-elevation floodplain along the right bank becomes accessible to the river, and was in fact occupied by the mainstem in the GLO-era map. Although the available airphoto record shows only one meander loop encroaching into this area in 1965 and 1991 (between RM 19.2 and 18.3; Figure 2-2), the topography documents an additional right-bank channel (at RM 19.5) that extends over 3,000 feet to the northwest (corresponding to the GLO-era mainstem) before being blocked by the (subsequently constructed) Startup levee. This levee also blocked a GLO-era connection between the Skykomish and Wallace rivers, which now only join 2.5 miles downriver. A 1,500-foot-long segment of the right bank centered on RM 19.35 has been retreating at an average rate of about 10 feet/decade since 1991, which if persisting into the future may reopen a major northwest-trending channel, namely the GLO-era mainstem and readily identifiable in the HAWS mapping (Figure 2-1).



Figure 2-2 Modern view of RM 19.2–18.3.
Boundaries of the active channel as of 1991 are outlined in green. Small circles mark 0.1-mile intervals along the channel. Red-roofed structure in the center of both the image and the meander loop was constructed sometime between 1989 and 2003. Imagery from Google Earth, July 2018.

The overall gradient of the river through subreach 7 is the greatest throughout the Lower Skykomish River (0.32%), but this average obscures the even steeper 1% drop in the water-surface elevation over the first 0.3 miles of the river in the study area. The channel then maintains a relatively steady gradient of 0.29%, with only a slight flattening at the bottom of the subreach that presages a zone of more active sediment deposition. The channel itself has a typical bankfull width of about 350 feet and a bankfull depth of 8 feet, dimensions that vary only modestly and non-systematically through the subreach.

The channel has migrated actively at several locations in this subreach. The upstream-most zone, above an outside bend along the left bank at RM 21.4–21.1, impinges on an active landslide complex that involves the mass failure of almost 2,000 lineal feet of streambank sediment over 100 feet thick. This bend migrated 530 feet to the west between 1921 and at least 1991, yielding an average rate of 8 ft/yr and providing what is now the first major recruitment of large woody material into the channel of the Lower Skykomish River (Figure 2-3), although this bank was largely denuded of vegetation from logging in the 1938 air photo.



Figure 2-3 Recruitment of large woody material (and also relatively young, thin alder stems) into the channel at RM 21.2.
Channel migration is eroding into the toe of the large left-bank landslide complex at RM 21.4–21.1.

Other zones of past and ongoing migration are located along the river's right bank at RM 19.6–19.2 as the active channel moves away from the BNSF Railroad revetment and encroaches on the broad forested floodplain to the river's northwest, and on the next bend downstream (RM 19.0) along the opposite bank. Migration rates at both sites average about 15 ft/yr, with neither mature forest nor clay at river level imposing any obvious impediments to bank erosion. Probably not coincidentally, the largest accumulation of logs in this subreach (at RMs 21.3, 21.0, 20.6, and 19.1) lie within a few tenths of a mile downstream of the migration zones where trees are actively falling into the river. However, migration does not *guarantee* log accumulation; for example, there is almost no significant accumulation of logs for over a mile downstream of RM 19.0, despite more than 400 feet of migration into forested floodplain between 1991 and 2018 at this location.

2.1.2 Sediment characterization

2.1.2.1 Terraces and bars

Much of the subreach 7 channel is bounded by terraces standing well above the modern floodplain, or even higher alluvial surfaces that postdate ice retreat but are nonetheless fully disassociated from the modern fluvial regime. As the river emerges from the confinement of these highest terraces at RM 22, it flows within a recent floodplain no more than about 0.25 miles wide flanked by terraces standing 15–20 feet above the low-flow water surface. This pattern is readily visible on Figure 2-1, where the one or two active channels of the river between RM 22.0 to RM 19.5 traverse relatively narrow, low paths (in shades of yellow and green on the figure) between markedly higher surfaces (in brown). This pattern abruptly ends at 19.5, where the right bank opens out into a relatively unconstrained surface displaying a complex of (relatively) recently occupied channel traces. The left bank remains confined by a high terrace down to RM 18.5, perhaps explaining the limited amount of channel migration despite the lack of right-bank constraints. The downstream end of this zone (and that of subreach 7) is marked by the outlet of the one looping meander developed into the low right-bank area over the past 100 years (Figure 2-2).

The subreach hosts two zones of extensive gravel-bar deposition. The first is associated with the channel bifurcations and islands around RM 21.5–20.0; the second forms a classic point-bar pair on the inside bends of the (currently expanding) meander from RM 19.6–18.8. Other sites of gravel deposition are more limited in extent and generally stand only a foot or two above the low-water surface, suggesting

either a low sediment load or (more likely) local hydraulic conditions in this moderately confined section more suited to transport than to deposition.

2.1.2.2 Grain size

The point bars at RM 19.6–18.8 provide well-defined locations for collecting sediment-size data representative of the typical bedload of the river during moderate to high flows. The surface layers at these two sites yielded median grain diameters of 188 mm and 105 mm, declining in the downstream direction. Two prominent bars in the upper, most confined portion of the subreach comprised gravels too large for any traditional measuring technique; median sizes were estimated at 800 mm (nearly 3 feet in diameter) just upstream of the subreach (Figure 2-4), declining to 500 mm on the narrow bar at RM 22.8.



Figure 2-4 Very coarse gravels (D_{50} ≈ 800 mm) at the head of the RM 23.6 point bar.
The confining post-glacial terrace cross-river stands over 100 ft above the modern channel. River flow is right to left.

2.1.3 Processes

The input of water and sediment into the subreach is almost exclusively from upstream. The drainage area of the river increases by less than 4% between the upstream and downstream ends of the subreach, and only the left-bank landslide at RM 21.4–21.1 constitutes a significant, recognizable source of new sediment input. A relatively uniform channel gradient below RM 23.2 implies no chronic state of either deposition or incision, with localized bar deposits now simply reflecting changes in local channel hydraulics. Nonetheless, the broad extent of high terraces through this subreach that now stand above the active floodplain suggest that deposition was once much more active, and that a subsequent period of incision was required to create the modern profile of the river. Given the vast accumulations of sediment that must have collected at (and fully choked) the head of the valley during glacial time, and the near-absence of those deposits today, the most plausible explanation for the modern valley-bottom topography and river profile is a period of massive sediment transport and redistribution, possibly lasting some

millennia after ice retreat, followed by reestablishment of an equilibrium channel profile under (relatively) steady-state conditions of climate, sediment supply, and base level (i.e., sea level).

Despite long-term topographic evidence of multiple channel traces, implying a long prior history of channel migration and avulsion, the last 100 years of the map and photographic record indicate more subdued channel behavior. Several episodes of avulsion during this period have nonetheless occurred through the lower half of this subreach, and migration rates on the order of 100 ft/decade are documented along several meander bends. These migrating bends are also the sites of extensive large wood recruitment, with several log-deposition sites located not far downstream of active migration zones hosting over 100 individual pieces in large jams.

Widespread floodplain engagement is similarly limited to the lower part of the subreach, once the confinement of the high terraces upstream of RM 19.5 is passed. Flood levels are sufficient to inundate much of the forested area north of the river along the right bank, even if channel migration has not fully exploited this low ground over the last century. Several avulsion pathways traverse this right-bank floodplain, with inlets adjacent to the modern channel between RM 19.5 and 19.2 that appear to be likely prospects for reoccupation under recent conditions of channel migration and/or high flood flows.

2.1.4 Anthropogenic influences

The dominant anthropogenic influence over this subreach is the bisecting of the once-active floodplain in the vicinity of Gold Bar by the BNSF Railroad, which reduces the area of available floodplain by about half downstream of RM 22. Snohomish County (2018) reports this to have been constructed in the 1890s. At present the modern channel directly impinges on about 0.5 miles of revetment as it passes due southwest of Gold Bar, but even if this revetment was absent the high terraces along this segment of the river might continue to force a relatively narrow channel path. Downstream of RM 19.6, however, the low-elevation floodplain abruptly widens to as much as 8,000 feet. Although the river presently flows along the southern edge of the floodplain through a historical side channel slough alignment, and so does not engage the revetment, future migration and/or avulsion to the northwest is likely to occur and will again bring the river against the constraining structures of both the railroad and the adjacent Startup levee.

Only two other localities of riprap were noted in this subreach. The first, at RM 22.2, is an isolated patch of angular rock adjacent to a more extensive slope below the BNSF Railroad embankment; the second (at RM 21.7) protects the 20-foot-high embankment below a house off the east end of 172nd Street SE. The house is presently set back about 25 feet from the top-of-bank; based on the mapped edge of the 1991 active channel relative to that of 2018, unconstrained bank retreat rates are on the order of 10 feet per decade.

The only other anthropogenic structures in the active channel zone are USGS gage 12134500 (Skykomish River near Gold Bar) at RM 22.7, constructed arrays of vertically installed logs and an apex jam on bars between RM 21.4 and 20.6 (installed in 2009 and 2010), and the two high bridges (State Route 2 and BNSF Railroad) near the head of the reach. In all, 32 vertical log arrays were installed in the channel and on vegetated bars and forested island settings in this subreach. The vertical arrays (broadly termed “flood fencing”) typically consist of taller pile arrays or short pile clusters driven into a bar or the bed of the river to catch floating logs, induce sedimentation, provide areas for revegetation, protect maturing vegetation and mid-channel island development. In this subreach they have created transverse bar jams and revegetation, augmented a large apex jam, provided protection to an existing mid channel island, snagged a few downed trees (Figure 2-5), and induced short-term bedform changes. Their performance and influence on channel conditions are being evaluated through other County efforts. River-level bedrock along this reach imposes a far greater constraint to fluvial processes, however, than any of these artificial structures in the decade since their installation.



Figure 2-5 Flood fencing at the entrance to the avulsion channel at RM 21.4.
As of 2020 the observed right-most set of log piles had trapped a few trees on the surface of the bar; elsewhere across the mouth of the channel beyond, repeat cross-sectional surveys suggested about one foot or less of channel-wide aggradation in the three years following installation. River flow is right to left and inundates this inlet with 6- to 7-foot-deep water at a 2-year discharge (as modeled by WSE 2020).

2.2 Subreach 6

Subreach # and length (mi)	Upstream RM	Downstream RM	Length (mi)	Gradient (from LiDAR DEM)	Pebble count RMs (D_{50})	Major features (upstream to downstream)
6	18.3	14.7	3.6	0.0023	17.9 (112 mm) 17.4 (88 mm) 16.6 (73 mm) 14.9 (69 mm)	• Town of Startup • Startup levee (lower part) • Startup training levee • Wallace R. confluence

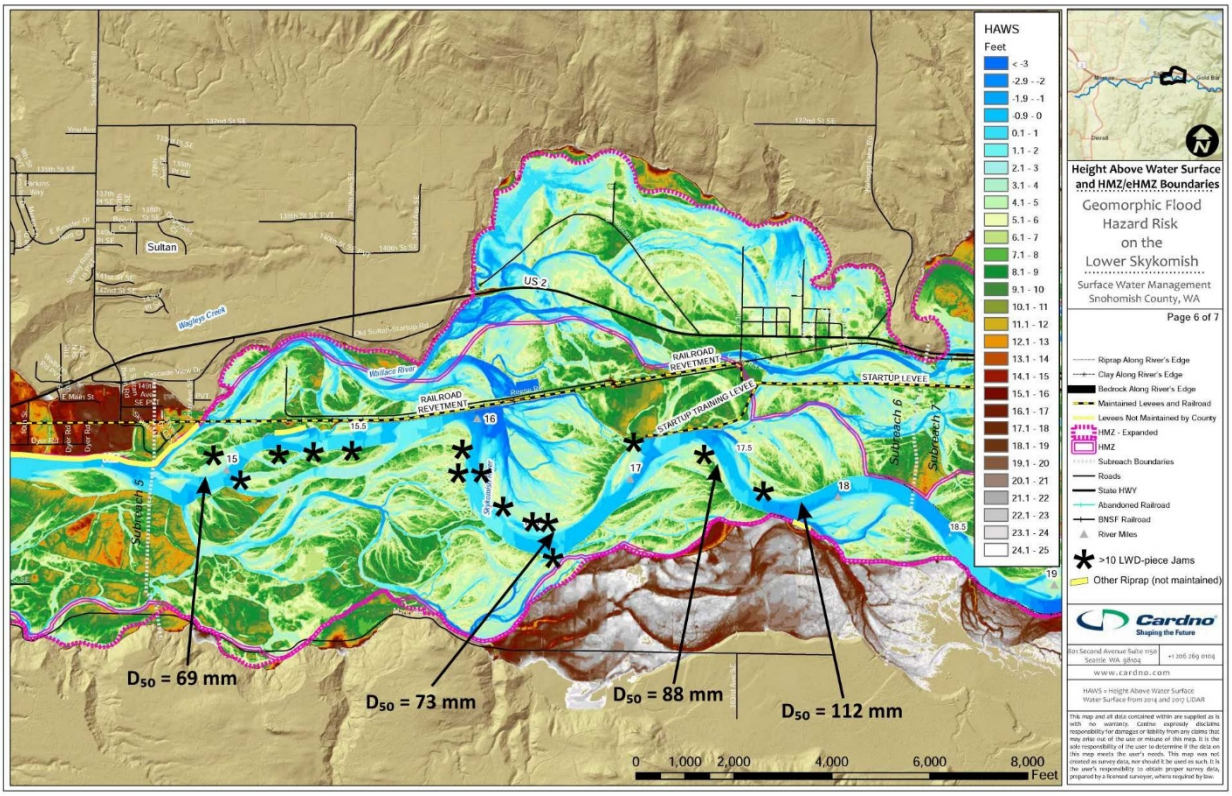


Figure 2-6 HAWS (Height Above Water Surface) map of subreach 6, highlighting the locations of pebble counts and median diameters (D_{50}), significant Large Woody Debris jams, and riprap.
Base map from the Cardno (2020) Channel Migration Zone study.

2.2.1 Channel features

Subreach 6 continues the overall channel patterns from the lower part of subreach 7, displaying a complex of active, episodically activated, and recently abandoned anabranches and side channels (Figure 2-6). It too is constrained by levees and revetments that continuously form the northern edge of the modern accessible floodplain, but unlike subreach 7 the active channel has more fully occupied the remaining areas over the last 100 years of the map and photographic record, albeit at a declining degree of occupancy over time.

Predating construction of the blockage created by the BNSF Railroad and the Startup levee, the 1921 map shows the lowermost 3 miles of what is today the Wallace River as a major channel of the Skykomish River. By 1938, the channels of these two rivers had been separated by revetments, with the Skykomish River confined to the southern half of its historical floodplain. As of 1938, 2 to 3 near-equal channels were present. Only 2 parallel channels were present as of 1965, which further consolidated to

no more than 1 or 2 channels as of 1991. Today the low-flow channel of the river is almost entirely single-thread, with only a few remnant side channels and one anabranching zone from RM 15.6 to 14.8 evoking a legacy of prior, more dynamic behavior (Figure 2-7). Nonetheless, flow is still episodically active in these remnant side channels, and one network in particular (the "South Slough complex," a set of hillside drainage and side channels with one outlet [of several] that reenters the Skykomish River at RM 14.8) has reportedly increased in activity in recent years. Multiple inlets to this side-channel network are present along the left bank, particularly between RM 16.65 and 16.40, including three that are presently part of the active channel network and three additional inlets that are likely to become active with continued downvalley bend migration.

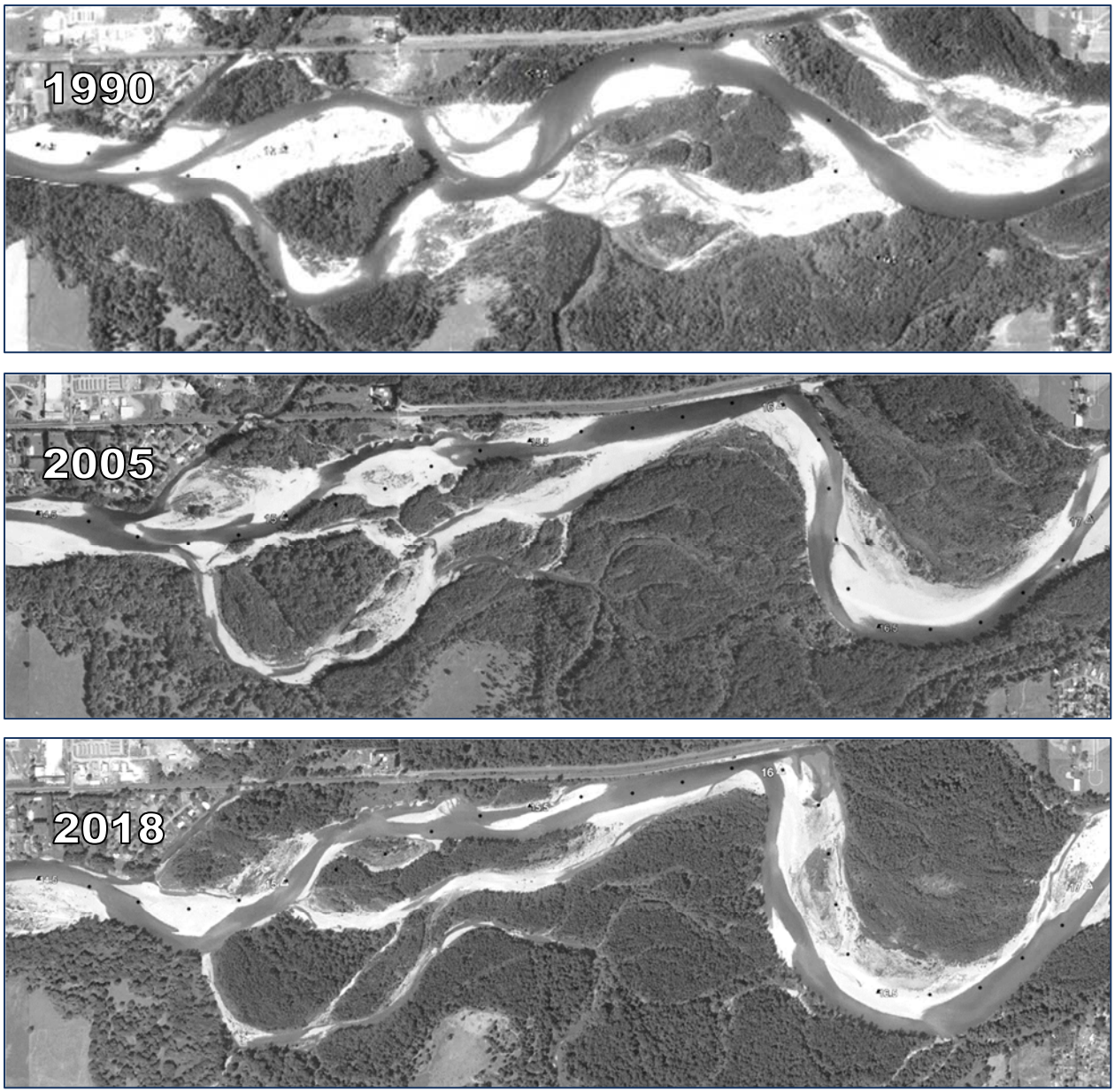


Figure 2-7 Sequential airphotos of lower subreach 6, from RM 17 downstream (i.e., right-to-left) to the junction with the Wallace River (left edge of images).
Note the progressive reductions in the area active channel occupation and the number of active threads, and the steady encroachment of vegetation onto once-bare gravel bars. An outlet of the South Slough complex is the southwest-most (lower left) channel in each image—it was a subdominant channel in 1990 but only a minor side channel as of 2018. Black dots mark 1/10th mile intervals along the center of the 2018 active channel; river miles and half-miles are noted at triangles.

The channel gradient through subreach 6 is relatively uniform and significantly flatter than that of subreach 7 (0.23% vs. 0.32%). The transition occurs a few tenths of a mile upstream of the subreach boundary, where the channel moves away from the constraining high terrace along the left bank of the active channel in subreach 7. Recognizable downstream increases in both channel-migration activity and deposited gravel-bar areas are undoubtedly related to each other, a consequence of the river's declining competence to transport its load of gravel-sized sediment.

Multiple zones of active channel migration reflect the dynamic behavior of the river. The early-20th century anabranching pattern, which occupied much of the floodplain through avulsions and other channel changes, is not well-documented by the multi-decade gaps between sequential airphotos. Rates of more recent migration, however, can be reliably measured at several locations (Table 2-1 and Figure 2-8). They highlight typical locations (at the outside of well-developed meander bends); typical rates (about 10–20 ft/yr when averaged over a decade or more); and the apparent insensitivity of those rates to local (natural) bank conditions, such as terrace height, bank sediment (clay vs. gravel), or floodplain vegetation. The constraining influence of artificial revetments (e.g., in the center of Figure 2-8, along the Startup training levee), however, is clear from the imagery.

Table 2-1 Sites of well-defined channel migration in subreach 6 (data from Cardno 2020; see also Figure 2-8).

Type of Boundary	RM	From Year	To Year	Migration Distance (ft)	Avg. rate (ft/yr)	Notes
Mid-level floodplain (9–12')	18.1	1991	2018	550	20.4	Clay in bank, outside bend
High terrace (>20')	17.7	1991	2018	230	8.6	Clay in bank, outside bend
Mid-level floodplain (9–12')	16.4	1991	2018	610*	22.6	Outside bend

* An additional 100' of migration occurred at this site between 2018 and 2020, making it the most active location for channel migration along the entire Lower Skykomish River over the last three decades.

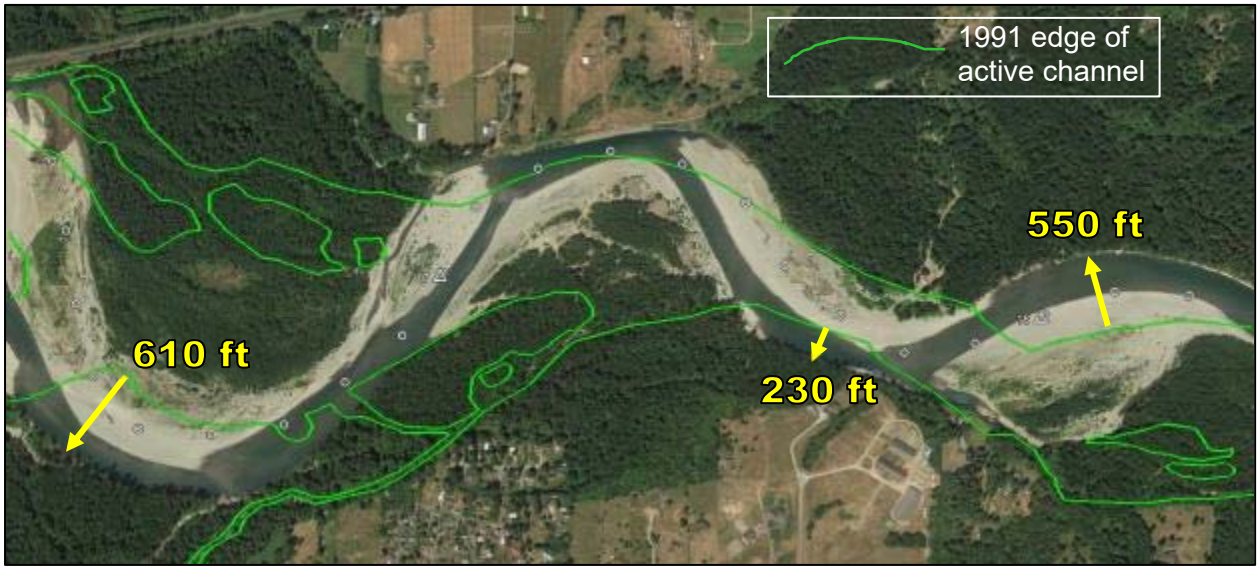


Figure 2-8 Well-defined zones of channel migration between 1991 (green outline) and 2018 in subreach 6. Labeled distances indicate the total migration of the active channel edge over this 27-year period. Airphoto base from Google Earth.

2.2.2 Sediment characterization

2.2.2.1 Terraces and bars

Subreach 6 is marked by the almost complete absence of the high channel-bounding terraces present farther upstream. The river flows through a broad terrain little higher than the bankfull depth of the channel itself (about 6–7 feet above the low-water level), with the only extensive area of higher ground protected behind the Startup training levee and so not reworked by the river since the 1921–1938 interval (during which the levee was constructed).

Consistent with the substantial decline in channel gradient that begins just upstream of the upper subreach boundary, gravel bars are relatively voluminous and the size of the deposited sediment declines downstream fairly rapidly as the river loses its competence to move the larger fractions of its total load. The channel is consistently flanked by alternating gravel bars that form an active zone almost uniformly more than 600 feet wide, and several of the bars in this subreach stand as much as 5 feet above low-water level (Figure 2-9).



Figure 2-9 Voluminous gravel bar at RM 15.0, along the left bank just above the confluence of an outlet of the South Slough complex and the mainstem river.

2.2.2.2 Grain size

Also reflecting the downstream-declining channel gradient, the median sediment size on point bars declines monotonically by almost half from the top of the subreach to the bottom, a pattern repeated in the coarser size fractions (D_{84} and D_{95}) as well. The largely unconstrained, meandering planform of the river through this subreach provides multiple localities for collecting morphologically consistent sediment samples, and they paint a consistent pattern of downstream decline. The distance over which this decline occurs is far too short to invoke actual reduction in the size of individual gravel clasts by abrasion; instead, it implies relatively rapid rates of sediment deposition, which is also consistent with the close coupling observed between the elevations of the channel and its adjacent floodplain.

2.2.3 Processes

2.2.3.1 Water and sediment inputs

Virtually no tributaries contribute water or sediment to subreach 6, with the drainage area increasing less than 3 percent between the upstream boundary of the subreach and its confluence with the Wallace River. The latter, however, adds almost 10 percent to the total upstream drainage area of the Skykomish River at this point, and so the river leaves subreach 6 with a significantly augmented discharge. Its sediment load, however, is likely little changed, since the gradient of the lower Wallace River is almost certainly insufficient to transport significant quantities of sediment as coarse as the median-sized grains of the mainstem river.

2.2.3.2 Lateral channel migration & avulsion

The rapid decline in sediment sizes on point bars of this subreach implies the progressive deposition of bedload sediment. This deposition, in turn, is the fundamental driver of channel migration and avulsion, since the deflection of flow around deposited sediment "steers" the water flow along erodible banks or into previously occupied floodplain channels. Although the photographic record since 1991 primarily documents progressive channel migration within a broadly constant planform, the longer record provides multiple examples of avulsion and rapid rearrangement of the channel network. Broad tracts of bare gravel bars in the 1938 photos, for example, suggest a particularly active braided-river environment at that time (Figure 2-10), but one with progressively reduced activity over the subsequent decades (compare with Figure 2-7). Although much floodplain clearing of large timber for milling, homesteading, and agricultural uses had occurred by 1938, broad zones adjacent to the multiple channel courses through this subreach clearly express the direct influence of recent overbank flows and sediment deposition rather than direct human modifications.



Figure 2-10 Aerial photograph from 1938 of lower subreach 6, showing broad areas of braided channels along with more sinuous, single-thread zones in the south part of the image.
The present-day trace of the channel is marked by the small black dots (at 0.1-mile intervals, mainly along the top of the image) and by the triangles (labeled by river mile).

The channel configuration during the pre-photographic period, as recorded by the 1921 topographic map, comprised three to four branching and recombining channels that occupied the entire floodplain from valley wall to valley wall. Traces of these channels are still evident in the topography (Figure 2-6), but with a more dominant, singular thread emerging by 1938 (Figure 2-10), albeit with broad areas of still-active floodplain to the north of the main channel. The following decades showed progressive, more dominant

occupation of the northern channels and distributaries by the active flow. An avulsive style of channel shifting in the old photographs becomes more uniformly single-thread meandering by 2003. This evolution is expressed along the two northerly meander bends that now intersect the Startup training levee (RM 17.4–17.1) and the BNSF Railroad revetment (RM 16.0–15.6): a freely avulsing channel persists until the northern boundary of the migration zone is blocked by the revetment, at which point the zone of activity collapses into a meandering/migrating pattern.

Although the post-2003 aerial photographs do not document widespread return to the early-twentieth century mechanism of avulsion as the dominant process, a few side channels remain quite active to the present day. The most prominent of these is fed by a branching network of active and nearly active inlets, forming the head of South Slough and showing abundant evidence of active flow during the winter of 2019–2020 (Figure 2-11). As the bend at RM 16.4 (at the lower left corner of Figure 2-8) continues to migrate downvalley, it will sharpen the "kink" in the channel held in place along the BNSF revetment at RM 16.0, potentially below the typical range of natural radii of channel curvature and so encouraging a new and more direct westerly flow path. Although any such avulsion across this kink would need to breach abundant accumulations of LWD blocking at least one of these inlets (see Figure 2-6), field evidence suggests that this process is likely to remain active in this area and potentially increase, however, for the foreseeable future.



Figure 2-11 View down the active avulsion channel at RM 16.40 (left bank).
Despite a significant LWD jam near its entrance, wintertime flow is obviously quite active. Photograph from September 2020.

Another zone of rapid recent bank erosion, encroaching on the inlet of a potential avulsion channel, is present along the left bank at RM 14.75 just downstream of an outlet of the South Slough complex. Although minimal bank erosion occurred between 1991 and 2018, recent airphotos document 140 feet of bank retreat in the last two years (2018–2020). At present the channel is encroaching only on riparian forest, but continued migration could reopen an avulsion pathway that may have been occupied as recently as 1965, and which trends almost due west across the floodplain for one mile before passing under Mann Road.

2.2.3.3 Riparian large woody debris recruitment and retention

This subreach contains the highest density of LWD accumulations in the entire Lower Skykomish River, as previously documented by Snohomish County (Snohomish County 2005). LWD prevalence likely reflects both an abundance of nearby upstream sources (i.e., broad meander bends migrating across mature forested land) and a complex channel–floodplain geometry that offers multiple sites for wood retention (i.e., broad point bars, side-channel inlets, and irregular near-channel topography) (Wohl 2017).

A more detailed inspection of one of the largest LWD jams in the subreach, that on the bar crest of RM 16.3, provides insight into temporal changes associated with wood loading (Figure 2-12). Nearly devoid of wood in summer 2006, the November 2006 flood of record (129,000 cfs at Gold Bar) induced substantial channel migration throughout subreaches 6 and 7 and precipitated a large jam over 200 feet long on the bar crest. Stabilization of the sediment by the jam, plus the increasing lateral migration of the channel away from this jam, allowed nearly complete revegetation by 2014 but with little additional wood accumulation. One or more subsequent high flows, however (presumably that of November 2015; 95,500 cfs), initiated another large jam and also transported multiple logs into the outlet of the side-channel inlets on the left bank of the channel.



Figure 2-12 Sequential photographs (from Google Earth) of the bar at RM 16.3 (flow from bottom to top). Ovals, scale bar, and image outlines are unmoved from one panel to the next. Large floods initiated jam formation, first that in November 2006 (red oval) and then that in November 2015 (turquoise oval). Eight sets of vertical log arrays were installed on this bar prior to the 2014 image; three of them appear to have successfully triggered formation of the 2017 turquoise-marked jams, with a fourth augmenting a pre-existing accumulation.

2.2.3.4 Floodplain connectivity and inundation

The modern channel is relatively well-connected with its floodplain throughout the valley lying south of State Route 2, the BNSF Railroad, and the Startup training levee. Large tracts of accessible, low-elevation floodplain are present down to about RM 15.5, with a modestly greater degree of channelization and higher terraces below this point to the end of the subreach. Much of this high-terrace area in the downstream part of the subreach was forested even as of 1938, suggesting that the modern pattern of westerly rising relative terrace elevations, if associated with aggrading terraces (as opposed to reflecting an incising channel), would not be a recent phenomenon.

2.2.4 Anthropogenic influences

2.2.4.1 Riprap and levees

The northern edge of the floodplain through subreach 6 is entirely truncated by levees and revetments, whose impacts on channel patterns and channel processes are profound. The riprapped bank formed by the BNSF Railroad, presently engaging the channel from RM 16.0–15.5, has formed the right bank of the river in every image since its first appearance in 1938. The phenomenon of a smooth, straight, armored bank imposing a near-permanent channel position is readily observed in this and other rivers throughout western Washington, converting what was once a fully dynamic system with multiple, mobile channels into one with segments that are entirely fixed in space. It likely explains much, if not all, of the progressive consolidation of multiple channels into a more limited, largely single-thread planform exhibited in this subreach over time (Figure 2-7).

The Startup training levee (RM 17.4–17.1, constructed in the 1960s according to Snohomish County [2018]), is of more limited lateral extent and has had a similar but more limited influence on channel planform. It has created a "shadow" of high terrace deposits on its landward side, not engaged by the 1921 (i.e., pre-levee-construction) channel and isolated (post-levee-construction) from all subsequent channel positions. It has not been a fixed channel boundary as persistently as the BNSF Railroad (for example, from 1938 to 1965 the channel pulled *away* more than 500 feet from the levee). Since reengaging the levee sometime between 1990 and 2003, however, the channel has remained pinned against its southern face.

A few hundred yards downstream of the continuous revetment along the railroad, a set of 5 rock groins were built out into the channel sometime between 1990 and 2005 (RM 15.3–15.2). They are evenly spaced about 180 feet apart and project into the flow between 30 and 40 feet perpendicular to the bank. As of 2005 they directly engaged the main flow of the river, but since about 2009 they have become more isolated by growth of a large bar along the right bank of the river at RM 15.4 that has extended downstream over time, forcing progressively more of the flow towards river-left, away from the groins (and also away from the face of the levee).

2.2.4.2 Other anthropogenic impacts

Aside from the two major levees, few direct human actions or structures have significantly affected the river. A short stretch of left-bank riprap along a side channel at RM 17.9–17.8 protects the toe of a 20-foot-high terrace with farmland and structures above; bank armoring also limits erosion on the right bank at RM 15.3, paralleling the railroad embankment but closer to the modern channel. The right bank of the lower Wallace River is also armored from the railroad bridge down to its confluence with the mainstem Skykomish River (and beyond, into subreach 5).

Three sets of flood fences are located in this subreach. The most extensive installation, in eight separate clusters on the right-bank point bar between RM 16.5 and 16.2, appears to have provided a nucleus for 4 large LWD accumulations in late 2015 (see Figure 2-12), with other log accumulations also present on this bar having collected around existing vegetation.

At RM 15.53, two small log-pile clusters adjacent to the BNSF Railroad revetment provided some additional support to an existing, upstream-expanding bar. This upstream-expanding bar has shifted the riffle crest upstream which likely supports a higher river stage elevation facilitating overtopping of flows to the left bank (middle floodplain side channel) and away from a downstream riprap revetment. Lastly, a three-cluster flood fence at RM 15.4 (left bank) surrounded a pre-existing log jam at the head of a partly vegetated point bar. Some additional logs were caught on the upstream-most cluster in the first few years following installation, but high flows between 2015 and 2017 removed all but the most landward cluster altogether, and little apparent long-term change to LWD accumulation has occurred.

In this subreach as elsewhere, once-cabled concrete pylons remain in the river, relics of past river training attempts. Here, concrete pylons were placed to limit channel avulsion and migration toward the mouth of the Wallace River. A set of at least 8 pylons, installed prior to 1938, were still visible as of the 2003 airphoto.

2.3 Subreach 5

Subreach # and length (mi)	Upstream RM	Downstream RM	Length (mi)	Gradient (from LiDAR DEM)	Pebble count RMs (D_{50})	Major features (upstream to downstream)
5	14.7	13.5	1.2	0.0013	14.1 (50 mm)	• Town of Sultan • 311th Ave Plug Levee • Mann Road bridge

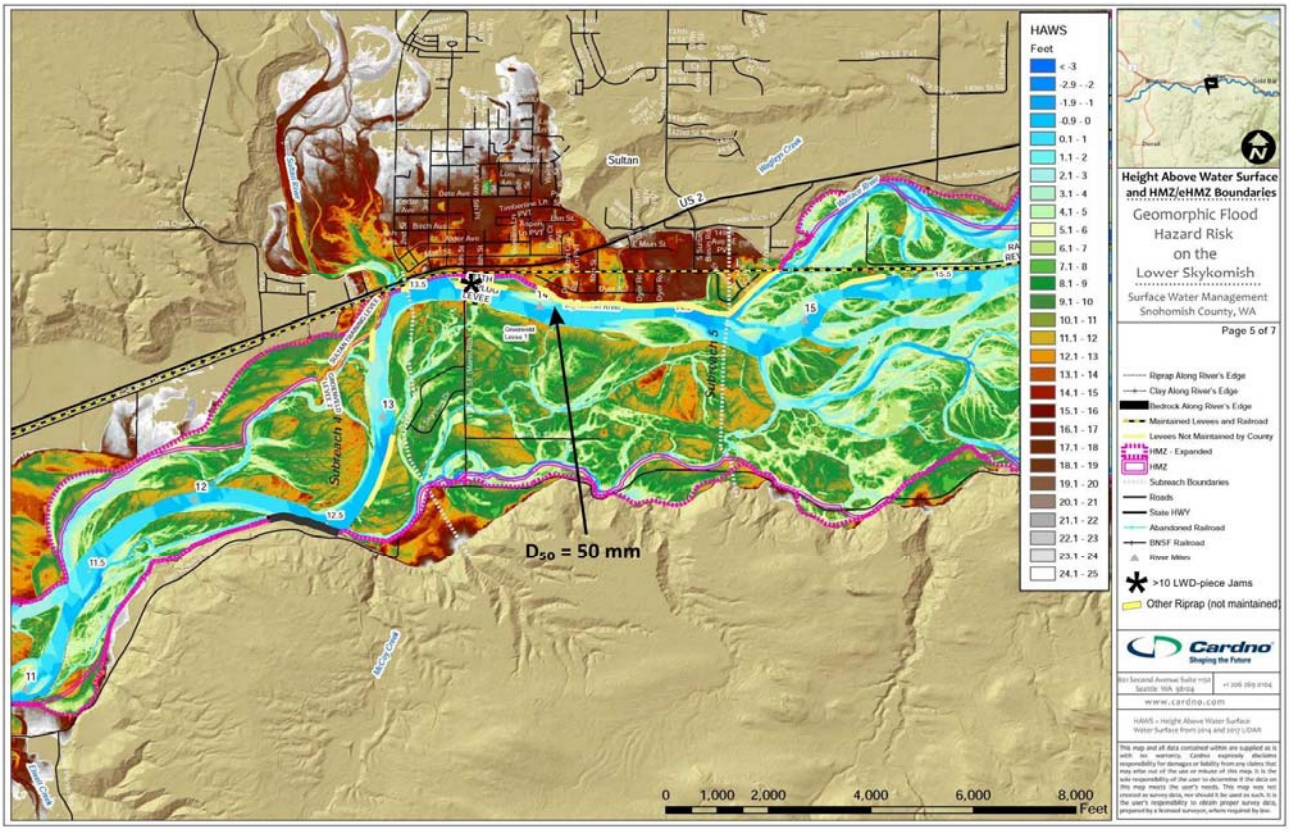


Figure 2-13 HAWS (Height Above Water Surface) map of subreach 5, highlighting the locations of pebble count and median diameter (D_{50}), one significant Large Woody Debris jam, and riprap.
Base map from the Cardno (2020) Channel Migration Zone study.

2.3.1 Channel features

Subreach 5 marks a transitional zone of the river, from a multi-thread side-channel-rich system to one dominated by a single mainstem bounded by high and less frequently floodwater-inundated terraces (Figure 2-13). It also continues the pattern of downstream reduction in channel gradient, commensurate reduction in bedload grain sizes, and an increase in the fraction of the channel having riprapped banks.

The low-water profile of the river through this subreach exhibits several discrete zones. It maintains the (relatively) steep gradient of subreach 6 until just past the Wallace River confluence, and then flattens to less than 0.1% behind the bar at RM 14.0. Once downstream of that low-water obstruction, it then steepens somewhat down to its confluence to the Sultan River (marking the start of subreach 4). Overall, the subreach gradient is only about half of the channel upstream, and so significant deposition (and associated channel migration) would be expected in response.

In the 1938 airphoto, a major side channel begins on the landward side of the upstream-most bar at RM 14.4, over 300 feet wide at its inlet and flowing crudely parallel to the course of the mainstem river until

rejoining it near RM 13. By 1965 this path was only a minor forested channel, and it had been abandoned altogether by 1991.

Several low-elevation channels persist in the topography of the floodplain south of the modern channel. The largest and most continuous originates in subreach 6 as the South Slough complex, flows close to the south valley wall as "South Slough," and reenters the mainstem river at RM 12.5 (in subreach 4). This channel is likely shown on the 1921 map and is clearly discerned on the 1938 airphoto. Several other small anabranching channels, closer to the river, also appear in the 1938 airphoto and are sufficiently low in elevation to carry water today. The surrounding terrace surfaces, however, are up to 10 feet higher and are not inundated during periods of low to moderate flooding.

2.3.2 Sediment characterization

2.3.2.1 Terraces and bars

Virtually the entire valley floor north of the river through this subreach is a high terrace standing 15 feet or more above the river, part of the post-glacial alluvial deposits of the Skykomish River valley but no longer actively engaged by the modern river. The surface is densely populated with residential structures, and its toe is continuously armored with riprap (Figure 2-14). South of the river, terrace heights are broadly lower and more variable in elevation, but in general they still stand 10 or more feet above the main channel and the multiple floodplain side channels, continuing the trend of higher valley-bottom surfaces noted for the downstream-most end of subreach 6.



Figure 2-14 View of the river-bounding terrace along the north side of subreach 5 (RM 14.4).

The two active gravel bars in this reach have divergent histories. The larger, upstream bar (presently occupying RM 14.6–14.2) has occupied the left bank of the river in every nearly airphoto since 1938 (except those of 1990–1991), pinning the river between it and the right-bank revetment. In contrast, the channel has variously passed to the left, right, and through the downstream bar (presently RM 14.1–13.9) in response to transitory patterns of erosion and deposition.

Although the two bars here do cover broad areas, only in the upstream half of the subreach has much migration occurred in response to their deposition. Even there, however, the length of affected bank is only about 3,000 feet long with an average retreat of 200 feet from 1990 to 2018 and a maximum retreat at RM 14.4 of 340 ft (7 ft/yr [average], 12 ft/yr [maximum]). The lowermost 0.5 miles have experienced virtually no bank erosion or channel shifting at all.

2.3.2.2 Grain size

Only one site in this reach was judged sufficiently representative of other sampling locations to be included in the population of grain-size measurements. Its value (D_{50} = 50 mm) continues the pattern of downstream-declining sediment, commensurate with the reduction in channel slope and thus transport ability.

2.3.3 Processes

2.3.3.1 Water and sediment inputs

There are no contributing tributaries in subreach 5 downstream of the Wallace River confluence. As noted previously, the nearly 10 percent increase in drainage area provided by the Wallace River implies that the Skykomish River enters this subreach with a significantly augmented discharge. Its sediment load, however, is likely little changed, and so the channel might be expected to transport its load more effectively. This may explain the relatively static nature of the channel through this subreach, although the continuous right-bank terrace and revetment, plus additional constraints on both sides of the Mann Road bridge (RM 13.7) suggest that no additional explanation may be needed for this behavior.

2.3.3.2 Avulsion

Albeit limited, the most active channel-migration process in this reach has been avulsion, and it poses the greatest risk of a future redirection of flows. An additional 400 feet of left-bank retreat at RM 14.35 would be needed to breach the berm presently separating a 1938 flow path (“Sky River Slough”) from the mainstem river, but even lesser amounts could raise the potential for an overtopping flow that reactivated this pathway. Although the bank retreated 150 feet between 1991 and 2007, its position has now been stable for more than a decade. At present the berm is breached by only by a very narrow channel carrying minimal flow.

2.3.3.3 Riparian large woody debris recruitment and retention

Few sites for log accumulation are present in this subreach, with one of the supports of Mann Road bridge offering the only real accumulation site (Figure 2-15). The limited area of present-day channel erosion provides minimal recruitment. The forested left-bank floodplain is undergoing bank erosion between RM 14.6 and 14.0 and so contributes woody material, but bank retreat rates are no more than 12 ft/yr (and commonly less). Relative to the multiple zones of forested bank erosion farther upstream, this is a relatively limited source of LWD for the river.



Figure 2-15 Log accumulation at the right-side support of the Mann Road bridge (RM 13.7).

2.3.3.4 Floodplain connectivity and inundation

But for small relict side channels, floodplain connectivity is minimal in this subreach. Most of the floodplain surfaces are terraces standing 10 to 15 feet above modern river level, minimizing the area that ordinary floodwaters can reach and suggesting a long-term history of channel incision.

2.3.4 Anthropogenic influences

2.3.4.1 Riprap and levees

Riprap is extensive in this subreach, with virtually the entire right bank armored. Its presence likely reflects the sensitivity of the adjacent land use to any channel encroachment than to active erosion, as the bounding terrace surface stands well above the level of the river and shows no sign of past channel occupation. Although any faint topographic traces of pre-twentieth-century channels would likely have been obliterated during development of this neighborhood, at least since before 1921 the river has never advanced north into this area.

Other structures in this subreach include the Groeneveld levee 1 (RM 14.0–13.8) and the 311th Avenue plug levee (RM 13.8), both along the left bank.

2.3.4.2 Bridges and other hydraulic structures

The Mann Road bridge has two supports that interact with the active channel, although patterns of sediment deposition around them do not suggest major impacts. The south-side approach to the bridge, constructed by 1965 closed off what had been in 1938 a very active left-bank bar complex between RM 13.8-13.0 in 1938. The berm buried much of this complex, leaving only a single narrow crossing which became largely inactive by 1990 and entirely plowed over by 2005.

A flood fence was constructed along the left bank of the river at RM 14.05, presumably to block river access to an active side channel (“Shinglebolt Slough”) that ultimately passed under Mann Road about 500 feet south of the Skykomish River, and which was active until at least 1965. Although the logs were reportedly installed prior to 1938, the side channel behind them appears at least minimally active in the 1938 and 1965 airphotos (by 1990 it was likely abandoned, and by 2005 definitely so). In recent years the

flood fence has been modestly successful only at capturing a few logs (Figure 2-16); bank retreat has now proceeded for about 100 feet behind the now mid-channel position of the flood fence.



Figure 2-16 Flood fence at RM 14.05.

2.4 Subreach 4

Subreach # and length (mi)	Upstream RM	Downstream RM	Length (mi)	Gradient (from LiDAR DEM)	Pebble count RMs (D_{50})	Major features (upstream to downstream)
4	13.5	9.7	3.8	0.0012	12.9 (71 mm)	• Sultan River confluence • McCoy Creek confluence • Elwell Creek confluence

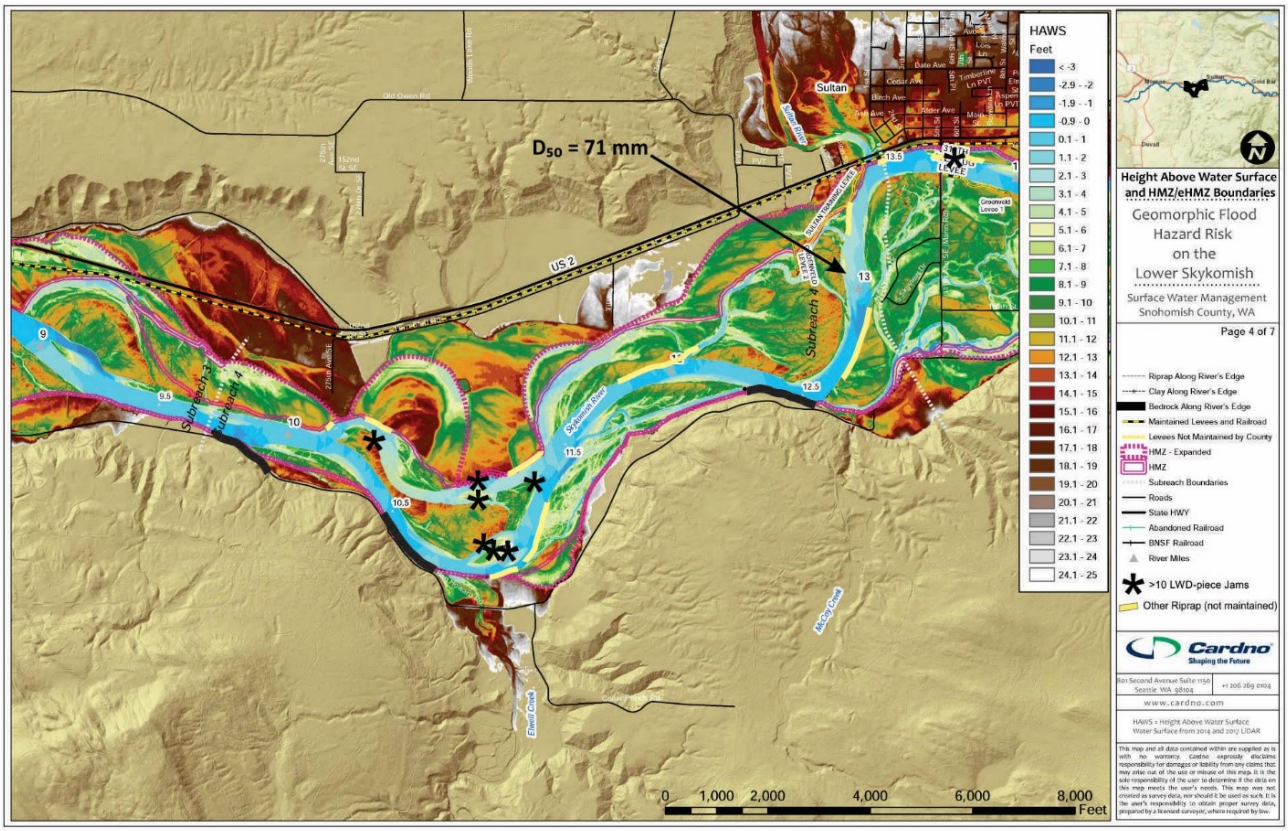


Figure 2-17 HAWS (Height Above Water Surface) map of subreach 4, highlighting the locations of the one pebble count, significant Large Woody Debris jams, and riprap.
Base map from the Cardno (2020) Channel Migration Zone study.

2.4.2 Channel features

2.4.2.1 Planform – channel patterns, sinuosity, confinement

Subreach 4 retains the upstream pattern of a predominantly single-thread channel with only a few, relatively short and narrow side channels and a sinuous mainstem planform (Figure 2-17). However, it also hosts the largest island downstream of the Sultan River confluence (at RM 11.4–10.2) that splits the mainstem into two channels nearly equal in size to one another, though this was not always the case. The relatively high terraces that flank the active channel in subreach 5 continue downvalley, constituting even more of the floodplain and increasing in elevation to as much as +13 feet relative to the low-water surface. Much of this near-channel floodplain zone has not displayed occupation by the river in any maps or airphotos of the last century, although the topography throughout this zone suggests geologically "recent" (albeit pre-historical) fluvial activity.

This zone of recent but pre-last-century river occupation is bounded on the south by the bedrock ridge forming the southern valley wall, and on the north by even higher fluvial terraces whose surfaces lie 15 to 20 feet above the town of Sultan (which occupies lower surfaces immediately east across the Sultan River). The distance between these two floodplain boundaries, and thus the area nominally available for past and future river occupation, narrows dramatically from the upper to the lower end of the subreach—at the top this inset fluvial valley is almost one mile wide (and the river traverses its entire width between RM 13.5 and RM 12.5); but at the bottom of the subreach less than 1,500 feet separate the high northern terrace from the southern bedrock. The river, with a bankfull width of 400 to 450 feet, occupies nearly one-third of this available floodplain area, with a plethora of local revetments throughout the subreach that confine it even further.

2.4.2.2 Slope & channel dimension

The average channel gradient of subreach 4 is nearly identical to that of subreach 5 (0.012% vs. 0.013%), despite the significant increase in drainage area at the top of the subreach from the Sultan River (which adds 105 square miles of watershed area to the 617 square miles of the Skykomish River). More noteworthy is the stairstep character of the subreach profile, particularly a segment over a mile in length with a low-water gradient little different from zero (Figure 2-18). This area is reported to be a long-term depositional zone, consistent with its extremely low slope. Possible factors for this low-gradient feature include the loss of fluid energy at the bedrock-imposed 90° bend at RM 12.5; the active left-bank side channel at RM 12.3, which undoubtedly reduces discharges in the main channel at moderate and high flows; and the island downstream, which may add significant flow resistance and backwatering at high flows. The hydraulic model for this reach shows only minimal variation (and no systematic reduction) in flow velocities through this segment of the river, but the model does express shallowing of flood flows as they approach the head of the island at RM 11.4.

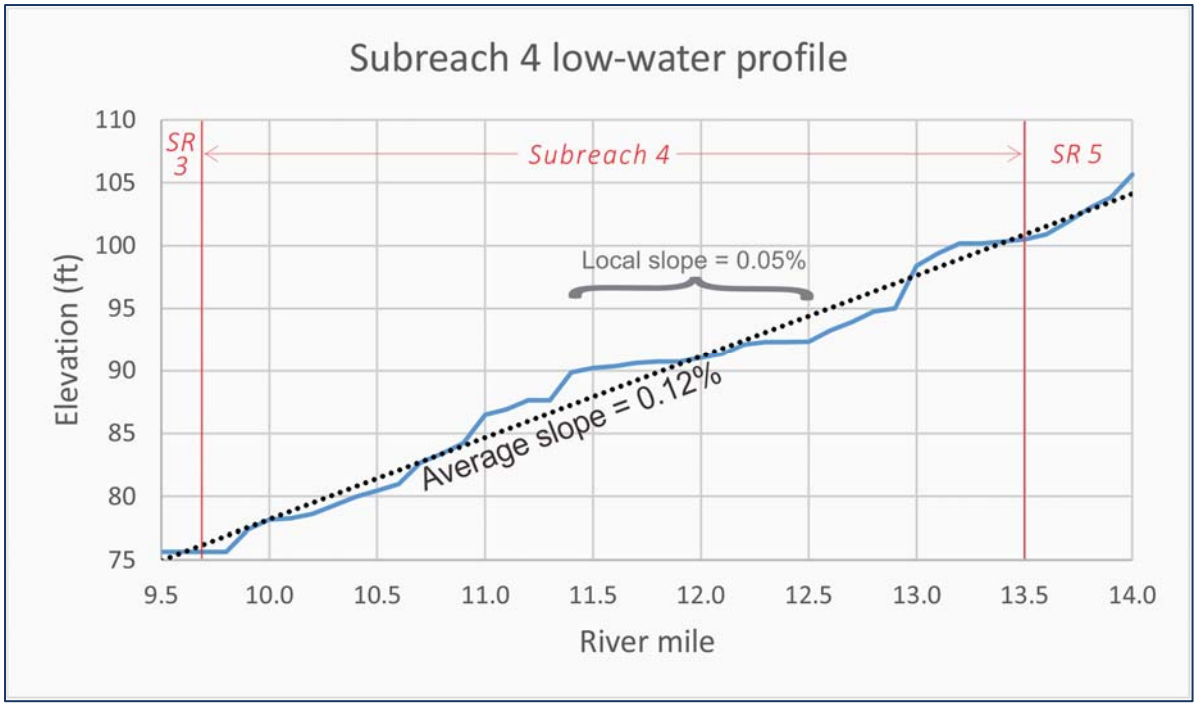


Figure 2-18 Low-water profile of subreach 4, highlighting the very low-slope zone between RM 12.5 and 11.4.
Note also the flattening of the slope at the bottom of the subreach and extending into subreach 3 (see next section). Water-surface topography from 2014–2017 LiDAR survey.

2.4.2.3 Migration history and rates

Upstream of the RM 11.4 island, channel migration has been modest and primarily expressed in side-channel formation and subsequent abandonment. This activity has been strongly mediated by

constructed bank armoring, particularly post-1965. From RM 13.8 (lowermost subreach 5) to RM 13.2, the 1921 channel had migrated to the northwest by 1938 up to 370 feet (an average rate of 21 ft/yr). Riprap along the right bank flanking the outlet of the Sultan River has held the channel in place since that time. Similarly, 1921-1938 retreat of the left bank at RM 12.70 was 416 feet (25 ft/yr); here, however, riprap was installed only after 1965, and so the period 1938–1965 added an additional 180 feet of migration (7 ft/yr).

Downstream of the left-bank bedrock wall at RM 12.5–12.3, a braided channel network in 1921 migrated north and west. By 1938 the modern channel configuration was largely in place, with almost 2,000 feet of riprap constructed along the right bank by 1965.

The island at RM 11.4–10.2, with its apex anchored by a large jam, was well-defined as of the 1965 airphoto, with the northern channel following the trace of a smaller side channel visible in the 1938 airphoto. The island persisted for nearly a half-century with only modest change. Since the 2006 flood, however, changes in channel position have accelerated. These changes are particularly rapid along the northern thread, where a bank scallop began eroding into the adjacent terrace during the winter of 2013–14 (10' of bank retreat), doubling in extent the following next winter, and more fully developing between 2015 and 2017. As of 2018 the eroded bank scallop was 600 feet wide (Figure 2-19) with 170 feet of total bank retreat at its apex (and a bank-erosion rate of about 50 ft/yr from 2015 to 2018). Farther downstream, the left bank of the northern thread breached the "neck" of the island at RM 10.4 in early 2020, rejoining the southern thread to reform the mainstem channel.



Figure 2-19 Eroded terrace along the north channel (about 300 yards downstream of the apex jam at RM 11.4).
The terrace surface is about 14 feet above low-water level; the deposit is overbank silty sand, nearly devoid of gravel.

2.4.3 Sediment characterization

A reduction in the width of the active channel zone, and commensurate stabilization and vegetation of once-active bars, characterizes the last 100 years in this subreach. Wide, bare gravel bars in the 1938 airphotos are now narrow threads of bare sediment as of 1991, with little change since that time. These changes are particularly notable for the 1938-era bars from RM 13.8–13.0 (left bank), 13.0–12.4 (right bank), and 12.2–11.0 (left bank). Two potential explanations for this reduction in channel dynamics: first (and almost certainly contributory), the construction of revetments, which in total line about 2 miles of riverbank in this subreach; and second, the modest reduction in peak flows contributed by the Sultan River following construction of Culmback Dam in 1965 and its subsequent raising in 1984 (Stillwater Sciences 2008).

Channel- and side-channel-flanking terraces are similar in this subreach to those immediately upstream in their relative elevation. Upstream of RM 11.4 they typically range from +8 to +13 feet above the low-water

surface. Downstream of this point, however, the channel locally abuts terrace surfaces up to +15 feet above the low-water surface, a condition that becomes progressively more common farther downstream.

2.4.3.1 Grain size

A rather poorly defined point bar in a slightly sinuous segment of the river (RM 13.05) provided the only site in this subreach for a credibly representative pebble count. Other point bars are present in the subreach, but their local hydraulics are strongly influenced by bedrock, riprap, or multiple channels (and, in some localities, all three). The measured D_{50} here was 71 mm, representing the first clear divergence of the downstream-fining pattern seen farther upstream. The most likely explanation is the contribution of a coarser sediment load from the Sultan River, which was first documented in Stillwater Sciences (2008) on Kien's Bar (1.1 miles upstream of the Skykomish River confluence, and with a D_{50} of 150 mm). The median grain size of the bed of the Sultan River just a few feet upstream of its confluence with the Skykomish River was measured in September 2020 at 112 mm, substantially coarser than both the upstream Skykomish mainstem sediment (D_{50} = 50 mm at RM 14.1) and the downstream mainstem stations.

This Skykomish River locality also offers an excellent expression of a channel bankfull depth of 7.5 feet, based on the left-bank floodplain surface that was part of the active channel at least as late as 1965 (Figure 2-20).



Figure 2-20 Well-defined bankfull depth at RM 13.0 along the left bank of the river, which equals the exposed height of the floodplain surface plus the water depth (about 0.5 feet).

2.4.4 Processes

2.4.4.1 Water and sediment inputs

Subreach 4 experiences a significant increase in contributing drainage area relative to upstream, with the Sultan River confluence at the upstream boundary of the subreach adding an additional 17 percent drainage area (less than 5 percent more is added through the rest of the subreach). The water and sediment contributions of the Sultan River are not entirely equivalent to one another, however, because its upper watershed is controlled by releases from Culmback Dam. Stillwater Science (2008) documented moderate reductions in the magnitude of peak flows but only minimal changes to sediment delivery at the confluence with the Skykomish River. Most of the natural sediment load of the Sultan River enters that channel downstream of the dam and its impounded reservoir, and the loss of transport capacity from reduced peak flows near its mouth has been largely balanced by the progressive narrowing of the downstream channel, increasing the transport efficiency of the flow that remains.

Thus, several factors affect the water–sediment balance in subreach 5 relative to Skykomish River farther upstream. The channel gradient is relatively continuous across these two subreaches but substantially lower than farther upstream. Sediment delivery from the Sultan River is significant, but the flow that carries it down that channel is less competent once it reaches the lower gradient of the Skykomish River.

Extensive revetments and three zones of bedrock channel boundaries limit favorable localities for sediment deposition, but the abrupt widening of the active channel zone around the long-lived island at RM 11.4 creates the one segment in this subreach where sediment can (and does) accumulate. The largest deposits are thus in this "island segment" (RM 11.4–10.2), on a large point bar at RM 11.0 along the left channel and nearly continuously along the right channel.

2.4.4.2 Lateral channel migration & avulsion

The combined influence of bedrock and revetments has limited the zones of channel migration in this subreach. The three major meander bends (with apexes at RM 12.5, 11.8, and 10.9) have seen little change since 1938. They all have had chute cut-offs that have remained active throughout the photographic record, however. The cutoff of the uppermost bend was partly blocked at RM 13.30 post-1990 by construction of the Sultan training levee, but another inlet just south of that levee (RM 12.95) has remained active (see Figure 2-17). Set back about 1,000 feet from the river, "Groeneveld levee 2" was subsequently built across the side channel but it had been flanked around its south end by 2003. Although flow in this side channel has persisted since at least 1965, the position of its inlets and the relative stability of the riverbank along this reach since at least 1991 suggest that significant changes to its activity are not likely for the foreseeable future, unless the condition of bank-armoring revetments further degrades.

The cutoff of the downstream-most bend has evolved into the co-equal channel that now defines the RM 11.4–10.2 island. This cut-off channel evolved from a small chute in 1938 to a significant channel in 1965 that has maintained its dimensions ever since. Although a large apex jam at RM 11.4 (Figure 2-21) appears to be the "cause" of the channel bifurcation, it is in fact an "effect"—the jam only appeared in 2005, well after island initiation, but it has remained very stable in size and location since that time.



Figure 2-21 The flow-splitting log jam at RM 11.4 (flow from left to right).
The jam covers about an acre, first appearing at about half its present size after the November 2006 flood and growing fairly steadily since that time.

This split-channel segment also displays the primary zone of rapid modern bank erosion in the subreach (see Figure 2-19). The sandy overbank sediment into which it is eroding delivers very little in the way of coarse sediment to the river, and so recent gravel deposition over the last decade on the bars surrounding the island have not been balanced locally by bank erosion.

Also along the right branch of this split-channel segment, but farther downstream (about 400 feet upstream of the bottom of the island as of 2018), significant scour first occurred along the right bank in winter 2006–2007, presumably a result of the November 2006 flood, and expended rapidly in the years thereafter. A series of habitat-based wood installations and a bioengineered bank treatment was installed in 2014. but most components were swept away within a few years. Future migratory activity is likely to cease for the immediate future, however, because as of the winter of 2019–2020 the two channels now recombine upstream of this past erosion site, shrinking area of the island by about one-third and leaving this area, adjacent to an isolated side channel, well outside of the margins of active flow.

2.4.4.3 Riparian large woody debris recruitment and retention

Seemingly favorable sites for wood accumulation in this subreach are, in general, devoid of significant log accumulations. Examples include the point bar at RM 12.6 and the opposite bar at RM 12.1. This may reflect either the limited magnitude of channel migration through this subreach (and the resulting lack of recruitment), and/or the commensurately limited zones of active sediment deposition. The only exception to this pattern is in the island segment, where the large apex jam (see Figure 2-21) is but one of seven

large jams through this part of the subreach. The magnitude of these accumulations suggests that a lack of truly "favorable" sites, rather than a lack of available woody material, is the primary cause for wood-poor conditions elsewhere in the subreach.

2.4.4.4 Floodplain connectivity and inundation

The river is broadly incised relative to its adjacent terraces, continuing the pattern first seen in the lower part of subreach 5. Locally, areas of recently active floodplain maintain channel–floodplain connectivity (e.g., Figure 2-20), but in general the channel lies well below its bounding terraces and experiences only infrequent interaction during high flows.

2.4.5 Fish use

Spawning ground survey data for the lower 13.5 miles of the Skykomish River, compiled for the years 2010–2019 (Peter Verhey, WDFW, written commun. 2020), found the highest densities of Chinook and steelhead redds in this subreach. Areas of particularly high redd concentrations were in the unarmored sections of the river at RM 13.0 and 12.6, and around the 11.2–10.4 island (Figure 2-22). In the densest area, the 1/10th of a mile of channel centered on RM 13.0, 376 Chinook redds (and 2 steelhead redds) were counted over the decade of available data. In total, 818 Chinook and steelhead redds were counted along this subreach, for an average density of about 22 redds/mile/year, with zones of localized concentration an order of magnitude greater.



Figure 2-22 Chinook and steelhead redds 2010–2019 between RM 11.5 and RM 10.1.
This is an area with particularly high redd densities within subreach 4. River miles denoted at triangles; "+" mark 1/10th-mile intervals along the active channel of the river. Image also displays the change in the dominant flow path around the island of RM 11.4–10.2 between 2018 and 2020, a consequence of high flows in February 2020. Flow is from right to left; image is about 1 mile across. Base photo April 2020 from Snohomish County.

2.4.6 Anthropogenic influences

2.4.6.1 Riprap and levees

About 1.4 miles of this 3.8-mile-long subreach channel is bounded no at least one bank by riprap. Although this constitutes a smaller fraction of the channel than in subreach 5, it differs in geomorphic effect. Upstream, bank armoring restricts access to the northern part of the river's (prehistorical) floodplain, but in most places half or more of the floodplain remains unrestricted to current or future river access. Here, however, revetments alternate banks, and in combination with the bedrock outcrops they have almost completely frozen the channel in its present configuration. Where riprap is not present at zones favorable to channel migration the rates of migration can be substantial (e.g., Figure 2-19), but in general such unarmored zones are virtually absent in this subreach.

2.4.6.2 Bridges and other hydraulic structures

Three vertical log-pile arrays were built on the point bar along the right bank of the right-side split channel (across from RM 10.45; see Figure 2-22) and three within the maturing vegetation in July 2014. Not surprisingly (but possibly coincidentally), additional growth of the point bar occurred in the years following flood-fence construction, expanding the distance between the channel and the vertical array, and the neck of the island was eroded away altogether in the winter of 2019–2020.

Three log structures were also constructed in 2014 about 500 and 800 feet farther downstream, along the right bank of the right-hand split channel. This was a segment of bank that had seen up to 150 feet of bank retreat between 2005 and 2015 (averaging ~15 ft/yr). The main two wood structures were largely gone by 2018 (while the bank continued to retreat 7-10 ft/yr). However, the main channel is now almost 700 feet distant by virtue of the recent breaching of the island neck, suggesting that additional bank retreat here is unlikely unless the river regains its prior course at a later date.

2.4.6.3 Riparian clearing

In general, areas north of the river have been in agricultural land uses since at least 1938; and with only one exception around RM 12.1, areas of riparian and valley-bottom forest have remained intact to the present day. More common is for once-bare bars and side channels to become revegetated, expressing a widespread trend along the Lower Skykomish River for greater channel stability and less dynamic change over the past 80 years. South of the river, past clearing for agriculture is much less widespread, and it too shows no significant change in the area of non-forested land since 1938.

2.5 Subreach 3

Subreach # and length (mi)	Upstream RM	Downstream RM	Length (mi)	Gradient (from LiDAR DEM)	Pebble count RMs (D_{50})	Major features (upstream to downstream)
3	9.7	6.0	3.7	0.0011	9.2 (45 mm) 6.6 (59 mm)	• Fern Bluff levee • Barr Creek confluence

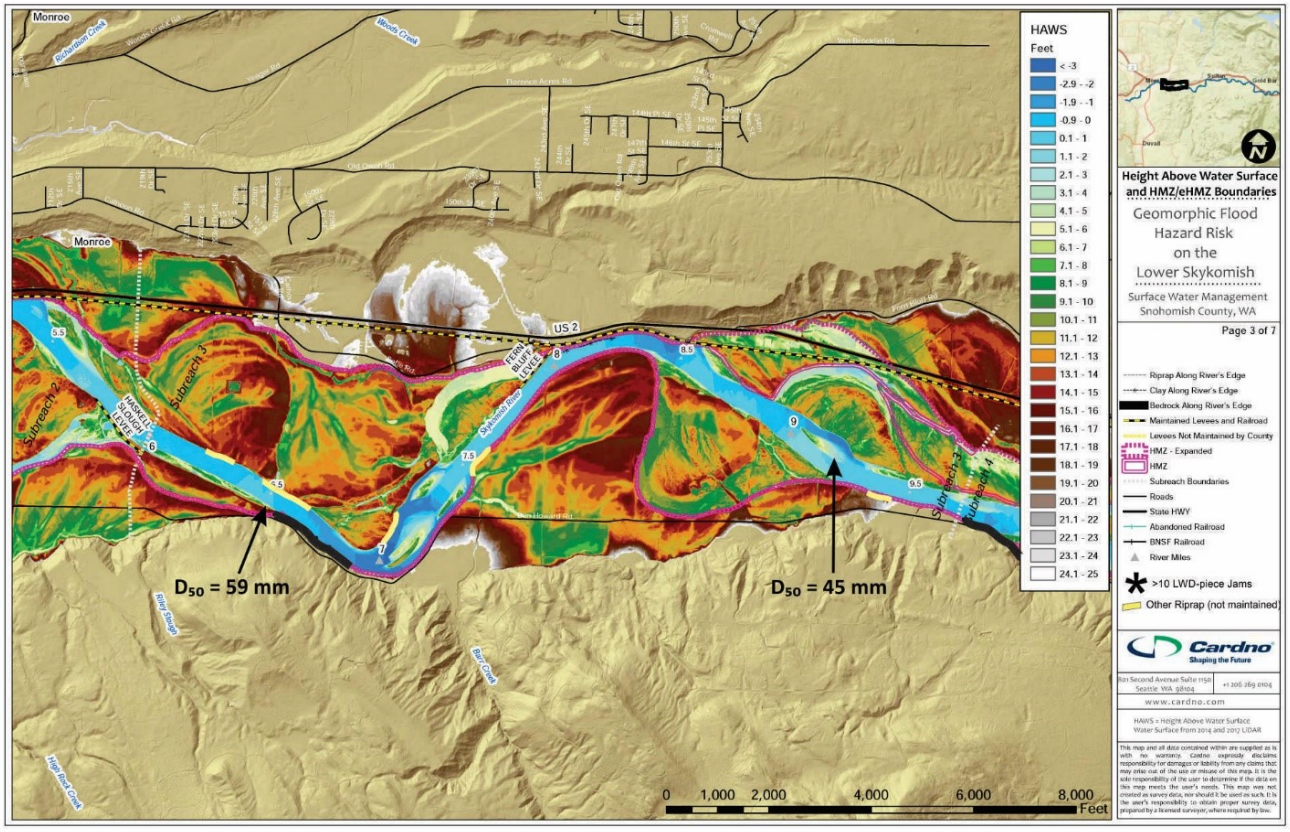


Figure 2-23 HAWS (Height Above Water Surface) map of subreach 3, highlighting the locations of pebble counts and median diameters (D_{50}) and riprap.
No significant Large Woody Debris jams are present here. Base map from the Cardno (2020) Channel Migration Zone study.

2.5.2 Channel features

2.5.2.1 Planform – channel patterns, sinuosity, confinement

The planform of subreach 3 has undergone dramatic changes in the last century. Although in 1938 the main channel of the river was in essentially the same location as it is today (Figure 2-24), fresh gravel bars in that image and even more localities of relict channels in the floodplain topography (Figure 2-23) testify to a far more sinuous, meandering planform not long before that time. Meander wavelengths of about 1 mile, clearly visible in the topography between RM 9.5 and 8.4, 8.0–7.5, and 6.5–6.0, have been cut off by long straight channel segments that now form a static zig-zag pattern across the floodplain. The relict meander-bend entrance at RM 8.0, in particular, was active as late as 1938. By 1965, however, it had been cut off by the Fern Bluff levee, which extends downstream from the BNSF Railroad revetment.



Figure 2-24 Aerial photo of subreach 3 in 1938.
Blue lines trace the 2018 active channel for comparison. Labeled triangles denote river miles; black dots mark 0.1-mile river miles; yellow lines mark the upstream and downstream boundaries of the subreach. Although the 2018 channel is virtually unchanged from that of 1938, recent pre-1938 activity is evident from the relict meander bends downstream of both RM 9.2 and RM 8.0. Although in general the active channel is much reduced in 2018 from 1938, note the one area of expansion between RMs 7.5 and 7.0.

The channel pattern of this subreach expresses, in effect, a single meander with a wavelength of 2 to 3 miles. This is not a pattern developed by typical fluvial processes, however, as demonstrated by the unconstrained relict channel traces with wavelengths half or less this distance. Instead, it is a pattern imposed by the combined influences of the BNSF Railroad revetment, which anchors the northern apex of the bend from RM 8.5 to 7.8; bedrock, which similarly anchors the southern apex from RM 6.9 (and likely upstream as well to 6.6); and more scattered revetments at RMs 9.4, 7.5, 7.1, 6.6, and 6.3 that hold the intervening channel position.

2.5.2.2 Slope & channel dimension

The channel slope retains the gradient from subreach 4, with no change to the average value (0.11%). This average, however, obscures two prominent features in the detailed profiled (Figure 2-25), namely the near-horizontal slopes at RM 9.8–9.2 and 8.4–7.4. Both of these low-slope zones are immediately upstream of the two major (in fact, the two only) zones of significant sediment deposition—a bar complex along the right bank from RM 9.2–8.8, and a more complex and even more voluminous deposit at RM 7.5–7.0. Deposition at the former location occurs in the only zone of relatively low floodplain surfaces adjacent to the channel, allowing for widening of the active channel. Deposition at the latter location may reflect backwatering imposed by the bedrock-controlled 90^{o} bend in the channel immediately downstream.

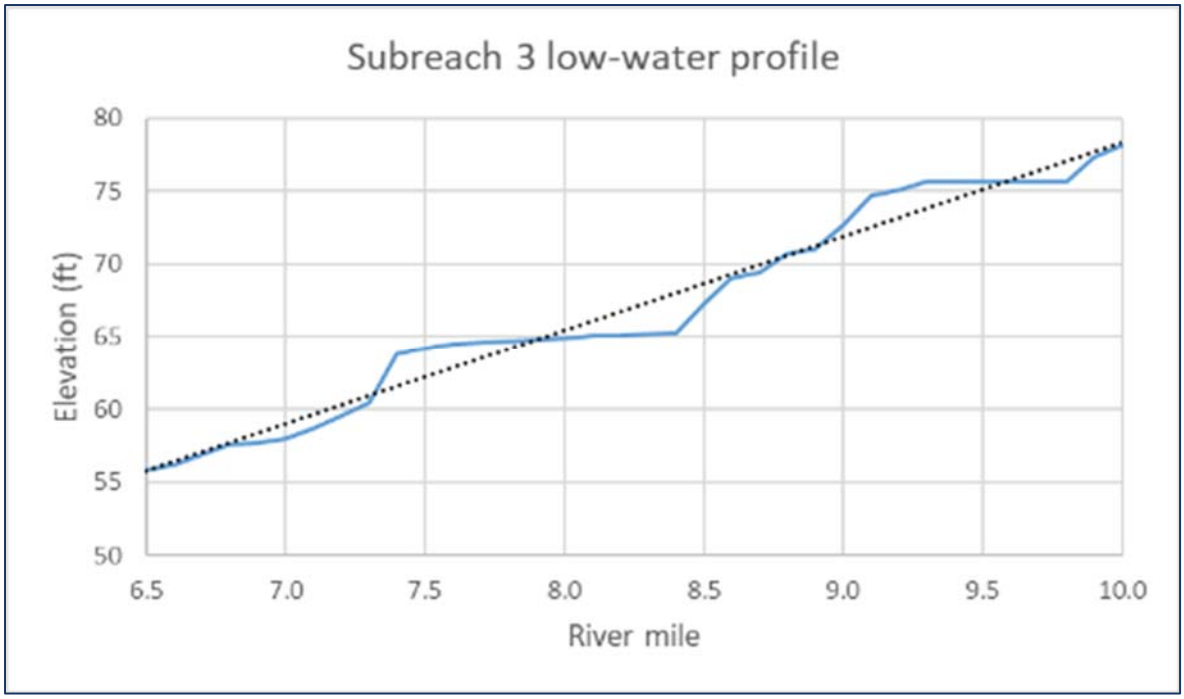


Figure 2-25 Low-water profile of subreach 3, highlighting the very low-slope zones between RMs 9.8–9.2 and 8.4-7.4.
Water-surface topography from 2014–2017 LiDAR survey.

2.5.2.3 Migration history and rates

No real "meandering" has occurred in this subreach during the 80 years of the photographic record. By 1938 the basic form of the channel planform had been set, and it has remained essentially unchanged by virtue of extensive revetments and non-eroding bedrock at key locations along the planform. Even in the two zones with extensive bar development the rate of channel change has been slow: at RM 9.2, a maximum bank retreat of 150 feet from 1990–2018 (4 ft/yr) is recorded; at RM 7.1 about twice this retreat has occurred but since 1965 (and essentially no change in active channel boundaries post-1990). Elsewhere, localized gaps in riprap or erosion along poorly vegetated channel banks have resulted in a few zones of bank retreat, of which the largest is along the left bank at RM 7.71 showing almost 60 feet of localized bank retreat between 2018 and 2020.

2.5.3 Sediment characterization

2.5.3.1 Terraces and bars

In general, this subreach is incised relative to its adjacent floodplain elevations. Channel-bounding surfaces are typically 10–20 feet above the low-water surface, greatly limiting the access to side channels and abandoned channel traces for all but the highest flows. The highest terraces are located on the inside (left-bank) bend of RM 8.2, which pinches the channel against the railroad revetment and provides minimal opportunity for point-bar deposition; and along the downstream end of the subreach, where high terraces flank both sides of the modern channel. Several sites express well the relationship between higher terraces (likely the active floodplain of an older, pre-incised channel) and the modern floodplain (Figure 2-26), and they suggest modern bankfull channel dimension of about 8 feet (depth) and 450 feet (width).

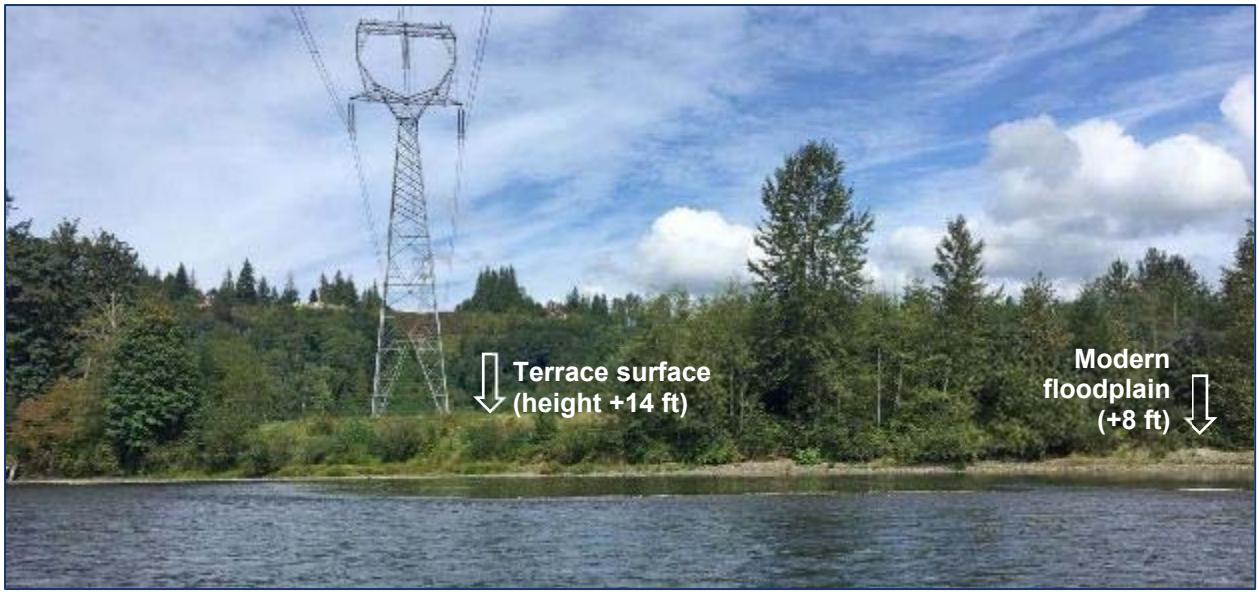


Figure 2-26 Good expression of typical terrace and bankfull (active floodplain) heights relative to the low-water surface elevation.
Photograph looking to right bank from RM 8.85; outlet of 1938 meander bend visible as low gravel bar between the two arrows.

Active gravel bars in this subreach are generally narrow and low-profile, with the exception of the two depositional zones noted above (RM 9.2–8.8 and 7.5–7.0). The contrast between these two depositional modes is nicely displayed in the reach from RM 7.5–6.3 (Figure 2-27), where the most voluminous bar deposit in the subreach is followed one-half mile downstream by an extremely low-profile bar.



Figure 2-27 Rapid change in bar morphology, from upstream (top inset image) to downstream (bottom inset image) across the sharp bend at RM 7.0.
White arrows show the location and direction of the camera; small circles mark 0.1-mile distances along the channel. Base image 2018 from Google Earth.

2.5.3.2 Grain size

Given the limited zones of sediment deposition, and the even fewer areas where the local hydraulics are not influenced by bank armoring and bedrock, only two sites for sediment-size distribution measurements were judged potentially representative. That in the wide portion of river (at RM 9.2) may be of limited value, given the minimal curvature in the channel at this point and the likelihood that the main thread of high-velocity flow remains closer to the center of the channel than the sampling site. The low bar at RM 6.6 (see Figure 2-27, lower inset image) is not a voluminous deposit but is more likely to provide a sampling of the high-flow bedload by virtue of the local channel geometry. The median grain sizes on these two bars (45 mm and 59 mm) are consistent with these inferences but are nonetheless judged to be only marginally representative of broader patterns along the river.

2.5.4 Processes

2.5.4.1 Water and sediment inputs

Only 1.3% is added to the net drainage area of the river along this subreach, primarily from the one named tributary (Barr Creek, entering at RM 7.4 on the left bank). The alluvial fan of this creek is marked by tan-colored dendritic channels in the lower right-hand corner of Figure 2-23, and the topography suggests that this has been a modest, but long-lived, contributor of sediment to the river over time. Otherwise, the lack of significant lateral inputs, active channel migration, or voluminous depositional zones all suggest that virtually all of the sediment that enters this reach leaves it, and it leaves with little augmentation. It is a “transport reach,” with only minimal interaction between the channel, its floodplain, and any tributaries.

2.5.4.2 Riparian large woody debris recruitment and retention

Minor accumulations of LWD are present on a few of the bars in this subreach and scattered sparsely along channel margins. These bar-top accumulations are typically composed of only a few logs, and they are concentrated in the two zones of sediment deposition previously noted. In general, this subreach neither contributes nor retains LWD to any significant degree.

2.5.4.3 Floodplain connectivity and inundation

As previously noted, a major characteristic of this subreach is its confinement by high terraces with only a few locations where access of low and moderate flows to a more extensive floodplain surface is possible. These areas correspond to active channels visible in 1938, with some yet older (and also higher) channels visible in the topography but not recorded as having carried flow during the period of photographic records. In general, however, the channel is consistently incised relative to its surrounding valley-bottom deposits.

2.5.5 Fish use

Chinook and steelhead redds identified during the surveys of 2010–2019 found about 400 redds in total along this subreach, with the highest densities in all years within the half-mile of channel centered on RM 9.0. This is a modestly wider zone of the channel, unconstrained by riprap and traversing a 1938-era meander bend with relatively low terraces flanking both sides of the river. Elsewhere in the subreach, other zones of more limited redd activity are located in the depositional zone just upstream of the bedrock-controlled bend at RM 7.0 and in a straight reach between two right-bank revetments at RM 6.35.

2.5.6 Anthropogenic influences

2.5.6.1 Riprap and levees

Of the approximately 1.5 miles of artificially armored banks in this subreach, only those along the BNSF Railroad (RM 8.6–8.0) and its downstream continuation (the Fern Bluff levee, RM 8.0–7.8) are officially maintained. The railroad revetment was present by the time the channel reached this boundary in 1938; the Fern Bluff levee, presently blocking the lowest abandoned meander channel in the subreach, was constructed sometime between 1938 and 1965.

2.5.6.2 Gravel mining

There is no record of gravel mining in this subreach, but the magnitude of channel incision and the known activity in the next subreach downstream suggest that this reach has felt the geomorphic effects of that known activity. Its consequences for this portion of the Lower Skykomish River are explored in the next section.

2.5.6.3 Riparian clearing

As farther upstream, few changes in riparian vegetation of land uses have occurred in the last 80 years. Extensive riparian forests have regrown on the terraces above the old, now-abandoned meander bends at RM 9.1–8.4 (left bank) and RM 8.0–7.5 (right bank, and continuing adjacent to the river down to RM 6.8). The only significant location of near-channel clearing during this period has been along the right bank at RM 8.8 (just behind the tower in Figure 2-26), with most of the forest clearing completed by 1965.

2.6 Subreach 2

Subreach # and length (mi)	Upstream RM	Downstream RM	Length (mi)	Gradient (from LiDAR DEM)	Pebble count RMs (D_{50})	Major features (upstream to downstream)
2	6.0	2.4	3.6	0.0011	3.3 (44 mm) 3.1 (53 mm)	• Haskell Slough • Haskell Slough levee • Woods Creek confluence • Lewis Street bridge • Town of Monroe • S Lewis Street bridge • Hansen levee

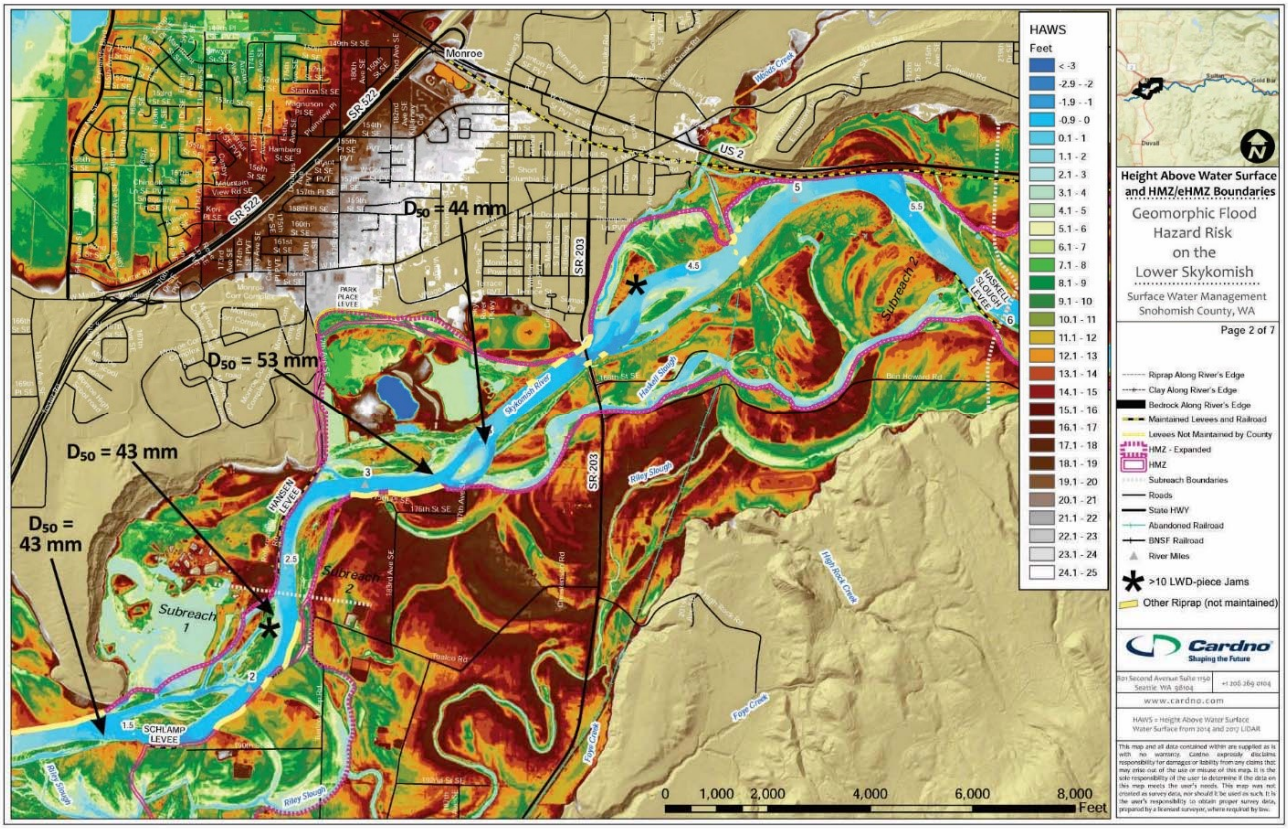


Figure 2-28 HAWS (Height Above Water Surface) map of subreach 2, highlighting the locations of pebble counts and median diameters (D_{50}), two significant Large Woody Debris jams, and multiple levees and revetments.
Base map from the Cardno (2020) Channel Migration Zone study.

2.6.2 Channel features

2.6.2.1 Planform – channel patterns, sinuosity, confinement

Subreach 2 comprises a long, nearly straight segment of river, bracketed at both ends by right-angle bends held in place by extensive, long-established revetments backed by high terraces (Figure 2-28).

Along the central 2+ miles of straight-to-slightly-sinuous between RM 5 and 3, two zones of persistent gravel deposition break up an otherwise near-uniform channel segment, flanked by a few largely inactive side channels marking the locations of prior channel positions. Most of the valley bottom is occupied by relatively high terraces, suggesting that this subreach has incised relative to its adjacent historical floodplain—similar to that inferred immediately upstream.

The other major channel feature of this subreach is Haskell Slough, which begins near the upstream end of the reach (RM 5.9) and parallels the main channel through the south-side floodplain to rejoin it at RM 3.4. It is presently inactive, a consequence of the levee constructed across its inlet, but elevations along its 2.3-mile-long extent are sufficiently low to maintain multiple pools of standing water throughout its length. Although never the main channel in any photograph since 1938, the 1921 topographic map suggests that it was one of two near-equal channels (at least by map-view width) at that time, with the other channel rather close to the present alignment of the modern-day river. The other major divergence from present conditions was the 1921 existence of a large meander loop to the north, occupying the low area of the floodplain between RM 3.8 and 2.9, site of historical gravel-mining operations for many decades.

Following the flood of November 1990 (second-largest on record), an investigation into the potential reactivation of Haskell Slough was commissioned by Snohomish County (NHC 2000). It identified a zone of left-bank overbank flow, downstream of the Haskell Slough inlet at RM 5.5, and a flow path that could result in significant river discharge reentering the slough about 2,000 feet below its inlet. The potential for subsequent headcutting along this flow path, which can be seen as a relict scroll bar in the topography (see Figure 2-28), raised concerns for the safety of developed property farther downstream along the slough, whose channel lacks capacity to carry significant discharge. An earth-and-timber-pile avulsion barrier was subsequently built near the river's edge across this potential flow path in 2001. Some combination of the barrier, and the unusually sharp bend that any substantive flow would need to take in order to maintain a channel, has proven successful to date in avoiding further significant occupation of this route.

2.6.2.2 Slope & channel dimension

The channel exhibits a fairly uniform gradient, continuing the average low-water-surface slope of 0.11% from subreach 3 (but without the stairstep irregularities). An excellent expression of the bankfull channel at RM 5.5 yields channel dimensions of 7 feet (depth) and 450 feet (width) (Figure 2-29).



Figure 2-29 Downstream view of the river at RM 5.5.
Excellent expression of the modern floodplain and bankfull depth present along the left bank. Revetment along the BNSF Railroad visible in the middle distance along the right bank.

2.6.2.3 Migration history and rates

Since 1938, channel migration and side-channel changes have been limited to a few localities. Between 1965 and 1990, realignment of a railroad spur from a river crossing at RM 4.75 to RM 4.40 permitted a 2,000-foot-long side channel to form on the right bank between RM 5.05 and 4.71. It has remained open and active to the present day (the crossing was removed altogether between July 2005 and August 2006). A large right-bank meander loop in 1938 between RM 4.5–4.0 was bypassed by the main channel as of the 1965 airphotos. In the approximate midpoint of this bypassing reach, the channel then began to re-expand along its right bank: 230 feet between 1965 and 1991 (9 ft/yr), 90 feet between 1991 and 2002 (8 ft/yr), an additional 110 feet by 2009 (16 ft/yr), and an additional 90 feet in just two additional years (45 ft/yr). Expansion of this bend has largely ceased since 2011, with the width-constraining influence of the S Lewis Street bridge at RM 4.0 a likely cause.

The other zone of major channel shifting is the zone from RM 3.6–2.9, where the combined influences of natural channel-migration processes and active gravel mining have created a dynamic zone in this stretch of otherwise fairly static river. Almost 4,000 feet of bare mid-channel and lateral bars in 1938, with an active Haskell Slough entering the main channel from river left at the bars' approximate midpoint, had been reduced in size by channel shifting and largely reforested by 1965. Along the left bank of the main channel, up to 360 feet of migration into the adjacent floodplain occurred during this 27-year period (13 ft/yr), accompanied by significant channel widening (but little bar growth). Between 1965 and 1990, major gravel-mining operations had commenced, and riprap along the left bank between RM 3.30–3.05 had held the channel to its 1965 position (and continues to do so). However, the gravel mining (which included pushing sediment out from the right bank into the river) had shifted the upstream left bank of the active channel at RM 3.4 by 90 feet by 1990; and by 2002 another 140 feet of bank had been lost (12 ft/yr), in the 0.2 miles upstream of the existing riprap. The bank has been relatively static since that time.

Most instructive for purposes of understanding the evolution of the channel through this subreach, however, is the now-straight reach of channel from RM 6.0 to 5.5 (Figure 2-30). In 1921 the channel apparently flowed directly over what is now part of the right-bank floodplain, with a sub-equal splitting of

the flow into Haskell Slough at RM 5.9. As of the 1938 airphoto, that zone of prior channel occupation is a bare right-bank lateral bar, with the channel having shifted left by up to 550 feet. By the 1965 airphoto the bar is largely reforested and the entrance to Haskell Slough has been blocked off. In the subsequent decades, sediment was deposited along the right bank downstream as the river engages the BNSF Railroad revetment at RM 5.3, and some additional leftward channel shifting occurred opposite that newly formed bar.

Of key relevance, however, is that the right-bank bar at RM 6.0–5.6, part of the active channel as of 1921 and a bare and apparently well-engaged bar as of 1938, is a largely inactive terrace surface now standing about 12–14 feet above the low-water-surface elevation. As part of the once-active channel zone, its present elevation relative to modern river level suggests that there has been a vertical divergence of 5 to 7 feet since 1938, most plausibly caused by river incision over this 80-year period.

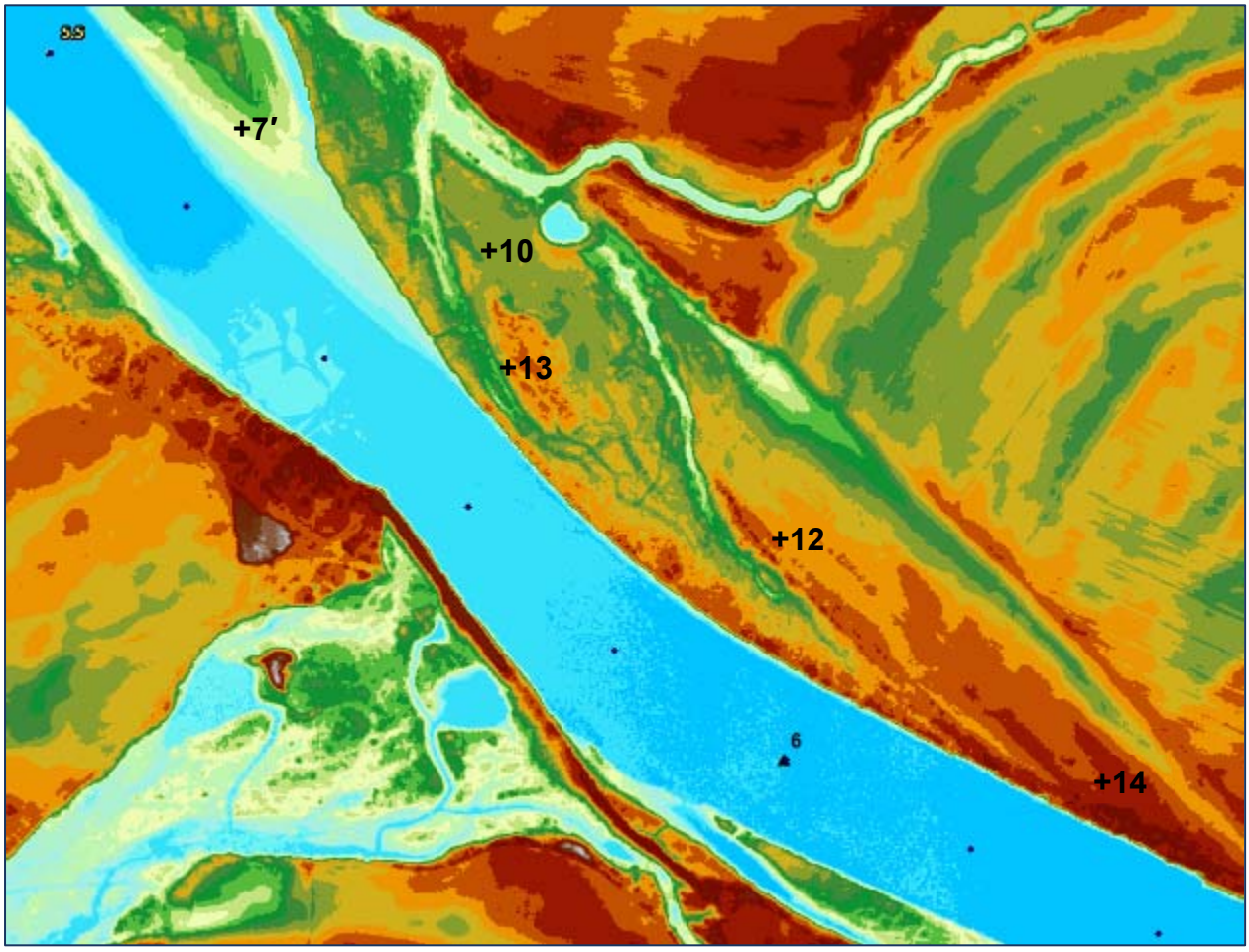


Figure 2-30 Close-up view of the HAWS map of Figure 2-28 between RM 6.2 and 5.5.
Haskell Slough entrance (now blocked by a levee) occupies the left bank between RM 5.95 and 5.78. The river-right bar opposite Haskell Slough has a crest elevation +12 to +14 feet above low-water level (orange and red colors), in contrast to the modern bankfull level of about +7 feet (pale green colors, particularly well-expressed at RM 5.6). Given that this bar was within the channel as of 1921 and still part of the active channel zone in 1938, its present relative elevation suggests river incision of 5 to 7 feet over the last 80 years.

2.6.3 Sediment characterization

2.6.3.1 Terraces and bars

As with the upstream subreach, the channel is largely confined between high terrace surfaces throughout the subreach. Typical elevations for these surfaces are 10-15 feet above the low-water level, too high for

regular inundation by small-to-moderate floods. Except for Haskell Slough, the berm-protected gravel mine north of RM 3, and the two zones of lateral and midchannel bars (RM 4.6–4.1 and 3.5–3.3), almost nowhere along the channel are floodplain elevations low enough to allow for regular interaction.

Although in 1938 this subreach hosted large active gravel bars suggesting a zone of active deposition (which continued down through subreach 1), in modern times these active zones are of much more limited extent (Figure 2-31). Restrained channel migration, less sediment, and channel incision have likely all contributed to this general loss of channel activity and the stabilization of bars that have resulted.



Figure 2-31 Aerial views of subreach 2, highlighting the general loss of active bar area between 1938 (top, from Snohomish County digital archives) and 2018 (bottom, from Google Earth).
Red ovals are in the same location in both images.

2.6.3.2 Grain size

Two river bars in the zone of active gravel deposition provided representative sites for sediment-size determination (D_{50} = 44 mm at RM 3.5, D_{50} = 53 mm at RM 3.2). Differences in the two measurements likely reflect variations in local hydraulic conditions and the random variability and error in pebble counts. They continue the general size distribution seen in subreach 3 without any discernable trend.

2.6.4 Processes

2.6.4.1 Water and sediment inputs

The addition of Woods Creek at RM 4.0, just upstream of the S Lewis Street bridge, adds 8.3% to the watershed area of this subreach. Its low gradient in its lower reaches suggests that it is not a significant contributor of coarse sediment, consistent with the absence of any obvious deposition at the confluence. Other tributaries in this subreach add less than 1% to the total drainage area of the watershed.

2.6.4.2 Lateral channel migration & avulsion

Channel migration has progressively decreased in both extent and speed over the 80 years of the photographic record. At present, only one area shows any significant recent history of channel migration: 165 feet of bank retreat from 2002–2018 (10 ft/yr) at RM 4.9 (right bank). As previously noted, a few other zones have been active in prior decades, particularly around RM 4.4 and 3.4, but activity in these locations had largely ceased by the early- to mid-2000s. In general, there is little ongoing channel-migration activity in this subreach, and even the remnant gravel bars are showing progressive reduction in activity (Figure 2-31).

2.6.4.3 Riparian large woody debris recruitment and retention

Only one large accumulation of LWD, at RM 4.3 along the right bank in the zone of active gravel deposition, is present in this subreach. Other locations are favorable for wood retention but lack significant accumulations, particularly the side-channel inlet at the outside bend at RM 5.0 and the bar crests at RM 3.4 and 2.8. RM 4.5-4.1 is the only zone of any noticeable wood, but even the one “large” jam, which had formed by 2011 and persisted until at least 2018, is comparatively quite small relative to others farther upvalley.

2.6.4.4 Floodplain connectivity and inundation

The channel through this subreach is largely disconnected from its adjacent floodplain, both laterally and vertically. Laterally, the abundance of revetments limits the opportunities for channel migration and the reforming of floodplain surfaces graded to the present-day river level. Vertically, the pervasive confinement of the channel by high terraces is the most noteworthy attribute of this subreach. In addition to the 5 to 7 feet of incision inferred at RM 5.8 (Figure 2-30), an equivalent channel–bar relationship is evident at RM 3.1. Here, a partly forested island that was an active unvegetated bar in 1938 now stands up to 14 feet above the modern low-water surface, suggesting a magnitude of subsequent vertical incision akin to that inferred a few miles upriver.

Side-channel connectivity has also been lost, most prominently by the pre-1965 blockage of Haskell Slough. Near the bottom end of the slough its passage under S Lewis Street appears in the 1965 airphoto to have been facilitated by a wide bridge opening; by 1990, however, that crossing had narrowed with only a narrow channel emerging downstream of the crossing.

2.6.5 Fish use

The 2010–2019 Chinook and steelhead redd surveys identified a similar level of spawning in this subreach as immediately upstream, and well below that of subreach 4. The distribution of redds was more uniform in this subreach, with the greatest concentration centered on RM 4.6 in the revetment-free zone between bank armoring associated with the abandoned railroad trestle (at RM 4.7) and the S Lewis Street bridge (at RM 4.0).

2.6.6 Anthropogenic influences

2.6.6.1 Riprap and levees

Two levees (the right-bank Hansen levee, RM 2.87-2.48; and the BNSF Railroad revetment, RM 5.3–5.0 and visible in Figure 2-29) steer the river past several areas of intensive industrial and transportation infrastructure. Two other named levees provide less direct influence over channel position: the right-bank Park Place levee, now far-removed from the active channel, armors the bank of a long-inactive channel of the river, and the left-bank Haskell Slough levee (constructed in the 1930s, with its full extent spanning

RM 6.06–5.82) has effectively blocked river access to this major side channel for at least half a century but has not dramatically altered the pattern of mainstem channel migration. The other major extent of riprap, on the left bank opposite the quarry operations at RM 3.3–2.9, has been effective at blocking outward migration along its full length, but the bank immediately upstream has experienced up to 230 feet of bank retreat between 1965 and 2002 (and locally up to 100 feet of additional retreat through 2020). Remnants of a flood fence along the left bank, likely installed many decades ago when the bridge was in its pre-1965 alignment, retains an intermittent barrier of angular rock that provides nominal protection for the adjacent bank (and which has shown no discernable bank retreat since at least 1965).

2.6.6.2 Bridges and other hydraulic structures

Three bridges have crossed the Skykomish River in this subreach, of which only one (S Lewis Street at RM 4.0) still remains. The other two, both carrying railroad spurs, had both been removed as of mid-2006. Scattered riprap along the banks and even mid-channel still remain as legacies of these crossings.

2.6.6.3 Gravel mining

The largest well-documented record of gravel mining along the entire Lower Skykomish River occurred in this reach. The “Connelly bar” (RM 3.5-3.2) had offtakes of 84,000 tons/year from 1961-1969, 25,000 tons/yr from 1969-1976, and 17,000-25,000 from 1976-on (data compiled by nhc 1992, their Table 4.3). Assuming mining occurred through at least 1990, this represents 1,225,000 tons over this 30-year period (~40,000 tons/yr, on average). This site alone thus extracted about double what Dunne (1979) recommended as a likely sustainable yield for the river, and it provides one plausible explanation for the 5 to 7 feet of incision inferred for this reach over a period corresponding to that of the gravel extraction.

However, this reported magnitude of gravel removal, even if all obtained from the active bed and bars of the river, is too low to explain all of the inferred bed lowering through this subreach (and, by extension, of the subreach upstream that is also showing evidence of incision). Just a single mile of 450-foot-wide channel would require the removal of almost 500,000 cubic yards (over 600,000 tons) to fully account for 5 feet of incision. Documented gravel extraction is thus of the right order of magnitude as a clear contributor, but alone cannot explain about 6 miles of incised channel through subreaches 2 and 3. For this magnitude of net sediment removal, other conditions—likely additional downstream gravel mining (see next section), the reduction in supply from bank armoring, and the greater efficiency of transport from channel narrowing (also from bank armoring, plus vegetation encroachment onto one active bars)—probably were also relevant.

Gravel mining was reportedly halted by the mid-1990s. Significant regrading of the site in pursuit of reclamation, however, did not begin until after 2015.

2.6.6.4 Riparian clearing

Overall, the riparian zone of the river is more consistently forested in 2018 than it was in 1938, in part because the river had many more zones of active bar deposition during that earlier period. By 1965, most of the revegetation seen today had already occurred, with only minimal additional regrowth occurring outside of the restabilizing bars. Today, nearly the entire riparian zone is forested—locally, with a width of less than 50 feet (i.e., one tree-canopy’s worth) but more commonly one to several hundred feet wide. Woody material is available for recruitment as in-channel LWD, but the lack of channel migration makes that availability moot.

2.7 Subreach 1

Subreach # and length (mi)	Upstream RM	Downstream RM	Length (mi)	Gradient (from LiDAR DEM)	Pebble count RMs (D_{50})	Major features (upstream to downstream)
1	2.4	0.0	2.4	0.00080	2.3 (43 mm) 1.4 (43 mm)	• Schlamp levee • Riley Slough • Snohomish R. confluence

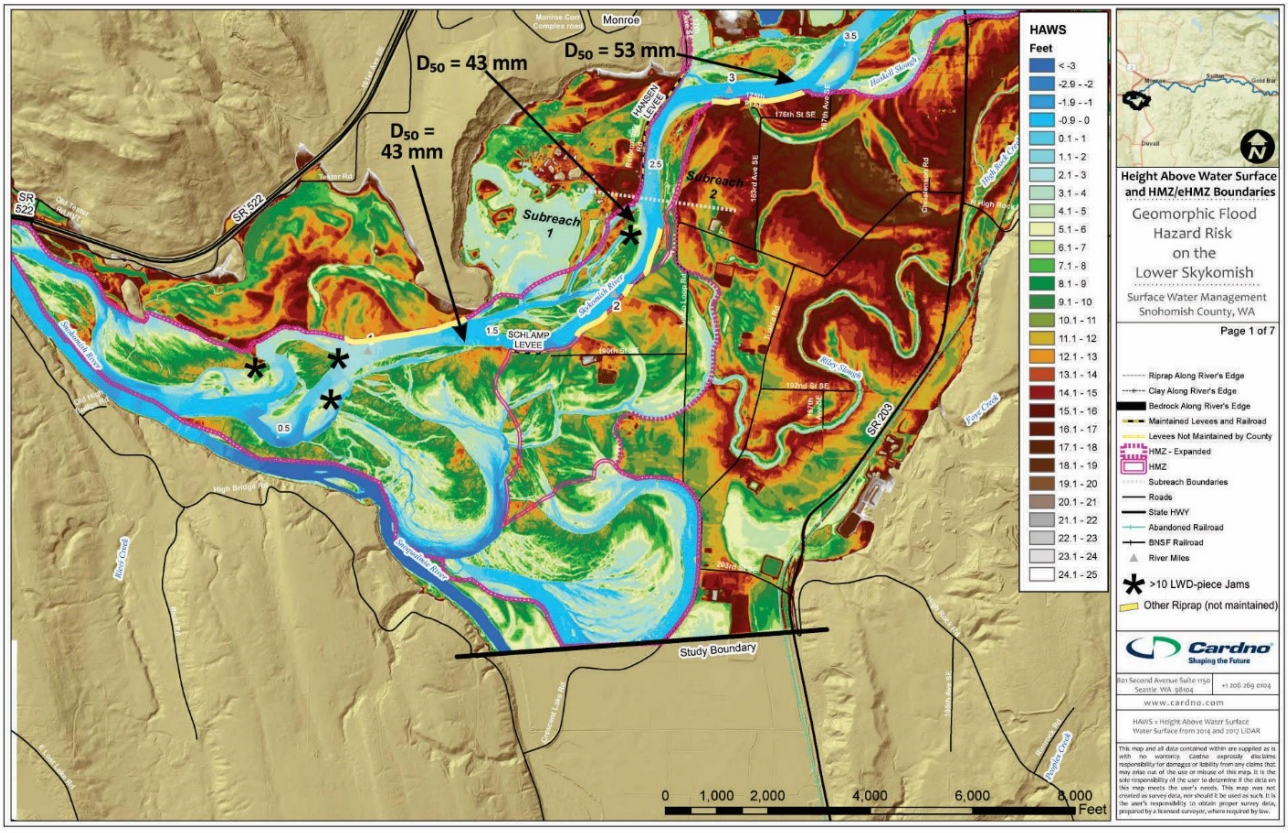


Figure 2-32 HAWS (Height Above Water Surface) map of subreach 1, highlighting the locations of pebble counts and median diameters (D_{50}), several significant Large Woody Debris jams, and riprap.
Base map from the Cardno (2020) Channel Migration Zone study.

2.7.2 Channel features

2.7.2.1 Planform – channel patterns, sinuosity, confinement

Subreach 1 marks the transition from a self-formed alluvial river to a fluvial system more akin to a delta, where backwater from the Snohomish River during high-flow events establishes a base level for the Skykomish River almost independent of other fluvial processes. This transition is expressed in the floodplain topography at the head of this reach, where the confinement provided by the high terraces of subreaches 3 and 2 gives way rather abruptly to a complex of low-elevation scroll bars, marking historical and pre-historical positions of the river (Figure 2-32). Defining which of those relict channels are "Skykomish" and which are "Snohomish" is somewhat arbitrary, since in this low-gradient environment they may well have flowed in both directions at one time or another. Similarly, the "confluence" of the two rivers has shifted substantially, even over recent history—in 1965 the rivers joined just 700 feet upstream of the SR 522 bridge (just off the left edge of Figure 2-32); by 1990 that junction had moved 4,000 feet farther upstream (and an additional 750 feet upstream by 2018) (Figure 2-33).



Figure 2-33 At the 2020 confluence of the Skykomish River (flowing towards the camera from the left) and the Snoqualmie River (flowing from the right).
The peninsula of fresh gravel that separates the two rivers was deposited in the winter of 2019–2020.

Downstream of RM 0.9, the river has been very dynamic, forming a complex of channels and islands that has been particularly active since 1990. Elsewhere in this subreach, however, and despite the obvious traces of a very dynamic channel history, the modern channel has been relatively static. Two sets of revetments are largely responsible for this restriction—the first is a discontinuous sequence of informal bank armoring segments along the left bank from RM 2.3 to 1.5, restraining outward migration along a wide bend of the river; the second is a nearly overlapping right-bank revetment from RM 1.4 to 0.9, constraining what would otherwise have been the next alternation of the migration pattern.

Elsewhere in the reach, significant change of any kind is evident only along the upstream-most bar (RM 2.4–1.5). Here, however, the change has been one of *reduced* activity—from an active, bare bar in 1938 to one that becomes progressively more vegetated in 1965, 1990, and beyond. Except for occasional vehicle tracks its surface and location have been essentially unchanged since 2012.

The other noteworthy channel feature in this subreach is Riley Slough, a narrow and sinuous channel that originates in subreach 2 from an abandoned meander bend, apparently unoccupied by the main channel for over a century, and continues for about 2 miles across the south-side floodplain to its terminus in another long-inactive meander bend. Its extreme sinuosity and narrow topographic expression (typically 100 feet wide or less) suggest that it may never have conveyed the full discharge of the Skykomish River, but it remains as a particularly long (and long-lasting) relict side channel. Snohomish County (2018) reports that it was a path of the river prior to 1888.

2.7.2.2 Slope & channel dimension

This lowest subreach of the river further flattens to an average gradient of 0.08 percent, a nearly 30 percent decline from that of subreaches 2 and 3. Within this average trend, however, the low-water-surface profile displays a flat bench between RM 1.7 and 0.9, reflecting a backwater from the depositional zone immediately downstream. In this lower-most segment of the river the channel splits into two channels, each of nearly the same width as the single-thread channel immediately upstream (a revetment-confined 350 feet wide).

2.7.2.3 Migration history and rates

Notable channel migration in this subreach is restricted to the lowermost 0.9 miles of the river, where rates have locally (and temporarily) exceeded 50 feet/yr of bank retreat (Figure 2-34).

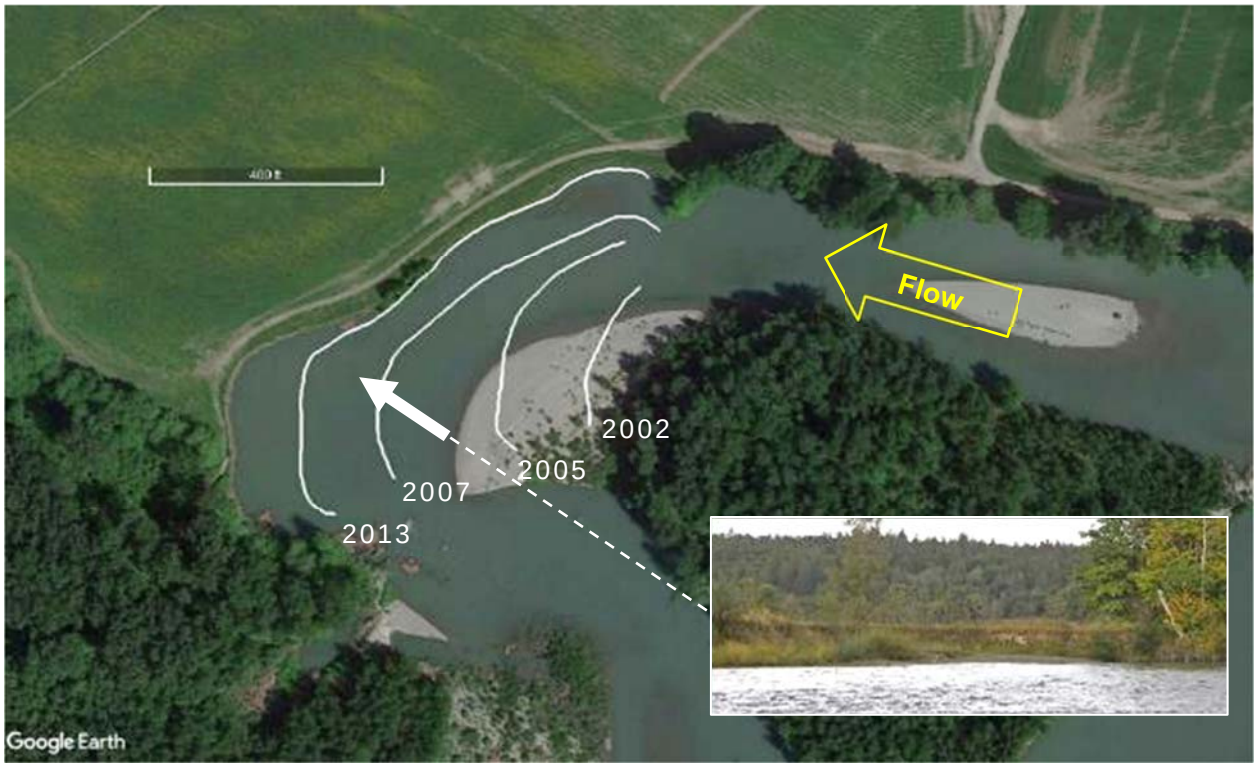


Figure 2-34 Example of lateral migration on the Skykomish River near RM 0.7.
White lines trace the bank position in the year indicated; base image from 2018 (Google Earth). White arrow marks the location and direction of the inset photograph, taken in September 2019. The most rapid change at this site, 150 feet in a single year (2006–2007), spanned the flood of record (November 2006). Other annual rates of migration here locally have exceeded 50 feet of bank retreat per year, although the long-term average here is less than half this rate. The bank was virtually static between 2018 and 2020 (image modified from Cardno 2020).

Elsewhere in the subreach, the general trend over time has been one of active channel narrowing and bar stabilization by vegetation, particularly from RM 1.3–1.0. Here, a lateral left-bank bar was fully unvegetated in the 1938 airphoto, became part of the low-flow channel in 1965, reemerged as a narrower and partly vegetated bar in 1990, and was almost entirely forest-covered by 2009. Only a narrow gravel bar now remains, with the upstream-most portion serving as a pebble-count locality. DeVries (2010) speculated that stabilization of this upper locality may have been an underlying cause for subsequent active migration in the lower 1 mile of this subreach, a plausible but likely unprovable mechanism.

2.7.3 Sediment characterization

2.7.3.1 Terraces and bars

The lower-most 1.5 miles of this subreach is flanked to the north by a terrace averaging about 12 feet above low-water level (the prominent flat surface in the inset photograph of Figure 2-34). To the south lies the complex of scroll bars and meander channels, filling a zone almost one mile wide between the Skykomish and Snoqualmie rivers. A similar set of channels and terraces persists farther upstream to the head of the subreach, but the north-side terrace has been greatly modified by mining activity and now is largely a low-elevation hollow barely a few feet above river level. The south-side scroll bars are less closely spaced, and intervening terraces between the relict channel inlets are of near-equivalent elevation to those across the river. Except for the lower 1 mile of this subreach, gravel bars are narrow and low; but in that lower mile, substantial deposition and rapid channel migration have gone hand-in-hand to create, at least locally, a very dynamic environment (Figure 2-35).



Figure 2-35 View down the southerly branch of the split channel of the Skykomish River at about RM 0.5. Substantial gravel deposition has induced rapid bank erosion, which also adds to the LWD load of the river. In the middle distance (above and to the right of the figure), trees along the left bank of the Snoqualmie River are visible.

2.7.3.2 Grain size

Two gravel bars in this subreach provided representative, relatively unconstrained sites for sediment sampling. They both returned median grain sizes of 43 mm, a somewhat unusual but not implausible coincidence along this fairly homogeneous segment of the river.

2.7.4 Processes

2.7.4.1 Water and sediment inputs

No significant tributaries add to the Skykomish River through this subreach. In total its watershed area increases by just 1.4 percent between its upstream and downstream boundaries. At the confluence with the Snoqualmie River, the drainage area measures 845 square miles.

2.7.4.2 Lateral channel migration & avulsion

The pattern of abandoned channels and scroll bars across the lower two miles of the southern floodplain testify to a long history of very active channel migration, avulsions, and associated creation/destruction of physical aquatic habitats. Several of these channels predate even the 1897 topographic map; but only one such channel is shown as still active in each of 1921 and 1938 tracings. None post-date 1938. Instead, the locus of channel migration has shifted to the lowermost 0.9 miles of the modern channel, in a much narrower zone with relatively modest changes between 1938 and 1990, but with quite rapid rates of migration since that time (see Figure 2-34).

2.7.4.3 Riparian large woody debris recruitment and retention

The overall lack of channel migration upstream of RM 0.9 has also resulted in minimal amounts of LWD recruitment. Two moderately large apex jams, at RM 2.3 and 0.8, have almost surely been constructed

from wood introduced into the channel from subreaches farther upstream. Large jams below RM 0.8 also are probably constructed from far-traveled sources. More local wood recruitment is active where channel migration is consuming the peninsula of forested land between the Skykomish and Snoqualmie rivers (Figure 2-35), with most of this wood being temporarily retained *in situ* before being flushed into the Snohomish River.

2.7.4.4 Floodplain connectivity and inundation

Flooding of the broad southern floodplain is ubiquitous from the comingling of waters from the Skykomish and Snoqualmie rivers, and backwater from the Snohomish River. The north-side terrace, however, is sufficiently high that it functions as a largely disconnected floodplain.

2.7.5 Fish use

The 2010–2019 Chinook and steelhead redd surveys document a further modest downstream decline in the intensity of spawning activity, with fewer than half the redds of those observed in the upstream subreaches. Activity here has been concentrated in three zones: at the head of the progressively stabilizing point bar at RM 2.3, in a short unconfined reach between two left-bank revetments at RM 1.8–1.7, and around the north and (particularly) the south sides of the island with its apex at RM 0.9 (with the latter showing a particularly high density of steelhead redds).

2.7.6 Anthropogenic influences

2.7.6.1 Riprap and levees

Only one publicly maintained levee, the Schlamp levee along the left bank at RM 1.7–1.5, is present in this subreach. It protects a portion of Frohning Road, a private residence, and farmland. Other revetments, however, line the left bank for 0.6 miles upstream of the Schlamp levee and the right bank for a half mile downstream, effectively locking the channel into place for over a mile. This continues a pattern of alternate-bank, outside-bend revetments that begin in subreach 2 at RM 3.3 and continue downstream to RM 0.9.

2.7.6.2 Gravel mining

During the period 1948–1961, nhc (1992, their Table 4.3) reported that “Sky Meadows” conducted gravel-mining operations between RM 2.0 and 1.5 that had offtakes of 12,000 tons/year. Although just a fraction of the reported rates and total volumes removed from the upstream Connelly bar, this activity nonetheless would have accounted for nearly 170,000 tons of gravel removed. By itself this is equivalent to a foot of channel degradation over a mile of river, and the upstream propagation of these geomorphic effects would have added to those of the more voluminous extraction upstream.

2.7.6.3 Riparian clearing

As elsewhere in the lower subreaches of the river, forested areas are little changed over the 80-year photographic record. The primary change has been the reforestation of once-active gravel bars. No significant areas that were forested in the 1938 airphoto have been cleared, and the extent of forested riparian zones has modestly expanded. Unfortunately, the limited area of active channel migration has given the river little opportunity to take full advantage of the habitat and process-based benefits of this vegetative zone.

3 Geomorphic Patterns, Variability, and Change

3.1 Spatial Patterns

3.1.1 Downstream changes in channel pattern and sediment sizes

Most broadly, the downstream progression of channel form of the Lower Skykomish River, from the top of the study area (RM 23.5) to its confluence with the Snoqualmie River, is a consequence of the watershed-scale conditions and processes of headwater erosion, sediment transport into the lower valley, and the progressive deposition of that load under the influence of monotonically decreasing valley and river gradients. This watershed framework has been recognized by all prior studies (DeVries 2010, Kopp 2017) as the fundamental driver of the finer-scale processes of most immediate human concern, which include channel migration, gravel-bar formation and erosion, and physical habitat creation.

The clearest expression of these large-scale processes is the long-recognized division of the Lower Skykomish River into the "Braided Reach" and the "Lower Skykomish River Reach," using the terminology of Snohomish County (2018) (demarcating subreaches 7, 6, and 5 from subreaches 4 through 1). Data collected for the present study allows a more quantitative evaluation of these observational trends. The analytical framework of Eaton et al. (2010), which integrates discharge, sediment size, bank resistance, and channel gradient to predict equilibrium channel patterns, confirms the broad discrimination of subreaches 7 and 6 from the rest of the study area (Figure 3-1). It also highlights the modest tendency for multi-thread channels in subreaches 2 and 1, and that subreach 5 is more akin to the lower subreaches than to those of the two braided, upper subreaches.

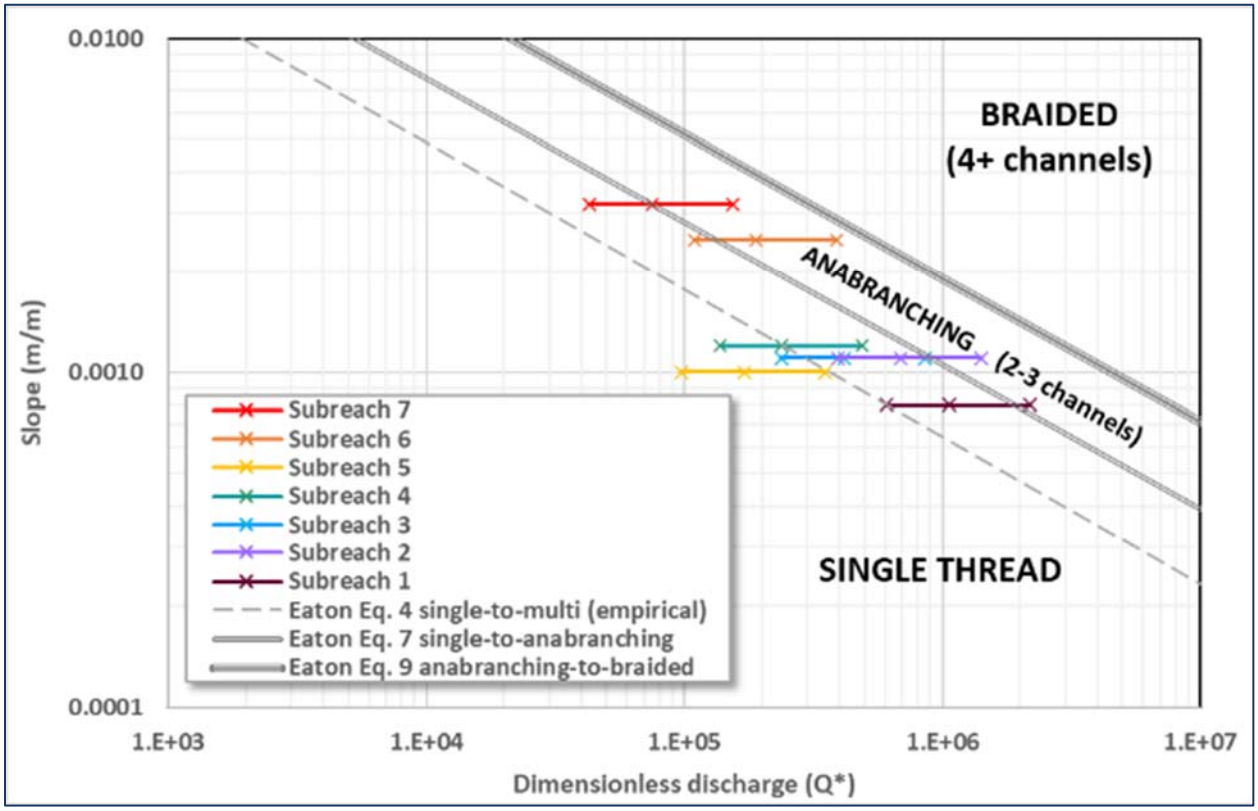
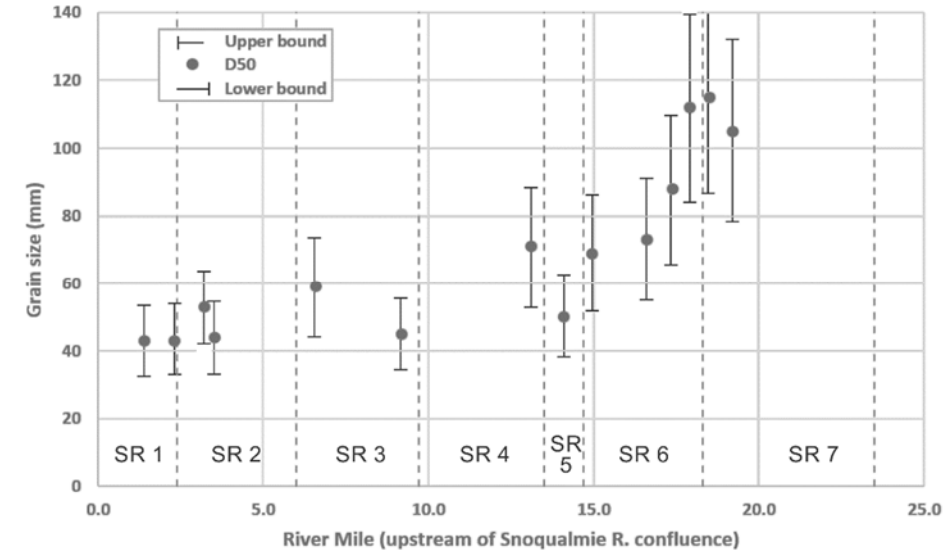


Figure 3-1 Subreach-scale assessment of theoretical channel pattern state, using the analysis of Eaton et al. (2010).
Dimensionless discharge is a function of the presumed "dominant discharge" (here, using Q_2) and a representative sediment size (here, the average D_{50} measured in the subreach). Horizontal uncertainty bars display the range of Q* calculated from sediment sizes +/- 25% from those reported to account for field-measurement errors and uncertainties (Bunte and Abt 2001).

Other attributes of the channel also follow trends strongly determined by the downstream decline in valley and channel slope. With only minor variation, median grain sizes reduce in size monotonically downstream (Figure 3-2 top), with variations in both local slope and sediment size also tracking one another with only minor divergences in overall pattern (Figure 3-2 bottom).



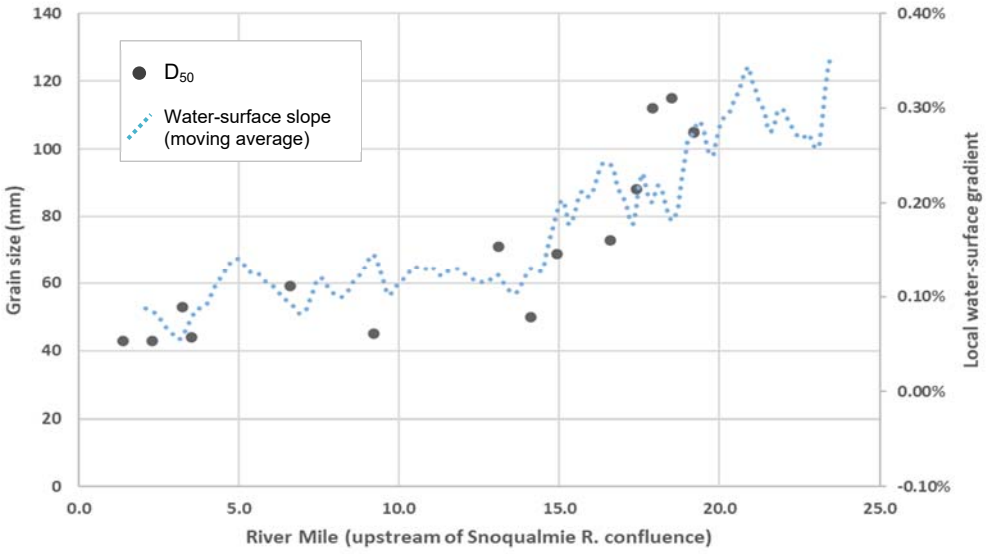


Figure 3-2 (TOP) All pebble counts conducted on geomorphically equivalent point bars. Horizontal uncertainty bars display +/- 25% measurement uncertainties (Bunte and Abt 2001). (BOTTOM) D_{50} data overlain with the local gradient measurements on the low-water LiDAR surface.

With suitable scaling the correspondence is very close, showing the dominant effect of the abrupt slope change at about RM 14 on sediment sizes above and below that transition. The “off-trend” large sediment at RM 13.1 (71 mm) almost certainly reflects local response to the influx of coarser sediment from the Sultan River, 0.4 miles upstream; the off-trend small sediment at RM 9.2 (45 mm) was collected at the head of a point bar with encroaching vegetation, suggesting that it may no longer be experiencing the direct impact of the thalweg at high flows.

A more descriptive characterization of the downstream changes in channel pattern is provided in Table 3-1.

Table 3-1 Summary of channel and floodplain characteristics, grouped by subreach.

Subreach (SR)	Channel and floodplain characteristics
7	Uppermost 2 miles is static, single thread encased by high terraces and bedrock. First anabranch at RM 21.4. Steep but rapidly declining gradient. Much active migration. Bounding high terraces down to RM 19.5, then a broad floodplain with multiple recent channel traces.
6	Channel pattern similar to upstream, with complex of active, episodically activated, and recently abandoned anabranches and side channels. More fully occupied unconstrained floodplain over last century. Mainly single-thread, one active anabranching zone remains. Major side channel complex (South Slough). Multiple sites of active migration 10–20 ft/yr. No high bounding terraces and good floodplain connection; voluminous gravel bars.
5	Abrupt transition from SR 6's side-channel-rich planform to a single thread bounded by higher terraces. Channel gradient still lowering, but limited opportunity for deposition given bounding S-side terraces and N-side revetments. Sinuosity declines from SR 7 and 6's value of 1.2 to just 1.04. Two active bars in this subreach, but they induce only limited lateral migration. Terraces south of the river are 10+ feet above river level, continuing the moderately confining floodplain topography from the bottom of SR 6.
4	Still predominantly single-thread with short, narrow side channels, but sinuosity increases to 1.4, greatest value in the study area. Also includes large island near downstream end. Fluvial valley narrows from 5000 ft to 1500 ft over the course of this subreach, bounded on the south by the bedrock edge of the valley and on the north by high terraces of late-glacial and postglacial age. Extensive low-slope zone imposed by bend and log-jam flow resistance, but average slope near-equivalent to upstream. Progressive vegetation of once-active bars seen over time. Transition between +10' terrace heights, as in SR 5, to +15' farther downstream.
3	Three straight segments separated by bends anchored by revetments and bedrock; historical variability and sinuosity now lost. Functionally, essentially a straight channel. Stair-step profile with an average gradient as upstream. Two local zones of bar deposition exist; otherwise, the channel is incised relative to its bounding terraces with 10-20' of relief between these surfaces.
2	Straight segment bracketed by two right-angle bends; not nearly as "functionally" sinuous as its measured sinuosity (1.25) would imply. Haskell Slough was a major, presumably active feature of the 1921 channel. No change in the trend from upstream subreach. Terraces are consistently high (+10–15') and most bars have become vegetation-stabilized.
1	Transition to deltaic system as gradient flattens (and likely more so during floods) with multiple, pre-20th-century scroll bars now inactive and/or blocked off. Anastomosing pattern downstream of last revetment. Active shifting of bars and channels in the vicinity of the confluence. High terraces left-bank fall away high in this reach, with a near-open floodplain between the Skykomish and the Snoqualmie. Large, old right-bank scallops, but the terraces remain high but likely never part of any recent period of channel occupation downstream of RM 1.5.

3.1.2 Downstream changes in watershed conditions and channel processes

At the watershed scale, the dominant characteristic is the progressive, roughly four-fold decline in channel gradient from the top of the study area to the bottom. In addition, three abrupt but relatively modest increases in drainage area accompany major tributary inputs—the Wallace River confluence (RM 14.6), adding 10 percent to the Skykomish River's drainage area at that point; the Sultan River confluence (RM 13.5), adding 17 percent; and the Woods Creek confluence (RM 4.0), adding 8 percent. None of these inputs directly impose obvious changes in the form or function of the Skykomish River, although the Wallace River confluence does mark the transition from a strongly anastomosing pattern in subreach 6 to a much more subdued, single-thread pattern in subreach 5 (although this is also the initiation of near-constant riprap along the river's right bank, a more likely primary cause). An unusually coarse sediment deposit expresses a local effect of the Sultan River's entrance. Otherwise, no downstream changes are even speculatively associated with any of these tributary contributions, which in combination account for two-thirds of the 311 square miles of increased drainage area experienced by the river from RM 23.5 (534 mi^2) to the mouth (845 mi^2).

Magnitudes and rates of channel migration reflect the interaction of intrinsic channel dynamics, as determined by bank armoring and the watershed drivers of discharge, sediment, and slope. The downstream expression of these processes and constraints are summarized in Table 3-2.

Table 3-2 Summary of channel dynamics and constraining structures, grouped by subreach.

Subreach (SR)	Channel dynamics and constraining structures
7	Some avulsion in last 100 years, common migration with typical long-term rates of ~10 ft/yr. Primary constrain is floodplain bisection by RR; otherwise, minimal revetments.
6	Moderate rates of migration since 1991, but more active avulsion and much network rearrangement have occurred earlier in the record. Northern floodplain edge entirely truncated by levees and revetments; otherwise, minimal revetments. Capture of the channel against the RR + Startup training levee may explain the long-term decline in multi-thread channel activity.
5	Limited migration at one site (7 ft/yr avg rate). Moderate future avulsion potential. Small side channels are only substantive channel–floodplain interaction. Full armoring along right bank (although high terrace would limit migration in any case) plus small left-bank levees. Constructed left-bank flood fence has provided little net benefit for either wood retention or reduction of bank erosion.
4	Active chute cutoffs across the three major bends, but only the lowermost one is actively growing and migrating (maximum rate of 50 ft/yr, 2015–2018). Very limited floodplain connectivity but for local recent bars. Alternating-bank riprap, plus bedrock outcrops, have largely frozen the channel planform.
3	Minimal floodplain interaction, with only a few local areas of inundation corresponding to 1938 (and older), now-abandoned channels. Revetments are extensive, particularly in forcing the upstream bend and in limiting lateral migration between the two major bends.
2	Minimal channel migration (one zone with recent 10 ft/yr movement); bars are vegetation-stabilized. Historical gravel mining a dominant influence in this subreach (with effects extending upstream). Side channels (particularly, but not exclusively Haskell Slough) have been blocked or otherwise disconnected.
1	Lateral migration rates temporarily reached 50 ft/yr in the lowermost reach. Good floodplain connectivity to the south, little/none to the north. Gravel mining occurred here as well, but an order of magnitude less than in SR 2. Revetments lock the channel in place for over a mile, with alternating-bank armoring that precludes migration for two of the lowermost 3.3 miles of the river.

The introduction and retention of LWD also varies systematically downstream. In subreaches 7 and 6, recruitment via channel migration and bank erosion occurs at multiple locations, and retained jams are common below RM 21.4, particularly in subreach 6. These processes halt abruptly in subreach 5. This condition persists downstream, with two large jams present just below the Sultan River confluence in subreach 4 but then no significant accumulations over the next 2 miles. The "island segment" in lower subreach 4 (RM 11.4–10.2) provides the most abundant, multiple localities for wood accumulations since the multi-thread channels above RM 15. Below that feature, however, only three large jams are visible between RM 10 and RM 1, marking the lowest density of LWD along the entire study area (and likely in the entire Skykomish River system).

The dynamic, two-thread system of the lower mile of the river provides several sites of both accumulation sites and recruitment. Most of this wood is quickly or eventually flushed downstream into the Snohomish River, however, where favorable LWD retention sites are rare in that wide, uniform, and generally straight-to-mildly-sinuous channel.

3.1.3 Sediment budget

Sediment budgets for the Lower Skykomish River have been compiled by Dunne et al. (1980) and Collins and Dunne (1990) from pre-existing measurements of suspended sediment throughout the Snohomish River basin by Nelson (1967) and subsequent observations of gravel-mining effects in the river. Dunne et al. (1980, their Figure 7) determined that bedload constituted an average 5% of the total sediment load in the Snohomish River, and they estimated a net 21,000 cubic yards per year (about 30,000 tons/yr) of bedload is transported by the Skykomish River past Monroe at RM 4. Of this amount, they judged that at least 6,000 yd^3/yr must be deposited in the lowermost four miles of the river, insofar as the Snohomish River is not competent to transport more than 15,000 yd^3/yr (the Snoqualmie River likely adds only a modest increment of bedload to the Snohomish River; if present, that contribution would further increase the predicted upstream deposition in the lowermost Skykomish River).

A single bar (the Connelly bar at RM 3.5-3.2, discussed in subreach 2 above) was mined for gravel post-1961. Collins and Dunne (1990) noted that prior to mining the bar had been expanding at a rate of about 3,000 yd^3/yr). When mining began in 1961, the extraction rate (50,000 yd^3/yr) caused substantial reduction in the bar; when that extraction was subsequently reduced to 10,000–15,000 yd^3/yr, bar shrinkage ceased. This led Dunne et al. (1980) to conclude that about 12,000 yd^3/yr could be extracted without long-term geomorphic change, although Collins and Dunne (1990) acknowledged that other changes to channel morphology (such as channel incision) were not monitored and so could not be evaluated as potential impacts.

More recent data reported by Wise et al. (2007) calculated a suspended sediment flux at Monroe of 190,000 tons/yr (year-1997 measurements), a year whose peak flow was close to the median over the period of record and so considered most representative of long-term averages. Two other years of measurement (2000, with 105,000 tons/yr reported and 2001, with 15,300 tons/yr reported) were unusual low-water years and so not considered further. Using the Dunne et al. (1980) "best estimate" of bedload fraction (5% of total load), the 1997 value would represent 10,000 tons/yr of bedload (about 7,000 yd^3/yr). A somewhat greater bedload fraction of 10%, which is a value also well within commonly accepted parameters, would alternatively imply a bedload flux of 21,000 tons/yr (15,000 yd^3/yr). This latter, larger estimate is judged to be more consistent with the empirical relationships between gravel extraction and bar shrinkage, but it also suggests that even the 12,000 yd^3/yr "safe yield" suggested by Dunne et al. (1980) might still have resulted in significant up- and downstream changes to channel morphology, given that most-to-all of the bedload would be removed from the river under that rate of mining.

3.1.4 Distribution of salmonid redds

Although neither biological activity nor local-scale habitat conditions are a focus of this geomorphic assessment, aspects of available biological data show a number of relationships to geomorphic conditions along the river. The previously noted redd surveys, which provided spatially explicit redd locations for Chinook and steelhead in the lower 13.5 miles of the Skykomish River for the period 2010 through 2019 (Figure 3-3), display high spatial variability with several overarching trends (Figure 3-4):

- The spatial density of redds broadly declines downstream.

> Channel zones between unarmored banks are generally more favored than those constrained on one (or both) side(s), although this may reflect the typical locations for bank armoring as well as any simple causal relationship.

> Even within "favorable" zones, redds are clustered with a presumed preference for specific geomorphic settings.

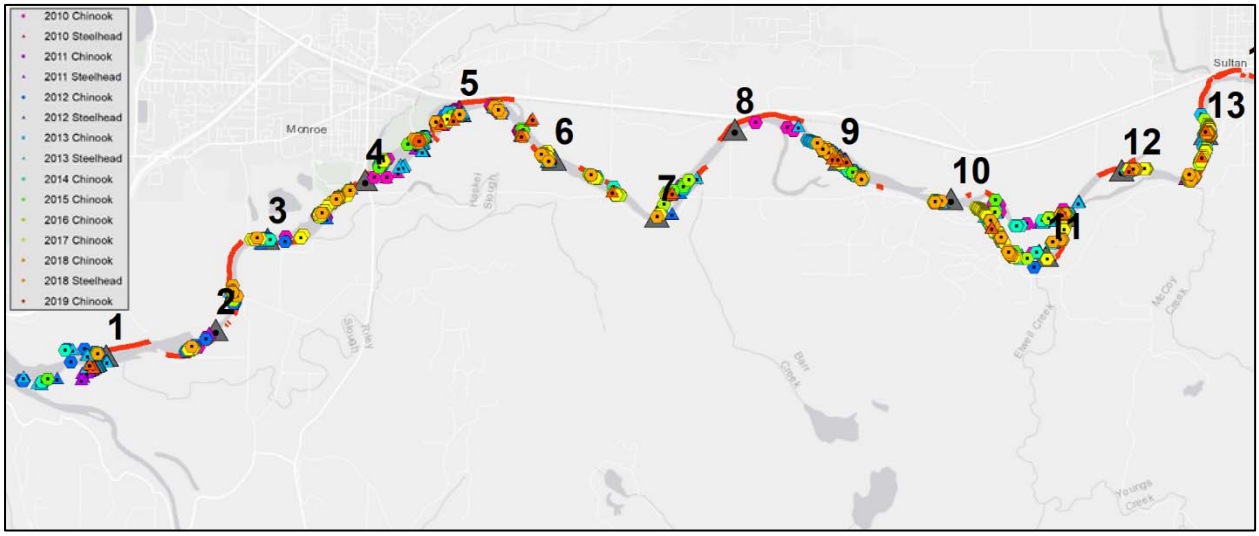


Figure 3-3 Locations of Chinook and steelhead redds for the combined period 2010–2019.
Red bank edges mark field-determined zones of riprap or other bank armoring; gray labeled triangles are river miles. Blank river reaches (light gray channel zones) indicate 1/10th-mile zones with no redds in any year of the 10-year period. Redd data 2014–2017 only available for Chinook.

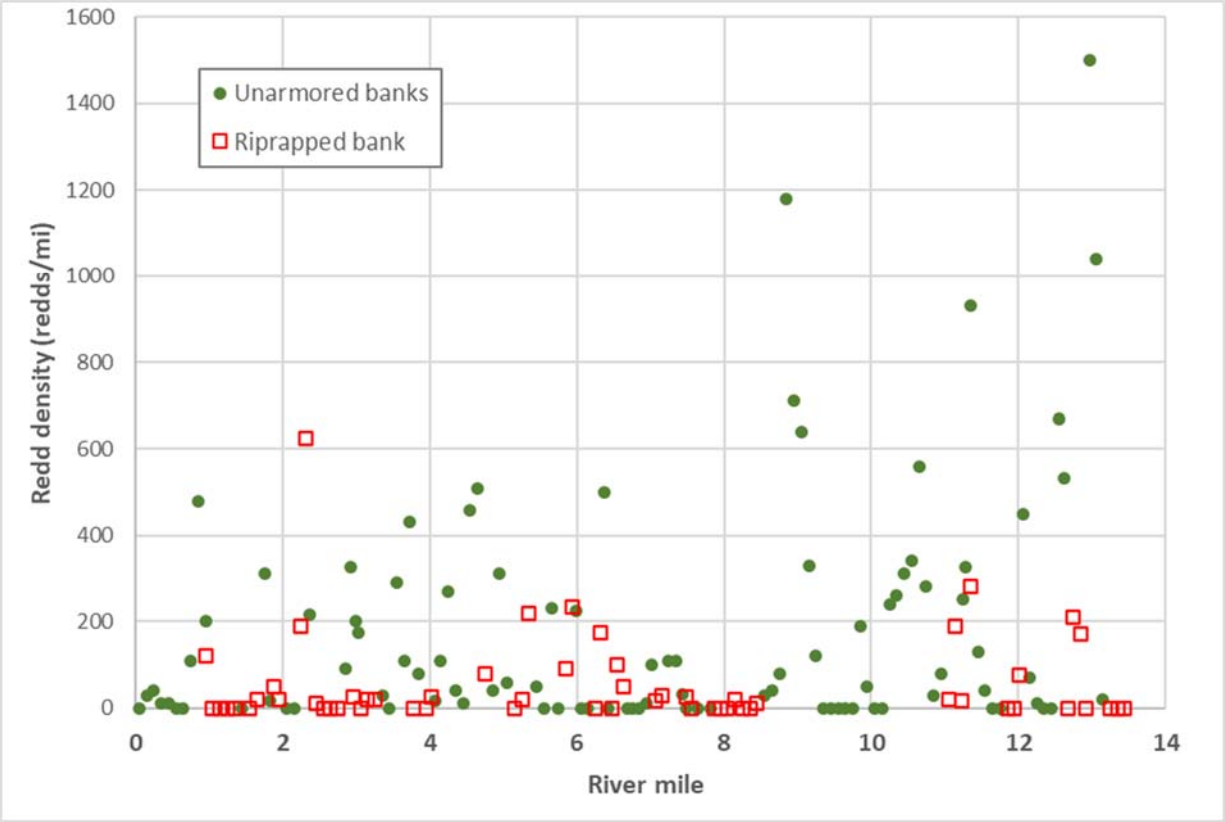


Figure 3-4 Density of observed Chinook and steelhead redds for the combined period 2010–2019. Segments over which densities were determined are 1/10th mile long, unless a shorter interval is needed to characterize homogenous segments having unarmored vs. riprapped bank. Zero values denote 1/10th-mile zones with no redds of either species in any year of the 10-year measurement period. A preferential association of high red density with unarmored banks is evident in these data.

These patterns can be explained, at least in part, by a combination of both natural and human-constrained attributes of the channel. Unarmored banks are generally areas of more dynamic channel processes, locally wider active channel zones, and more active sediment deposition. Although riprap (and other armoring) restrains these processes, bank armoring is also most common on bends where spawning would not be expected in any case—and so although there is a clear correlation, assertions of causality are somewhat more tenuous. Nonetheless, local examples (e.g., between RMs 4 and 3, a relatively straight reach with alternating armored/unarmored segments) suggest a clear (inverse) relationship between redds and bank armoring. Overall, redd densities over this 10-year period average 181 redds/mile for unarmored banks, and 54 redds/mile where at least one bank is riprapped.

The broad downstream declines in both redd density and in absolute numbers likely also have multiple causes. The fraction of the channel length with some degree of bank armoring increases downstream (Figure 3-5); but the gradient of the channel is also decreasing, and sediment sizes are similarly reduced (from a median of 71 mm in subreach 4 to 43 mm in subreach 1).

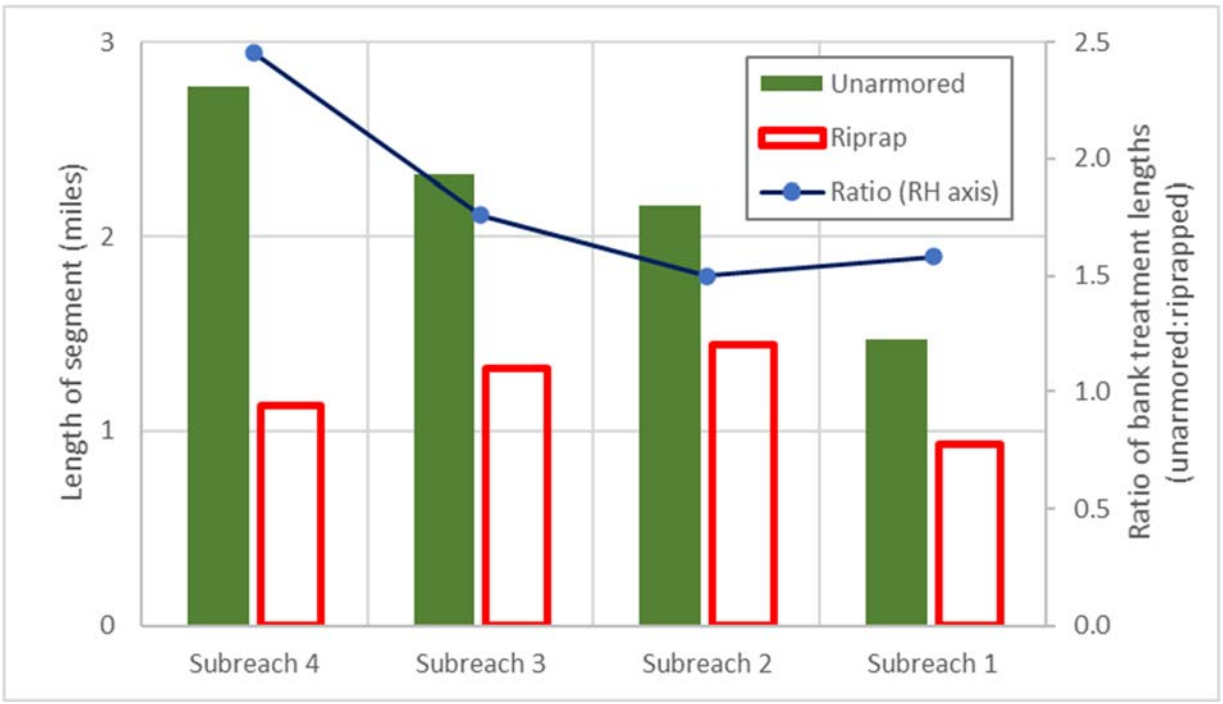


Figure 3-5 Downstream changes in the length of bank treatments, grouped by subreach.
Note that "riprap" includes segments with only one side armored (almost nowhere are both banks armored at the same location in the channel). Unarmored lengths predominate throughout, but their relative dominance (by length of channel) reduces from 2.5:1 in subreach 4 to 1.5:1 in subreaches 2 and 1.

Local and reach-scale channel geomorphology, not captured by this analysis, undoubtedly also explains much of this fine-scale spatial variability. Riffle habitat is favored for spawning, with particularly combinations of substrate, depth, and water velocity being preferred on a species-by-species basis. In contrast, wide slow channels with homogeneous depths and finer substrate will not be favored for spawning. These attributes are partly a function of bank conditions, but they are probably most dependent on the presence or absence of dynamic channel processes, which leave a mosaic of habitats that, in total, have the highest likelihood of supporting all life stages of the aquatic organisms in the Skykomish River.

3.2 Temporal Change

3.2.1 Sediment changes over time

Rarely is it possible to compare any but the coarsest types of data on a river over periods of a decade or more. Aerial images, channel profiles, and cross sections are the most common opportunities for assessing long-term change, and they have been used here (and elsewhere) to characterize past changes and to project future trajectories. However, for the case of the Lower Skykomish River we also have the opportunity provided by the study of DeVries (2010), who collected sediment-size data using the same site-selection and measurement protocols as the present study. For such a common geomorphic activity this correspondence between different studies might be expected; but, in fact, it is quite rare that such data are sufficiently consistent as to be comparable. In the present case, they show a near-perfect correspondence over the ten years that spanned their collection periods (2009–2019) (Figure 3-6).

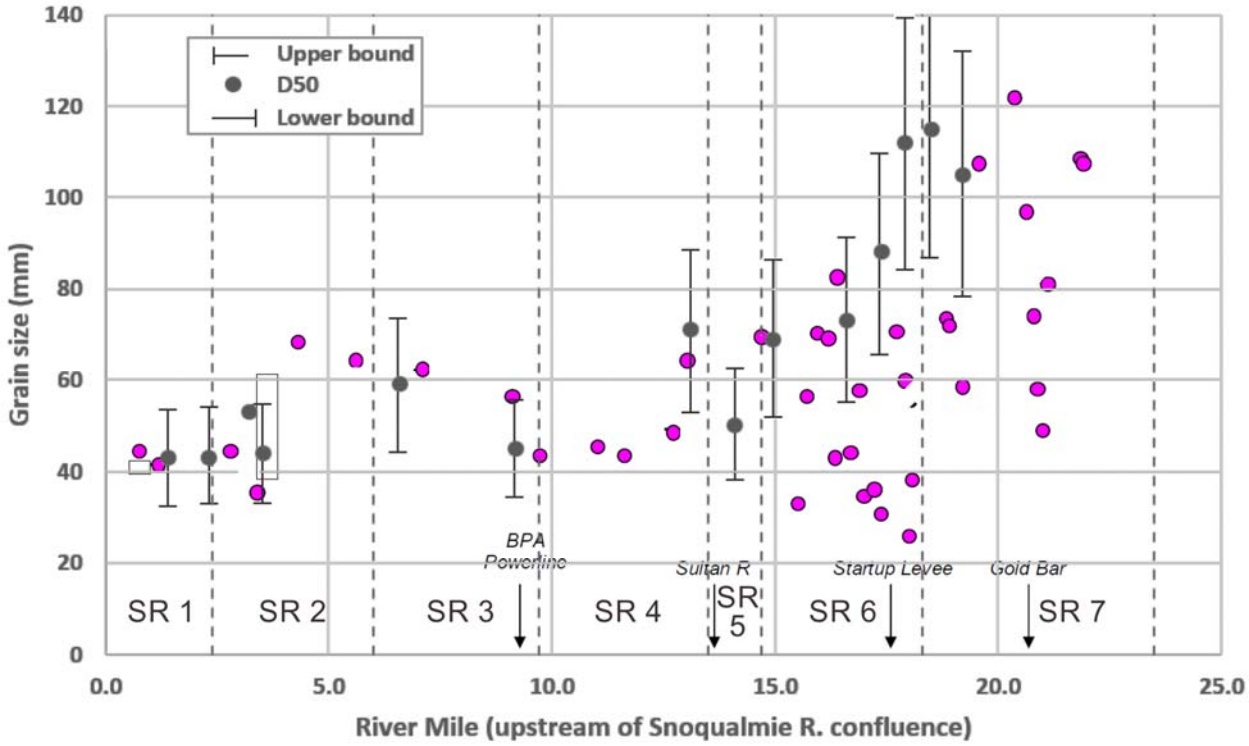


Figure 3-6 Comparison of the sediment-size data from DeVries (2010) (pink circles) and this study (gray circles, with uncertainty bounds as described for Figure 3-2).
Note the close correspondence for these decadally separated data sets. The large scatter in the 2010 data in subreaches 7 and 6 likely reflect a variety of geomorphic environments in which those sediment sizes were assessed, but the upper limit of those data match the values from the present study almost exactly.

Both the general trends and even the local variations in the lower half of the study area track almost precisely between the two studies. The primary difference is in the extreme scatter of the 2009 data in subreaches 7 and 6, but with their upper limit matching the 2019 data almost exactly. This is most likely an expression of multiple sampling sites during the earlier campaign located in areas of split flow or otherwise less-than-fully representative locations.

The obvious conclusion from this evaluation is that primary channel processes, at least those that are expressed in the grain-size distribution along the river, have maintained consistent equilibrium conditions over the last decade. Presumably they will do so into the future for as long as the underlying drivers (particularly the input of water and sediment, and the overall magnitude of anthropogenic disturbances), also remain steady. This assumption, apparently warranted for the second decade of the 21st century, may not remain as certain in a rapidly evolving future (see next section).

3.2.2 Channel changes over time

3.2.2.1 General trends

The overarching trend of channel changes has been a reduction in the area of the active channel and in the rates of channel migration. This has been mirrored by progressive encroachment of previously bare, active gravel bars by vegetation over the 80-year history of aerial photography (1938–2018) reviewed for this study. There are, of course, local exceptions, with the best examples at RM 21 (subreach 7; see Figure 3-7) and RM 0.7 (subreach 1; Figure 2-34). The general patterns, however, are of progressive narrowing of the channel-migration zone and vegetation encroachment and stabilization of active, once-bare gravel bars (see, for example, Figure 2-7 in subreach 6, or Figure 2-31 in subreach 2).

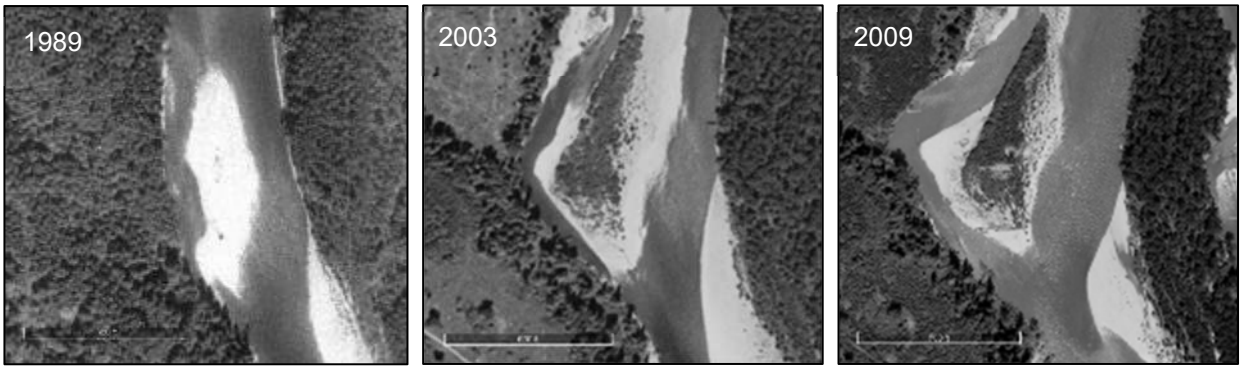


Figure 3-7 Local, recent expansion of the active channel at RM 21 (subreach 7) into a portion of the floodplain not previously occupied since before 1921.

3.2.2.2 Polygon analysis of active channel areas

A "polygon analysis," using the technique described by Rapp and Abbe (2003) was applied to the Lower Skykomish River by Cardno (2020). This approach overlays the area of the active channel traced from an image onto that of prior airphotos. It then classifies each individual polygon formed by the intersection of these two data sets into one of three categories: (1) the "intersection area," defined as an area of active channel that falls within the footprint of the previous active channel (i.e., no expansion of the prior active area); (2) the "erosion area," defined as the area of the new active channel that lies outside of the most recent, *previously* traced active channel but within one or more yet older active channel areas; and (3) the "new erosion area," defined as the areas where the channel had eroded into a location that was unoccupied by *any* prior year's channel areas.

This analysis revealed several findings:

1. With a few exceptions, the active channel area (i.e., the sum of the intersection, erosion, and new erosion areas) (Figure 3-8) has declined over time. This pattern is seemingly contradicted in the first interval (1897/1921 to 1938), but the change in data sources (map-based to airphoto-based) and the likely limitations of channel tracing on a topographic map probably provide the most likely explanation for this seeming anomaly (although significant upland and floodplain land disturbance also occurred in the early decades of the 20th century). The increase in active channel area in subreach 6 (and, to a lesser extent, in subreach 7) between 1965 and 1991 reflects the broad expanse of bare gravel bars left in the wake of the November 1990 flood, second-largest on record and occurring only a few months prior to the 1991 airphoto.
2. The broad decline in active channel area from 1938 through 2018 likely reflects a continued increase in bank armoring throughout much of the twentieth century, which muted (or, locally, halted altogether) channel-migration activity. The absence of any such trend in subreach 7 is consistent with the lack of constructed revetments post-1921. This temporal trend, evident elsewhere in along the river, cannot be adequately explained by changes in flood regime (see below).

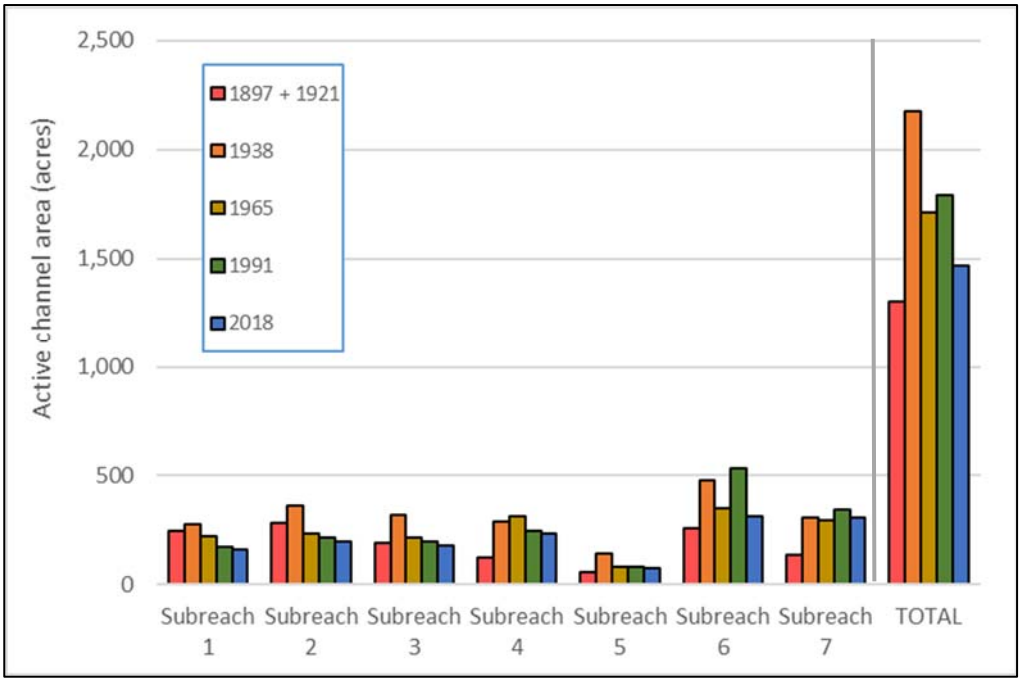


Figure 3-8 Overall active channel area recorded by the five periods of map/airphoto analysis, separated by subreach and also aggregated over the entire study area (right-hand cluster).

For subreaches 4 through 1, DeVries (2010, his Figure 9) also documented a progressive decrease over time in the area of active gravel bars and side channels (although note that his analysis did *not* include the open-water areas of the main channel). Although his methods and data sources were somewhat different from those employed by Cardno (2020), identified trends are fully consistent in both studies. DeVries found that nearly half of the total active-bar and side-channel areas present in 1965 had been lost by 1969, and that less than a quarter of even that diminished area remained as of 2007. In 1965, over 90 percent of the active channel area below the Sultan River was located in subreach 4, with virtually all of the remainder in subreach 1; by 2007, however, nearly all of the active-bar and side-channel area had been eliminated, with subreach 1 providing most of what little such features still remained (note that open-water area is included in Figure 3-8, but not in the DeVries analysis).

Construction of new revetments between 1965 and 2007 provides only a partial (and likely minor) explanation, since the river's edge had already reached all modern revetments by 1965. Only the Sultan training levee, between RM 13.45 and 13.20 on the right bank of the river, affected access to an existing side channel post-1965. A more likely explanation is that the progressive reduction in overall channel activity resulted in vegetation encroachment onto once-bare gravel bars (e.g., Figure 2-31 in subreach 2) that removed those features from the subsequent airphoto inventory of active surfaces.

3.2.2.3 Channel migration and changes in active channel areas

Based on the recent assessment of channel migration in the Lower Skykomish River (Cardno 2020), subreaches 2, 3, 4, and 5 have migrated little beyond their previously established migration boundaries, leaving active channel areas that have broadly declined since the 1938 baseline (Figure 3-9). The only exceptions to this pattern are a dramatic expansion, by 1965, of what had been a small side channel in 1938 in subreach 4 between RM 11.4 and 10.0; and continued downvalley translation of a meander bend associated with this expanding side channel into previously unoccupied floodplain areas after 1991.

Subreaches 6 and 7 show the only net positive increases in active channel area from the 1990 flood. They both displayed moderate expansions, particularly into previously unoccupied parts of the floodplain, as of 1991 (Figure 3-9). An even larger flood in 2006 showed similar but more muted effects, presumably

because the expansion into once-occupied floodplain in 1990 has left less available area for “first-time” (over the 80-year airphoto record, at least) occupation.

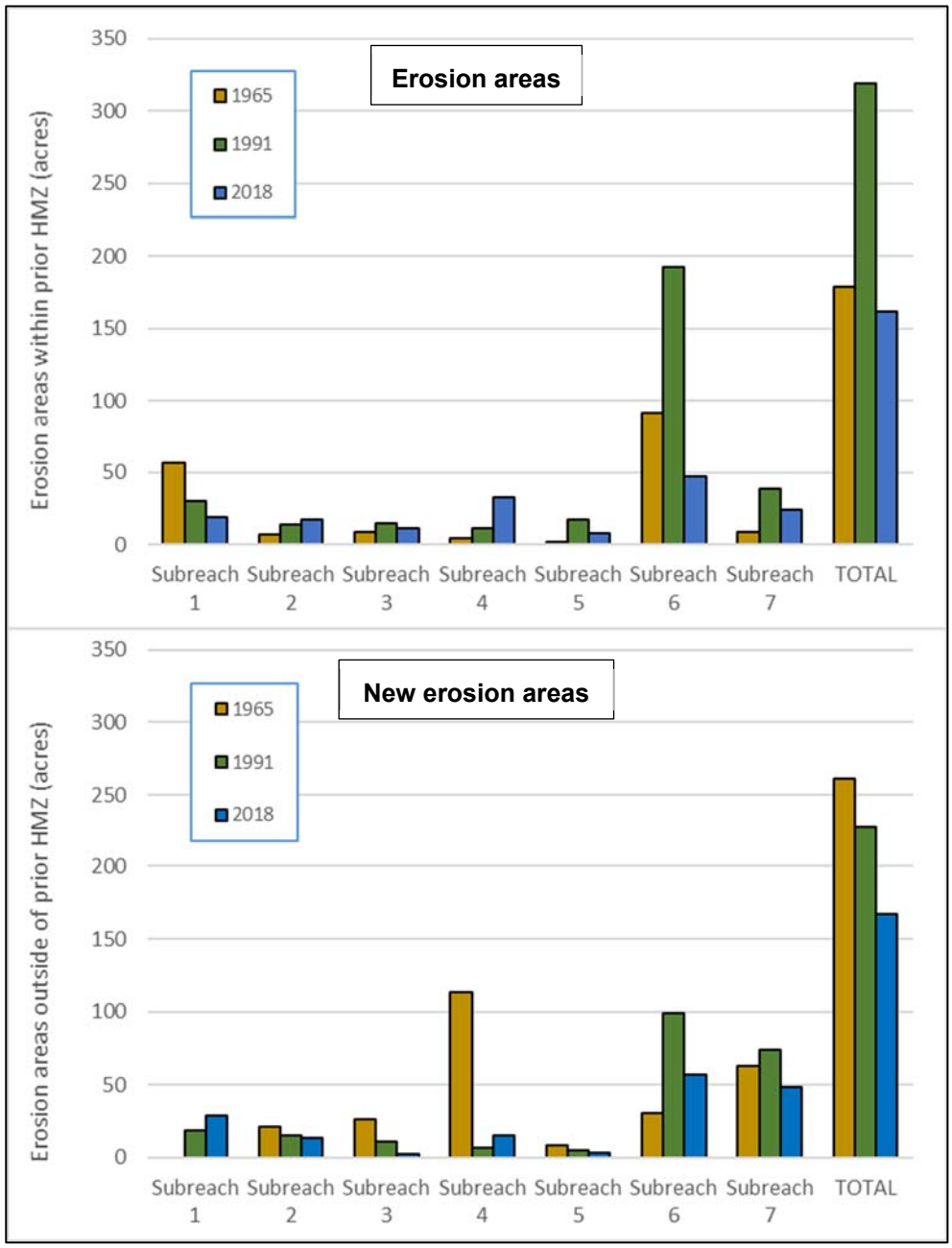


Figure 3-9 Areas of active channel occupation in comparison to the previous airphoto’s active channel boundaries.
These two graphs distinguish between areas outside of the prior active channel but still within the historical migration zone, as defined by all prior airphotos/map (top, the “Erosion areas”), and areas that expand the previously defined historical migration zone (bottom, the “New erosion areas”). Note that the baseline condition is defined by the earliest airphoto (1938); thus, the first period of change can only be defined with the 1965 airphotos (data for previously eroded areas as of 1938 are incomplete in subreach 1, owing to limited coverage from the 1921 map).

These patterns become even clearer if we omit the incongruous map-based channel traces (i.e., from 1897/1921) and normalize the active channel area by the corresponding subreach length (Figure 3-10). This display emphasizes the near-monotonic decline in active channel area over the last 80 years, the somewhat unusual behavior of subreach 4 in the 1938 to 1965 period, and the dramatic (and unique, within the study area) response of subreach 6 to the 1990 flood.

Several additional patterns are suggested:

- Subreach 6 is by far the most active and dynamic in the study area, as reflected in the data from all years but particularly from 1991.
- In subreach 5, the multiple channels across the central and southern floodplain were almost entirely abandoned post-1938, resulting in the greatest year-on-year decline in active channel area.
- From subreach 3 downstream to the confluence with the Snoqualmie River, active channel areas from the same year tended to increase downstream. This might reflect the modest progressive increase in drainage area and/or a similarly modest decrease in the length of armored banks.
- Subreach 7 is the least variable over time, and consistently amongst the subbasins with the smallest (length-normalized) active channel area. This likely reflects its confinement in the upper 1.5 miles by high, glacial-age outwash terraces, by erosion-resistant bedrock that crops out irregularly along the south side of the river at and above RM 21.4, and by the pre-1938 levee along the BNSF Railroad that protects the town of Gold Bar. Although the floodplain widens appreciably below RM 19.5, not until the river gets to about RM 17 (inside subreach 6) have the historical active channels made full use of the available floodplain width.

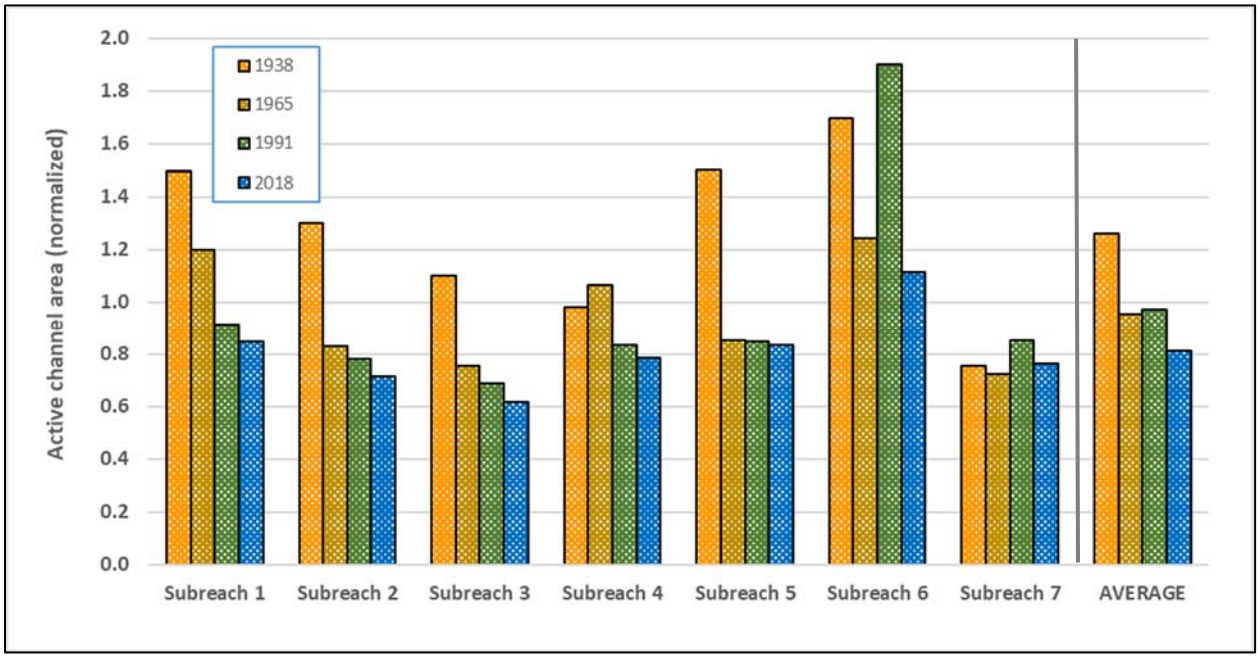


Figure 3-10 Active channel area, normalized by subreach length and scaled such that the average over all years and all subreaches = 1.000.

3.2.2.4 Drivers of reduced channel activity over time

It is reasonable to assume that the presumptive driver of channel migration, namely moderate and high discharges in the Skykomish River, would correlate with the magnitude of channel changes over time. Although various indices of "moderate and high discharge" have been used in past studies (e.g., the

cumulative discharge-over-threshold of Konrad et al. [2011] on the Green River, King County, Washington), the most straightforward is simply the maximum peak discharge for each water year. Those data (Figure 3-11) suggest that the pre-1965 period should show somewhat *less* dramatic channel changes than the interval from 1965 to 1991 (which included the second-largest flood on the river in 1990), or from 1991 to 2018 (which included the flood of record in 2006). As documented above, however, this is not the case: thus, variability in the occurrences of high flows does *not* provide an explanation for the systemic reduction in channel activity over the last 100 years.

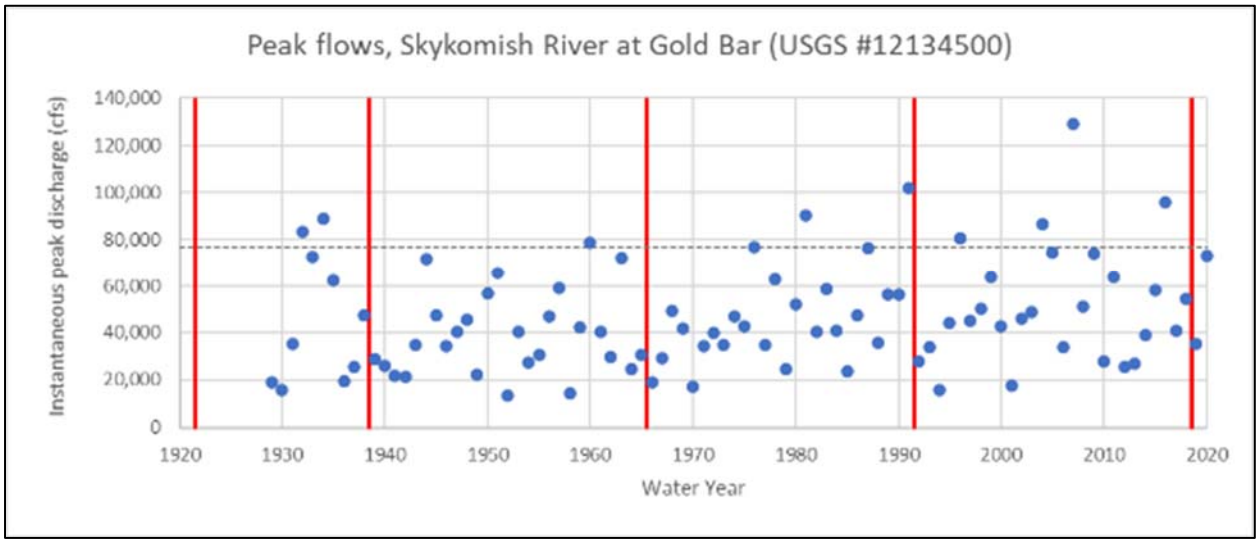


Figure 3-11 Annual maximum instantaneous peak discharges on the Skykomish River at the USGS Gold Bar gage.
Red lines delineate the time of the five maps and airphotos used in the migration analysis. The dashed line at 77,300 cubic feet per second highlights the approximate magnitude of a 10-year flood (from WSE 2020).

An additional factor that unequivocally influences channel migration is the construction of levees and revetments throughout the valley. Review of maps and airphotos indicates that some barriers to migration were in place prior to the 1921 map, whereas many others appear to have been constructed between 1921 and 1938. A few other examples testify to a period of continued levee/revetment construction during the period from 1938 to 1965 (see Cardno 2020). Nonetheless, the introduction of new revetments also does not fully explain the progressive reduction in active channel area, because most of the now-inaccessible floodplain areas and historical channel pathways had already been blocked as of 1938 (and nearly all of the rest by 1965). Furthermore, the loss of active bar area (rather than the wholesale abandonment of side channels) has determined most of the documented losses.

The most likely explanation lies in the influence of armored banks on the local hydraulics of a river. Revetments not only block the river's access to the floodplain, they also mute the overall dynamic response of the river to high flows. Gendaszek et al. (2012) reported that the planform morphology of the Cedar River (King County, WA) confined by revetments or valley walls remained "mostly unaltered" by a 30-year flood discharge on that river. Martínez-Fernández et al. (2017) documented substantial increases in the active channel and bar areas in the three years following revetment removal along the Órbigo River in northwest Spain (drainage area = 620 mi^2), with the increases occurring not only landward of the (removed) revetments but also by expansion into the previously unconstrained (but nonetheless previously unoccupied) floodplain.

This effect is demonstrated in subreach 7 (Figure 3-12) along two adjacent river bends—one against the BNSF Railroad revetment at RM 20 along its right bank, the next downstream being fully unconstrained. Although the left bank of the upstream bend is also unconstrained, only a small single side channel has exploited this floodplain area since the revetment was first engaged in the 1921–1938 period. The revetment is "sticky" with respect to the river planform, holding the channel in place far more than passive truncation of the available floodplain would otherwise imply. This phenomenon is repeated downstream,

with progressively more influence over channel dynamics as the frequency of such bank armoring increases. As a result, even though the construction of new revetments has largely ceased and the magnitude of large floods has actually *increased*, the activity of the channel has continued to decline.

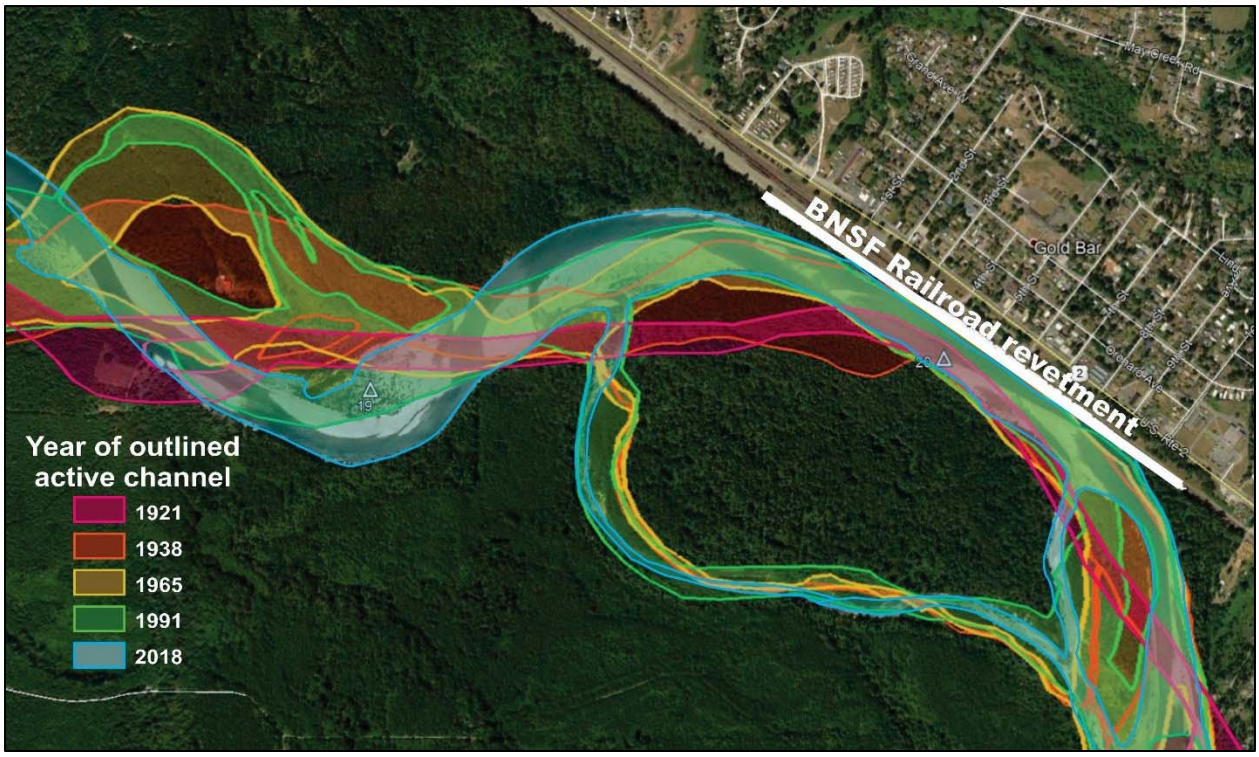


Figure 3-12 Two bends within an anastomosing portion of subreach 7.
The upper bend, at RM 20 (labeled triangle) first engaged the BNSF Railroad revetment sometime between 1921 and 1938; it has remained fixed in that position since then, with only minimal channel activity occurring elsewhere in the adjacent floodplain. In contrast, the lower bend at RM 20 has seen active migration over a half-mile-wide zone, with no apparent persistence in any one location.

3.3 The Influence of Future Climate Change

Snohomish County (2018) provided a comprehensive summary of the recent projections of the University of Washington's Climate Impacts Group on the hydrology and geomorphology of the Skykomish River. Predictions emphasize future increases in peak flows, particularly in the 2- to 10-year frequency range (Mauger et al. 2018). The magnitude of these discharges is sufficiently large, and their recurrences sufficiently frequent, that they typically have the greatest influence on sediment transport and channel geomorphology. Their increase implies a future with more dynamic channel processes, with greater rates of bank erosion, wood recruitment, and sediment erosion and deposition. These impending changes, however, make quantitative prediction of long-term rates of channel change infeasible because our understanding of these rates is based solely on the historical record. A future that diverges from that record will be novel, and without precedent. It will present an even greater challenge to management of flood hazards in the valley, because larger flows will occur more frequently, but it also implies that those restoration actions specifically implemented to enhance channel processes are likely to become even more effective and beneficial over time.

4 50-Year Projections for the Lower Skykomish River

4.1 Approach

On a dynamic system such as the Lower Skykomish River, predicting the precise location of the channel even a few years into the future is challenging; over multiple decades it is simply not possible. A variety of processes and conditions—particularly the creation and destruction of log jams, the magnitude and sequencing of large storm, the episodic delivery of large sediment loads via landslides, and the opening of avulsion pathways—are either random in their occurrence or dependent on small-scale features of the landscape that cannot be known deterministically from a regional study. Nonetheless, existing *patterns* of channel position and change can be recognized from the recent and long-term historical record, and in some localities those patterns can be projected forward with confidence. Even where this is not possible, zones of potential future channel occupation can be identified. In particular, areas can be highlighted as having a relatively high likelihood of occupation over a multi-decade timeframe, during which time one or more moderate to large floods can be assumed to occur. This is the approach used here to create the following 50-year projections for the Lower Skykomish River.

4.2 Alternative frameworks for definition of 50-year river occupation zones

Several conceptual frameworks can be used to identify the zone of high-potential 50-year river occupation. The most straightforward is that of the 100-year Channel Migration Zone (hereafter, the "100-year CMZ"), because it has already been defined for the Lower Skykomish River (Cardno 2020). A logical process was used to define this zone, namely the location of all historical river positions (termed the "Historical Migration Zone," hereafter abbreviated HMZ) plus potential avulsion pathways lying outside of that historical zone, with a buffer around all presently and potentially active channels to account for potential future migration resulting from 100 years of long-term average channel migration rates. This approach is not entirely suitable for the present application, however, and not just because its explicit time horizon is 100 years (rather than just 50). It is a conservative approach, wherein a location that "could" be occupied or reoccupied by the river is included without consideration of the *likelihood* of that happening. This can be appropriate for regulatory application, but it is overly crude to guide restoration and/or hazard reduction with limited resources and over a shorter time frame.

An alternative would be to define a "50-year CMZ," which in concept would consider past channel positions only for the past 50 years (i.e., the "50-year HMZ"), plus potential avulsion pathways and buffers around presently and potentially active channels equal to 50 years of average erosion. In practice, however, the result is little different from the 100-year CMZ for several reasons. First, only rarely do pre-1969 channels (i.e., those older than 50 years) occupy floodplain areas beyond those of the 1969 and later channels—in other words, the 50-year HMZ is nearly identical to the 100-year HMZ in the Lower Skykomish River. Second, avulsions are not particularly duration-dependent, because their occurrence can be initiated with a single large flow (given a channel configuration that favors an abrupt switch of location). Although 100 years offers twice as many years in which one such large flow might occur, even 50 years is nearly certain to include one or more 10-year floods, and an 87% probability for at least one 25-year discharge. Flows of these magnitudes are sufficient to initiate avulsions with suitable channel position and floodplain characteristics, and so allowing an additional 50 years for at least one such flow to occur does not significantly increase the likelihood of avulsion. Lastly, measured long-term channel migration distances have almost nowhere exceeded 1,000 feet along the Lower Skykomish River regardless of the length of record—a channel does not continue to migrate in the same direction forever, no matter how much time it is given to do so.

A final complication to using *any* historical patterns to predict future channel position is that hydrologic conditions are not static, and the flows that gave rise to the historical pattern will not be those that drive future river behavior. Current climate-change projections indicate that peak discharges in the Skykomish River will increase by 15–20% by 2080. As a consequence, the 50-year flood of the year 2080 will be greater in magnitude than today's 100-year flood. Of course, this increase will be progressive over the upcoming period, and so a hypothetical "50-year discharge" occurring early in this period will not be as

large as one occurring late in this period. This adds further uncertainty to any deterministic prediction of future channel positions or specific channel configuration.

4.3 Principles for designating the zone of high-potential 50-year river occupation

With the above considerations in mind, the following approach was taken to identify what is herein termed "the zone of high-potential 50-year river occupation":

- Define the 50-year HMZ, drawing a boundary around the floodplain area that encompasses all recognized channel positions from 1969-on. As noted above, this is little different from the 100-year HMZ in many areas, but significant disparities are noted in the subreach-specific discussions that follow.
- To this zone, include those avulsion pathways with a relatively high potential for reoccupation by virtue of a relatively low and narrow berm separating the potential pathway from the active channel.
- Exclude floodplain areas blocked by revetments or levees.
- Add a 1000-ft buffer around the 2018 active channel and potential avulsion pathways to account for the potential magnitude of future channel migration, wherever migration through that buffer would not be blocked by bank armoring, bedrock, or a high terrace.

Applying these "rules" identifies the zone of high-potential 50-year river occupation, which are described narratively below by subreach, making reference to both the terminology and the prior mapping of the 100-year CMZ (Cardno 2020). A few noteworthy locations are highlighted in the subsequent section by virtue of their particularly high likelihood and potential downstream consequences to developed property.

4.4 Projections of High-Potential 50-Year River Occupation

4.4.1 Subreach 7

In this subreach, the channel's positions over the last 50 years occupy no narrower a zone than that of the last 100 years—and so the HMZs for both periods are the same. The one major widening of the CMZ, along the RB (right bank) floodplain between RM 19.5 and 18.3, expresses the potential activation of avulsion pathways with inlets at RMs 19.5, 19.35, and 19.2. Their inlets are in a zone of active erosion and are presently overtopped at the 10-year flood by several feet of water flowing more than 4 ft/sec. They are therefore judged to have a high potential for occupation in the next 50 years, and so the 100-year CMZ also outlines the appropriate zone of high-potential 50-year river occupation in this subreach.

4.4.2 Subreach 6

Along the Lower Skykomish River, subreach 6 has the greatest number and density of potential avulsion pathways. Although most of these potentially (or currently) active channels traverse undeveloped, forested floodplain areas, two of them appear likely as future channel locations over a 50-year timeframe and pose a significant risk to developed property. These areas, left-bank floodplains with inlets between RM 17.73–17.59 and 16.62–16.21, are discussed in greater detail in the following section.

More general delineation of potential channel occupation zones based on the 100-year CMZ is generally suitable across this subreach, except for four localities. In each of them, a channel active in the 1938 airphoto lies outside of the 50-year HMZ, and so direct use of the 100-year CMZ to characterize the zone of high-potential 50-year river occupation may not be fully appropriate. Three of these locations, however (RM 18.1 RB, 17.6 LB, and 16.6 LB), lie within (or within 1000 feet of) an avulsion pathway that shows high potential for future occupation, given rapidly flowing and overtopping water modeled under a 10-year discharge. Therefore, these pathways (and their buffers) are included in the zone of high-potential 50-year river occupation, despite not having been occupied since before 1965.

The one area in this subreach where the 100-year CMZ likely overstates the potential for 50-year river occupation is at the downstream end of the subreach adjacent to Mann Road (Figure 4-1). Although 1938

side channels flowed through this area and are re-inundated by a modern 10-year flood, water velocities are low and the inlets to these avulsion pathways are not readily accessed by large discharges. However, channels to the north that are active today, part of what is termed here the “South Slough complex,” have a very high probability of additional expansion, given their direct connection to the mainstem river through multiple inlets at RM 16.6-16.2 in a zone of active bank erosion into those inlet areas. Thus, the zone of high-potential 50-year river occupation is modestly narrowed in this zone from the 100-year CMZ, but the likelihood of future channel expansion within that narrowed zone is judged to be high (see next section).

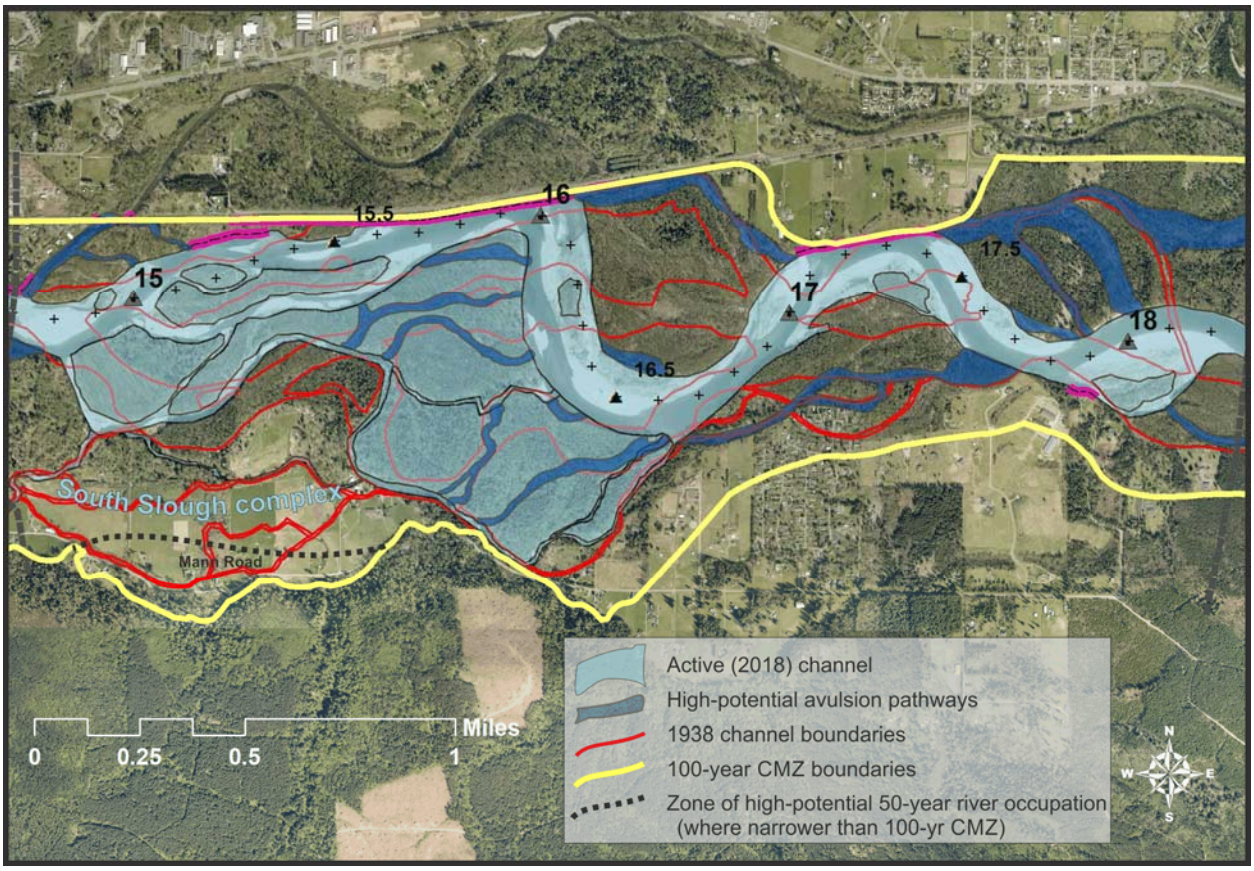


Figure 4-1 The portion of subreach 6 dominated by the “South Slough complex” and its network of potential and active inlet channels.
The zone of high-potential 50-year river occupation modestly is narrower than the full 100-year CMZ in this area. Note that shading of the delineated 2018 active channel also includes intervening upland terraces.

4.4.3 Subreach 5

Since 1969, the active channel has occupied only two zones—the mainstem river, and a continuous LB side channel (“South Slough”) extending from subreach 6 through all of subreach 5 just north of Mann Road, reentering the mainstem at RM 12.5 (in subreach 4). South Slough has a high probability of further expansion over the coming decades, given deep (>4 feet) and rapid (>3 ft/sec) flow during a 10-year flood, and which already causes significant flooding in this area.

Several 1938-era channels existed between these two modern active-channel zones, and they are all judged to be at significant risk for future re-occupation from avulsion with inlets at RM 14.8, 14.5, and 14.1—particularly that at RM 14.8, in a zone of recent rapid bank retreat into the inlet area (see additional discussion, next section). The 100-year CMZ is thus considered to be a reasonable surrogate for the zone of high-potential 50-year river occupation.

4.4.4 Subreach 4

In only two locations does the 1938 channel extend beyond the edge of the 50-year HMZ, and in both places the proximity of high terraces bounding the floodplain already restricts the extent of the 100-year CMZ. Mapping for the 100-year CMZ also included a broad zone of arcuate features visible in the LiDAR imagery along right-bank floodplain between RM 11.4 and 10.1, assumed to be pre-1921 meander scrolls by virtue of their geomorphic equivalence to other post-1921 channel traces. However, their reoccupation in a 50-year timeframe appears unlikely—even though backwater flooding during a 10-year event fills them locally more than 6 feet deep, velocities are generally low (<2 ft/sec) and throughgoing channels having well-defined and flood-accessible inlets are generally lacking. Therefore, 50-year river occupation in this area is most likely to result from bank erosion along the mainstem river (which has been locally rapid along this portion of the river). A right-bank boundary set back along the edge of relict channel traces about 1000 feet from the presently active channel, still substantial but locally less than one-half of the distance to the mapped 100-year CMZ boundary, is therefore appropriate (Figure 4-2). Along the south side of the river in this subreach, the 100-year CMZ is a reasonable surrogate for the zone of high-potential 50-year river occupation.

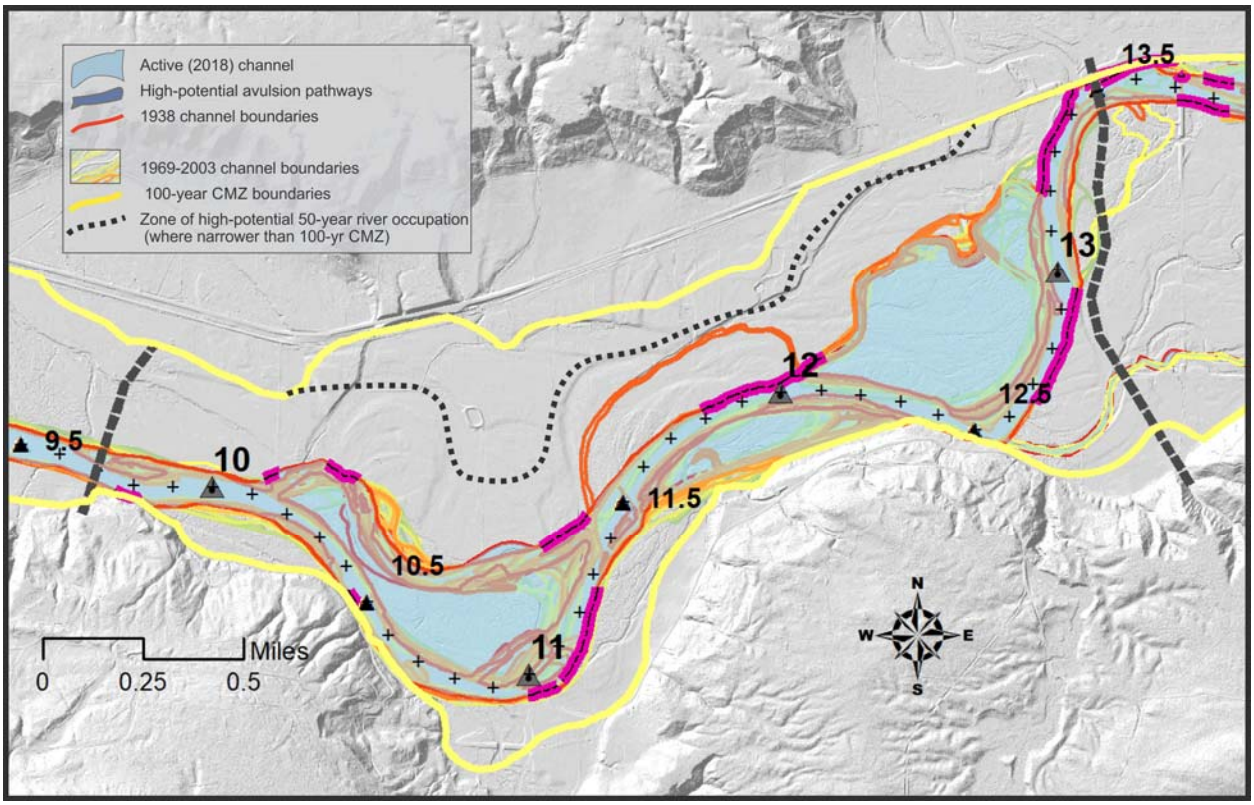


Figure 4-2 Area of reduced likelihood of 50-year channel occupation relative to the 100-year CMZ through subreach 4.

Pre-1921 channel traces are visible in the LiDAR topography of the floodplain north of RM 11.5–10.2, but they are too old to expand the zone of high-potential 50-year channel occupation (bounded by dotted black line) out to the mapped location of the 100-year CMZ.

4.4.5 Subreach 3

Subreach 3 displays a substantial divergence between the 100-year CMZ and the zone occupied only by 1969 and later channels (Figure 4-3). The most significant reductions in area are along the right bank between RM 9.7 and 8.8, where the inlet berm to a large 1938 side channel centered at RM 9.55 stands nearly at the level of the 10-year flood, with slow shallow water and stable riverbanks unlikely to result in a reopening of this pathway. Another large right-bank meander bend with an inlet around RM 8 was blocked post-1969 by the Fern Bluff levee, although backwater flooding up the outlet at RM 7.5 still results in deep

(but nearly quiescent) water during moderate to large floods. A channel running along the north edge of the floodplain emerges from this now-blocked channel, placing the outer boundary of the 100-year CMZ over 3,000 feet from the active channel. This is not a credible representation, however, of the zone of high-potential 50-year river occupation; this zone should include only the 1,000-ft right-bank buffer around the modern river from RM 7.8 to the downstream end of the subreach. Similarly, a small 1938 side channel along the left-bank floodplain downstream of RM 6.6 is no longer accessible by even moderate flows, and so the zone of high-potential 50-year river occupation should lie no farther than 1,000 feet from the modern riverbank.

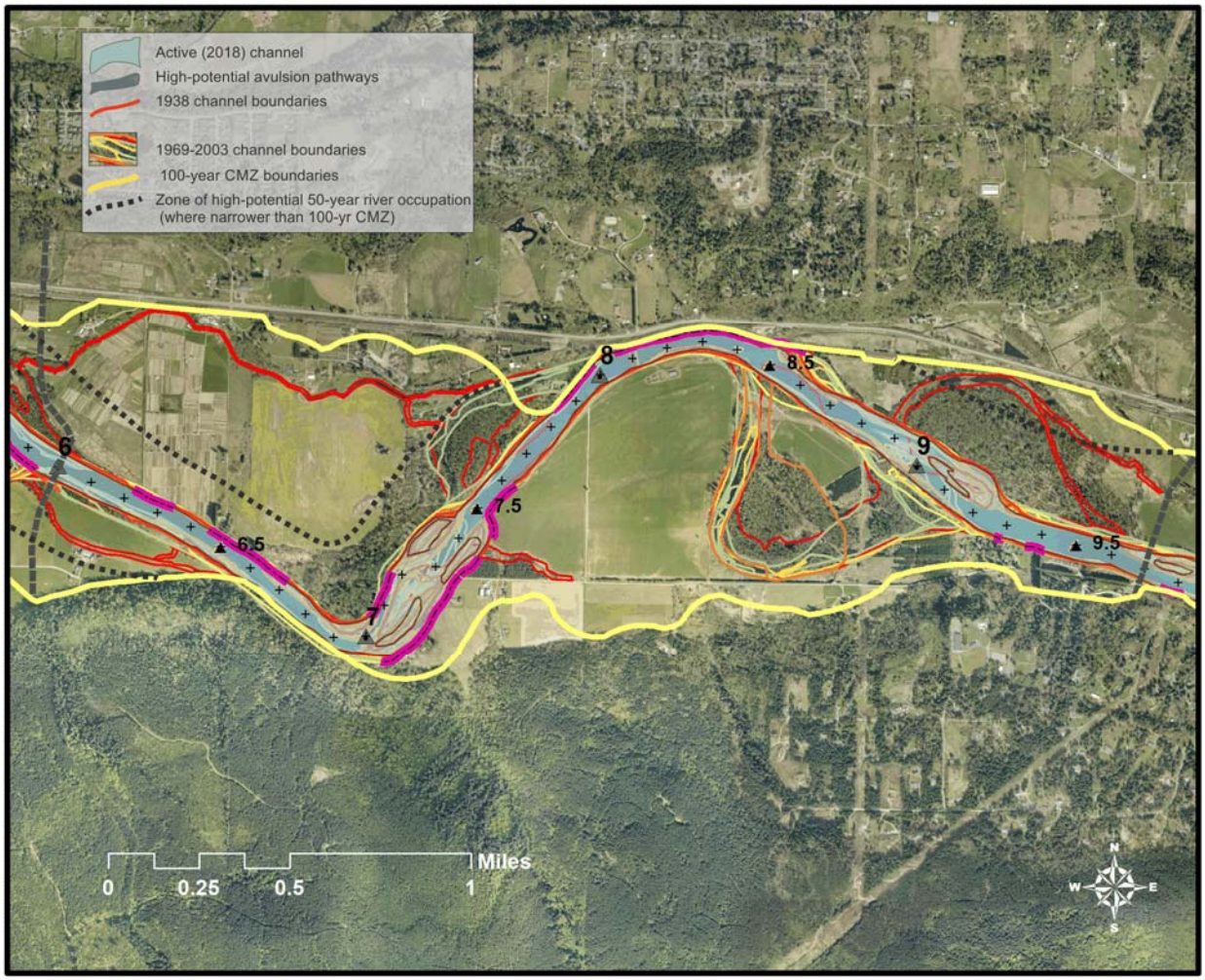


Figure 4-3 Boundaries of a narrowed high-potential 50-year channel occupation (dotted black line) relative to the 100-year CMZ in subreach 3.

4.4.6 Subreach 2

Subreach 2 also displays large divergences between the 100-year CMZ and the 50-year HMZ, here because the CMZ includes three areas with no photographic record of channel occupation but with strong topographic evidence of historical (and likely pre-1969) occupation. The CMZ boundary along the left-bank floodplain expands to incorporate a major meander trace that lies south of Haskell Slough, and which also includes the origin of Riley Slough as a distinct floodplain feature (Figure 4-4). Water depths in this side channel (and in Riley Slough) during a 10-year event are locally greater than 6 feet, so although flood potential is high the velocities are low. Thus, the risk of future channel occupation is judged to be very low, particularly given the recent reinforcement of the Haskell Slough levee at RM 5.8 (see additional discussion in the following section). Were this reoccupation to occur, however, then downstream developed property adjacent to the slough could be at significant risk from channel expansion.

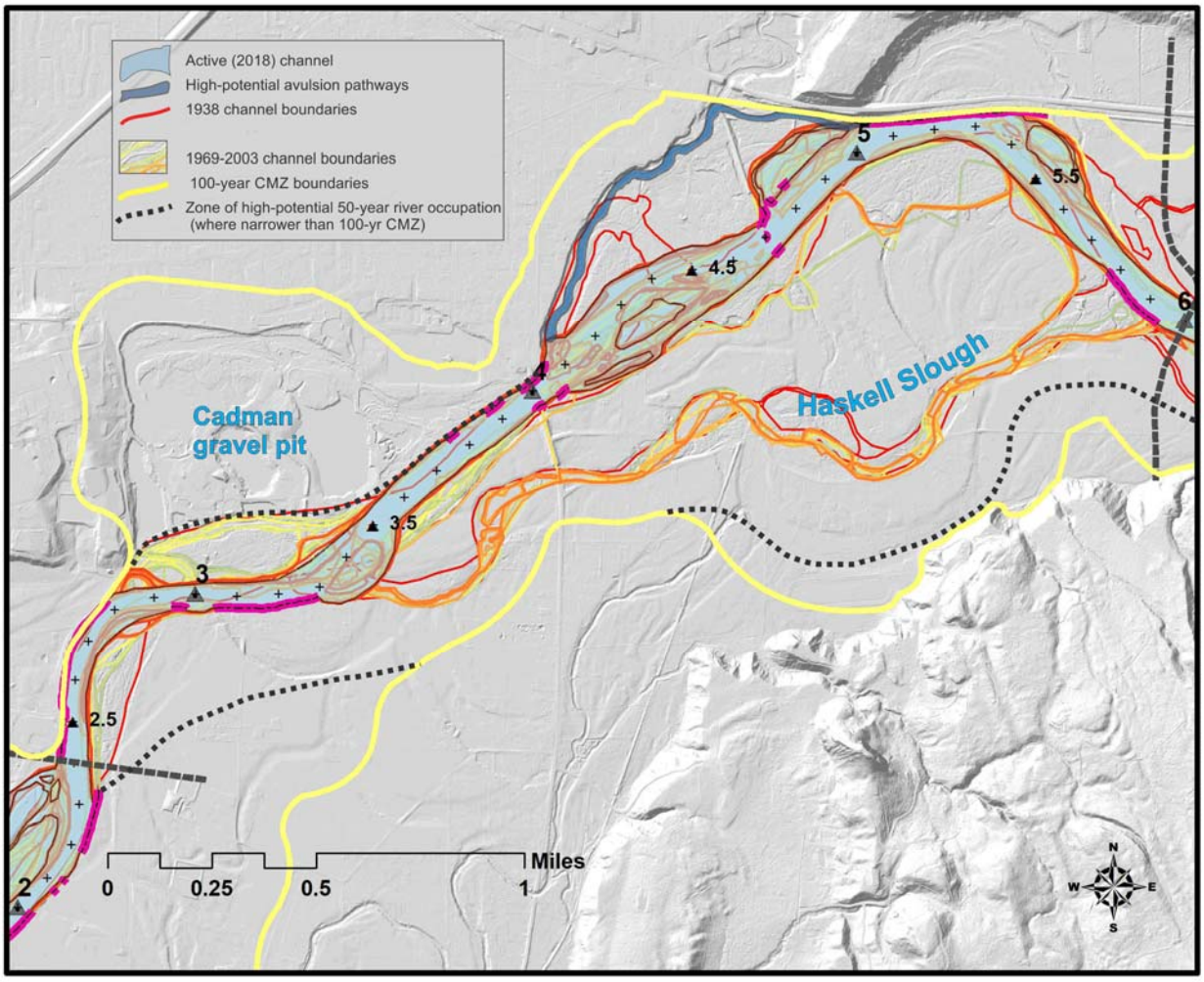


Figure 4-4 Reduced zone of high-potential 50-year channel occupation relative to the 100-year CMZ in subreach 2.
Discrimination is based on the lack of recent occupation of the channels visible in the topography south of Haskell Slough and the mainstem river below RM 3.5.

The second area of an overly wide 100-year CMZ relative to the zone of high-potential 50-year channel occupation is along the right bank between RM 3.8 and 2.9, which encompasses an old meander bend and the Cadman gravel pit. Although depressions within the pit fill with more than 10 feet of water during a 10-year flood, the berm separating them from the active channel is high, wide, and locally reinforced with rock revetments. Thus, channel (re)occupation in this area is judged very unlikely.

The third area of an overly wide 100-year CMZ is along the left bank floodplain, beginning just downstream of the Haskell Slough outlet (RM 3.3) and continuing south (downstream) into subreach 1. The CMZ was set back from pre-1938 channels in this area; and although 10-year flood water depths locally exceed 10 feet, flow velocities are generally low (excepting a single channel extending from RM 3.1 to 2.4, with 10-year velocities around 4 ft/sec and depths up to 6 feet).

Elsewhere in this subreach, active erosion is occurring along the right bank at RM 4.9, which raises the prospect of enhanced future flow into an existing side channel through a forested portion of Al Borlin Park. However, a railroad embankment that stands above the level of the 10-year flood, and which intersects the river at an armored bank at RM 4.7, limits the area that any future expansion of this channel is likely to affect. Downstream of that embankment, the 100-year CMZ expands to the north to accommodate a 1938 side channel (RM 4.45 to RM 4.05) not since occupied, although a relict side channel with a high potential

for future occupation via avulsion (along the RB floodplain from RM 5.0-4.1) remains an appropriate basis for defining the current zone of high-potential 50-year river occupation.

Elsewhere, some bank erosion is occurring at and just upstream of the Haskell Slough outlet (RM 3.3 and 3.5), but all such activity is encroaching into an area already included as having high potential for 50-year river occupation.

4.4.7 Subreach 1

The 100-year CMZ of this subreach includes a broad tract of left-bank floodplain between the Skykomish and Snoqualmie Rivers, and a somewhat more constrained pre-1938 right-bank meander loop subject to deep, but nearly stagnant, water during a 10-year flood. Despite the broad boundaries of the formally defined 100-year CMZ, fluvial activity and potential hazards are generally limited to flood inundation, not anticipated changes in channel configuration, particularly given the extensive revetments above RM 1.0 that have greatly limited channel migration over the last 50+ years. The only significant exception to these generalities is the active bank erosion in the lowermost mile of the river, where split channels around a forested island have created locally rapid, but ultimately short-lived, episodes of bank retreat. This pattern is likely to be further disrupted by ongoing left-bank erosion around RM 0.5, which is likely to breach a narrow peninsula separating the two rivers and move their confluence upstream by nearly one-half mile in the course of a single (future) flood event. This will result in a period of channel readjustment and, likely, a temporary reduction in bank retreat rates immediately upstream as the more sinuous channels are abandoned. Future erosion will undoubtedly continue, but within the confines of a more plausible 1,000-ft buffer around the modern channel (where not already armored) to better characterize the zone of high-potential 50-year river occupation.

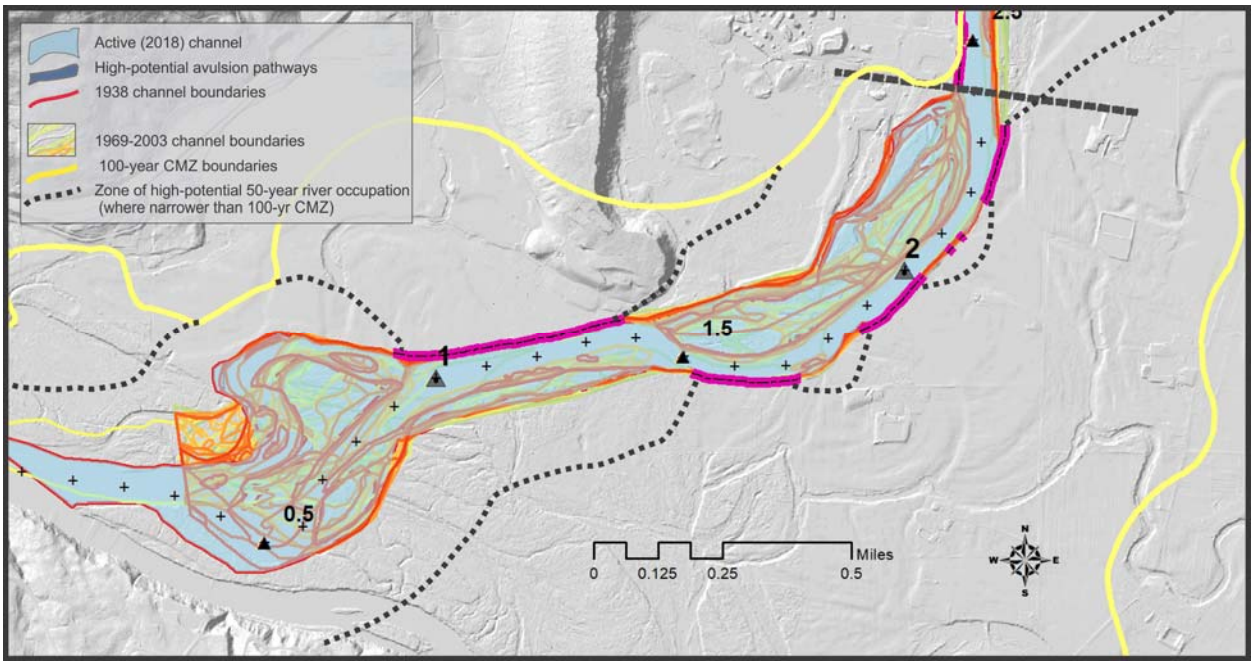


Figure 4-5 Reduced zone of high-potential 50-year channel occupation relative to the 100-year CMZ in subreach 1.
The adjusted boundaries are based on the lack of recent occupation of the pre-1921 meander scrolls visible in the LiDAR imagery in floodplain both south of the modern channel and north of the channel downstream of RM 2. This estimate of potential 50-year channel occupation also acknowledges the apparent effectiveness of bank armoring through most of this reach, even though only one (the Schlamp levee, between RM 1.7–1.5 along the left bank) is publicly maintained.

4.5 Areas of Greatest Concern for Future Channel Change

4.5.1 157th Place SE Neighborhood (RM 17.73–17.59)

Although standing slightly higher than much of the adjacent floodplain, this largely post-1990 left-bank neighborhood is already subject to floodwaters moving up to 3 feet/second during a 10-year event (Figure 4-6), with water depths between 1 and 4 feet. More problematic for the future, however, is the potential for active migration along the upstream bend of the mainstem river to open existing avulsion pathways at RM 17.73 and 17.65, capturing a fraction of the mainstem flow and bringing channelized floodwaters adjacent to the most riverward group of houses along the north side of 157th Place SE.

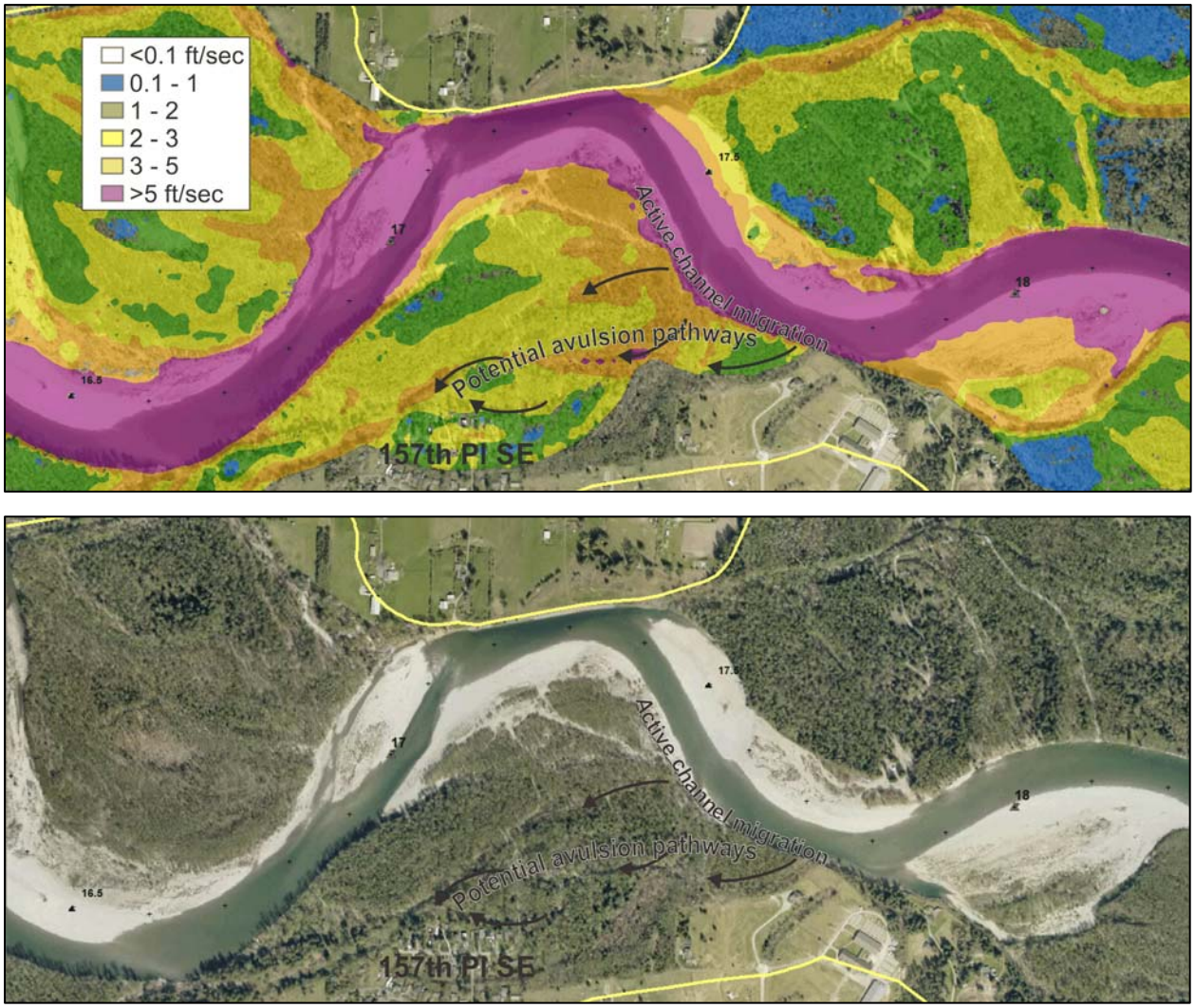


Figure 4-6 The 157th Place SE neighborhood, where active channel migration along the mainstem has the potential to reactivate pre-1938 avulsion pathways that run adjacent to a residential neighborhood.
Yellow lines mark the boundaries of the 100-year Channel Migration Zone. Top, flow velocities during a 10-year flood given the present channel configuration. Bottom, the same area with the 2020 airphoto as a base.

4.5.2 South Slough Complex (RM 16.62–16.21)

Along the Lower Skykomish River valley, eroding inlets of channels between RM 16.62 and 16.21 that feed the "South Slough complex" constitute the geomorphic process with the greatest potential for 50-year change from the modern channel configuration, and that poses the greatest risk to developed

property. Although the high-velocity, northern-most channel of the complex traverses only forested floodplain, it directly connects with South Slough itself, which is already an active channel flanked by fields and houses (Figure 4-7). An increasing proportion of mainstem flow is almost certain to occupy these channels in the years and decades ahead, with the potential for an eventual full avulsion of the river into one or more of these pathways.

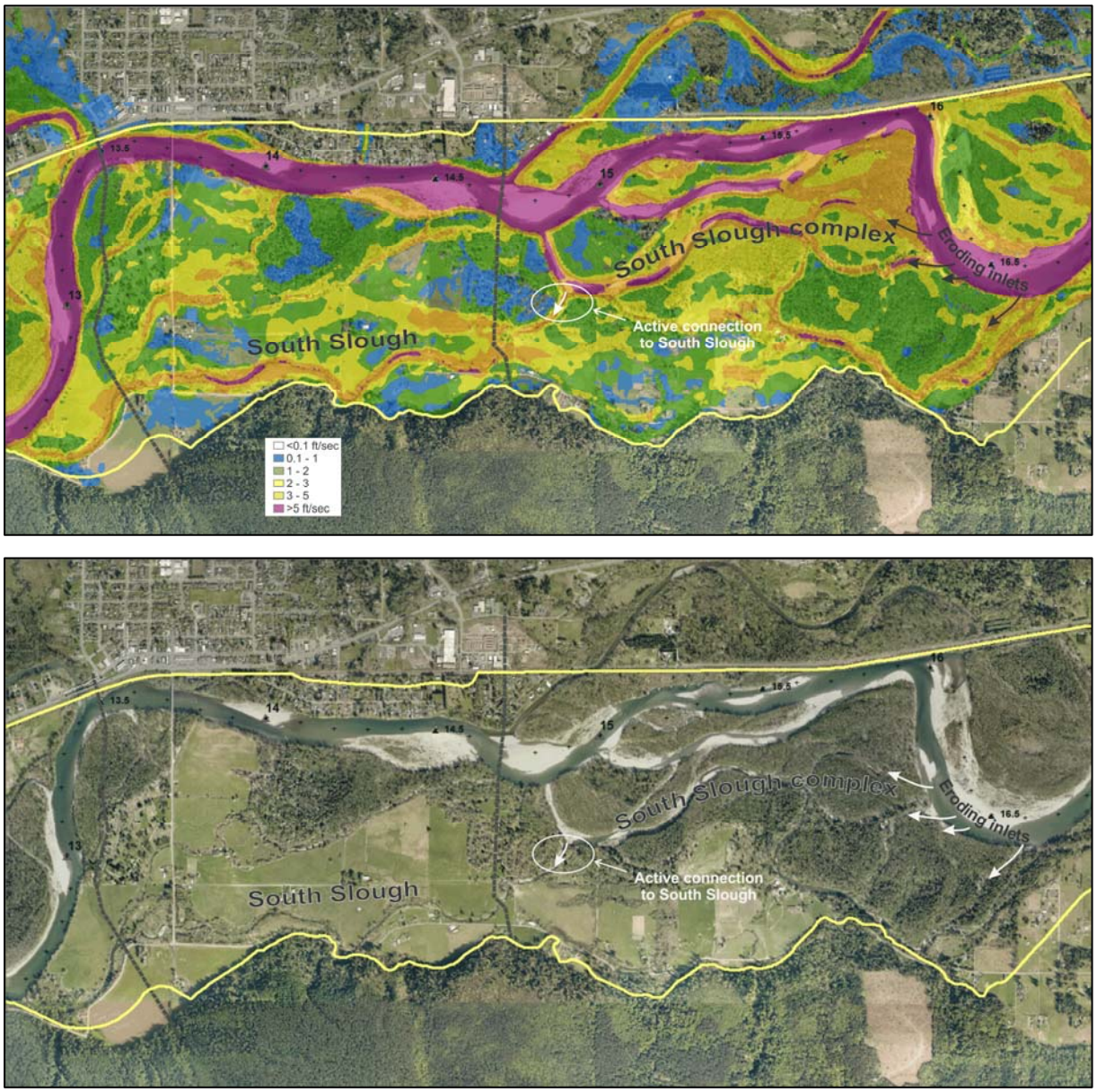


Figure 4-7 South Slough (in subreach 5) and the complex of avulsion pathways that contribute to it (the "South Slough complex" of subreach 6).
Inlets to those avulsion pathways have been actively eroding from downvalley migration of the meander bend around RM 16.5. Top panel, predicted flow velocities from a 10-year flood discharge; note the high (>5 ft/sec) flow rates in several of the channels, including that of South Slough itself. Bottom panel, same view with an airphoto base. Although channels of the South Slough complex are almost entirely in forested floodplain, South Slough itself is adjacent to active farmland and residences, which could be significantly impacted by future channel expansion. Top, flow velocities during a 10-year flood given the present channel configuration. Bottom, the same area with the 2020 airphoto as a base. Dashed gray lines mark the up- and downstream ends of subreach 5.

4.5.3 Sky River–Shinglebolt Slough Complex (RM 14.75–14.07)

Two sloughs that intersect the left bank of the mainstem river (Figure 4-8) form an anastomosing network of channels last occupied as of the 1938 airphotos (but *not* as of 1965). Pre-2018 bank erosion at the inlet to Shinglebolt Slough, and significant bank erosion post-2018 just upstream of the mouth of Sky River Slough, raise a significant probability of future reoccupation of one or both of these channels. Developed property is minimal along the two channels, but Mann Road could be severely impacted if either began to carry significantly greater flow.

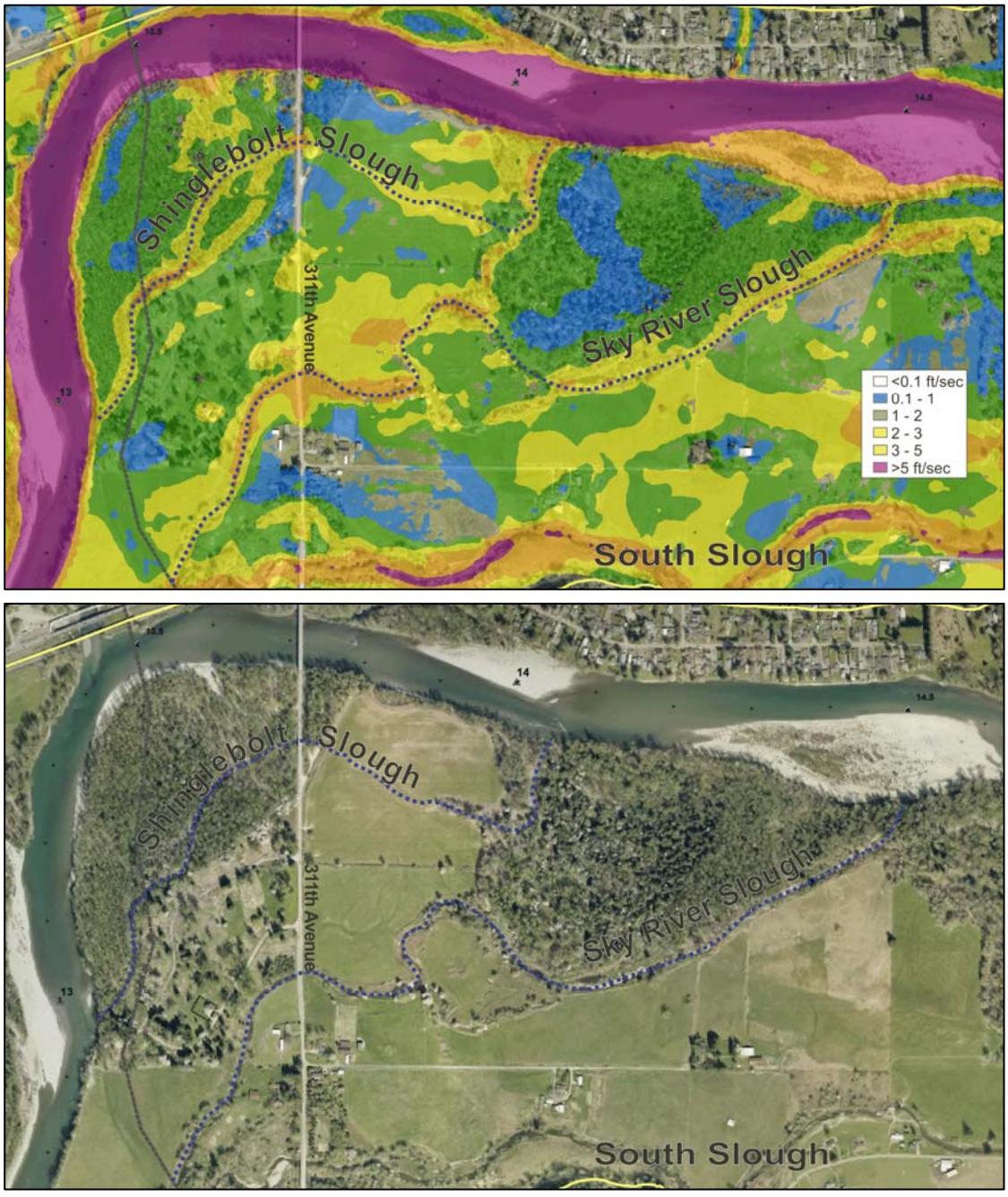


Figure 4-8 The Sky River–Shinglebolt Slough Complex in subreach 5.
Although neither slough has been active as of the 1965 airphotos, recent bank erosion near the Sky River inlet and a longer (but less immediate) history of bank retreat at the Shinglebolt inlet raise a significant potential for future (re)occupation. Top, flow velocities during a 10-year flood given the present channel configuration. Bottom, the same area with the 2020 airphoto as a base.

4.5.4 Haskell Slough (RM 5.94–5.78)

The Haskell Slough levee has been recently (November 2020) reinforced, which should limit the volume and rates of floodwater occupation of the slough through direct breaching or overtopping of the levee for the foreseeable future. Floodwaters have also exited the main channel at RM 5.6 during past high flows, overflowing the floodplain and entering Haskell Slough downstream of the inlet levee (see Figure 4-9). However, the geometry of the river through this reach (and a 100-year history of non-occupation) suggests that wholesale capture of the mainstem flow by avulsion is very unlikely through this area. Thus, the likelihood of continued flow through Haskell Slough is high, but major changes to channel position in this area are not.

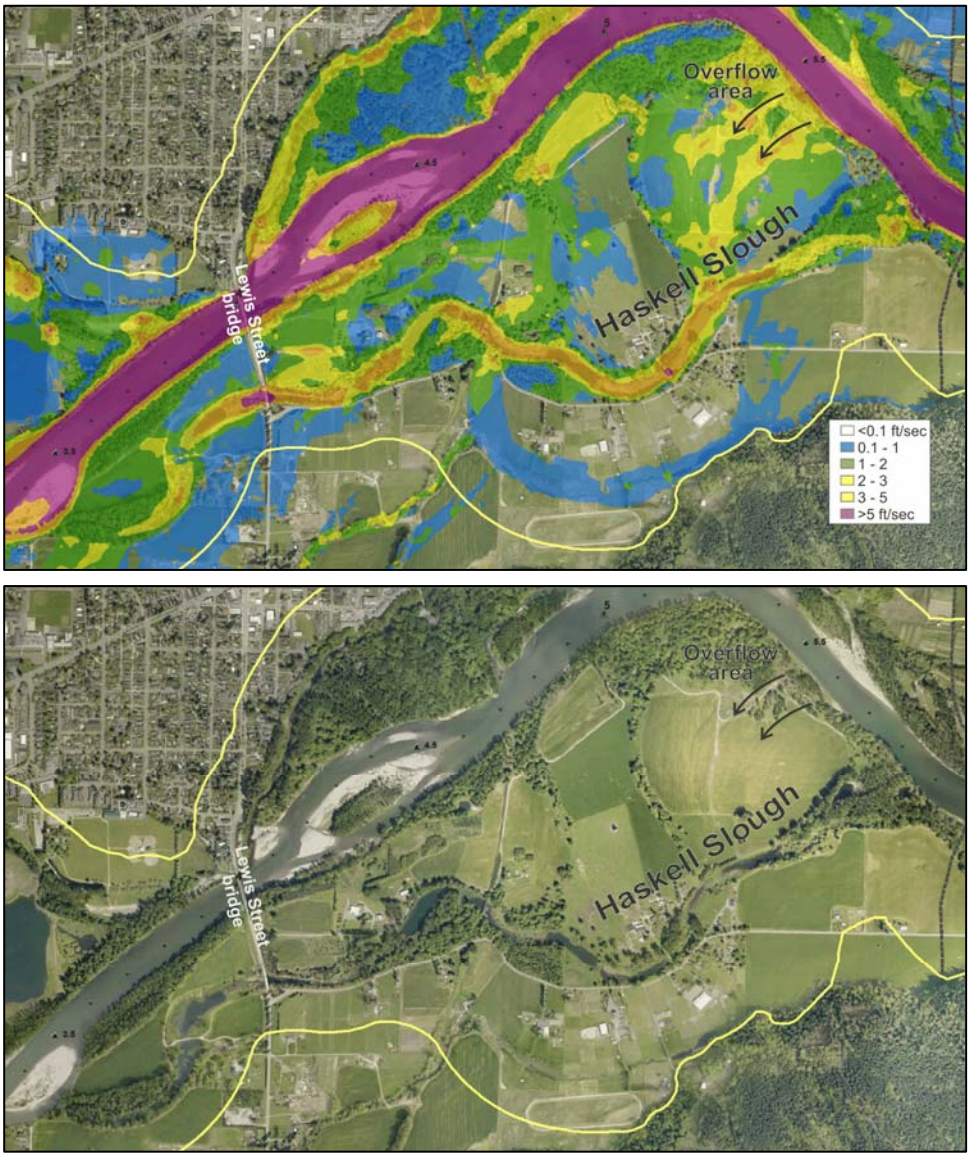


Figure 4-9 Haskell Slough, with 10-year flood depths (top) and faint channel traces (bottom) highlighting the area where past high flows have overflowed the main channel and reached the slough downstream of its inlet levee.
Despite such episodic overflows, however, the slough has not materially altered its position or form since at least 1938, and is judged unlikely to do so in the future. Top, flow velocities during a 10-year flood given the present channel configuration. Bottom, the same area with the 2020 airphoto as a base.

5 Implications for Restoration and Hazard Mitigation

Geomorphic considerations are *necessary*, but not *sufficient*, criteria for riverine management, and so there is no suggestion that the principles offered below to guide restoration and hazard-mitigation activities in the Lower Skykomish River valley "should" be adopted without considering social or economic factors. Similarly, the areas subsequently identified as promising locales for acquisition or restoration, based on these principles, are acknowledged as also being subject to constraints that will require a broader prioritization framework to adequately incorporate. Finally, the absence of favorable geomorphology should not necessarily disqualify a potential acquisition or restoration site that might require action to meet a pressing social need. Nonetheless, the geomorphic context of a site may determine what is feasible to accomplish, and the geomorphic setting of broader zones along the river can highlight where the risks and opportunities associated with acquisition and restoration merit greater attention.

5.1 Principles to Guide Restoration in the Lower Skykomish River Valley

Based on the observations and analyses of geomorphic processes and conditions, the following five principles should guide restoration. Similar lists have previously been recommended by DeVries (2010) and Snohomish County (2018); the current study has amplified and extended the scope of these earlier works but does not contradict their prior findings in any meaningful way. They also reflect the overarching guidance of Roni et al. (2002), who highlight the reconnection of isolated habitats and the restoration of watershed and fluvial processes as the highest priorities for restoration.

1. The greatest opportunities for long-term improvements to habitat, encouraging habitat-forming processes, and increasing habitat diversity and providing geomorphic support to the river's ecological health while requiring the least intensive intervention, is in the opening or reopening of side channels.
2. Channel migration and avulsion are the dominant habitat-forming processes in the river. Their protection and/or encouragement, by both passive (e.g., acquisition) or active (e.g., constructed features or removal of constraints) efforts, should be the highest priority for action.
3. The damping effects of existing levees and revetments on habitat-forming processes should be mitigated wherever possible, through either outright removal, landward repositioning from the river bank as "setbacks," surface roughening, or introduction of new structures that deflect flow away from the revetment face.
4. Any new restorative or bank-protection structures intended to alter river form and process at a reach scale should be fully engineered. Less extensive and less robust structures (e.g., log cribs, flood fences) have generally provided some localized benefits for habitat but have not proven particularly long-lived in their influence on river dynamics.
5. The extensive segments of simplified in-stream habitat are largely a consequence of the current level of impaired channel processes. Improving channel complexity should focus on addressing the underlying cause of impairments, whereas more localized "habitat-improvement projects" should be recognized as providing more limited, short-term benefits.

The basis for these principles, and their consequences for restoration, are discussed in the sections below.

5.1.1 Avulsion and side-channel reconnection

Multiple side channels, whose inlets are at elevations conducive to reconnection at low or moderate flows, are blocked by natural levees or (more commonly) artificial bank armoring. These channels would likely provide the greatest expansion of ecologically beneficial areas in the river valley for the least degree of intervention, because these features already exist on the landscape and once functioned as active side channels. The most prominent of these is Haskell Slough (RM 5.9) in subreach 2 and discussed above.

Several other such levee-blocked side channels are also present throughout the valley (Table 5-1). A comprehensive list of all potential avulsion pathways not already part of the 2018 active channel and with a high potential for reoccupation, by virtue of a relatively low and narrow berm separating the potential pathway from the active channel, is presented in Table 5-2.

Table 5-1 Levees and revetments blocking the inlets to once-active side channels.

Subreach	Inlet RM	Year of last river access		Levee or revetment	Length of relict blocked side channel (ft)
		1921	1938		
6	17.5	X		Startup levee	15,300
6	16.1	X		BNSF RR	8,900
5	14.0	X		Shinglebolt Slough	1,400
4	13.3		X	Sultan training levee & Groeneveld levee 2	8,600
4	8.0		X	Fern Bluff levee	9,600
2	5.9		X	Haskell Slough levee	12,300
2	3.8	X		unnamed	7,000
1	2.3	X		unnamed	1,500

Table 5-2 Channels with a high avulsion potential that could result in future reoccupation (does not include those inlet localities already mapped as part of the 2018 active channel). Note the almost complete absence of such channels below subreach 5 (RM 14.7–13.5).

Inlet RM	Bank	Comments
19.95	LB	Very low bank, active inlet channel, straight reach, opened post-1991
19.47	RB	Very low and narrow bank, active migration post-1991, low channel <100 ft beyond
19.34	RB	Very low and narrow bank, active migration post-1991, low channel <100 ft beyond
19.20	RB	Very low and narrow bank, channel open 1991, low channel 200 ft beyond
18.55	LB	High bank <200 ft wide separates channel from main channel; active 1991
18.34	RB	1991 side channel, now separated by forested low bank from active channel; significant migration post-1991
18.05	RB	High bank <100 ft wide separates channel from main channel; substantial bank retreat post-1991, but minimal post-2018
17.92	RB	High bank <100 ft wide separates channel from main channel; active bank retreat upstream and aggradation downstream, post-1991
17.89	RB	Active channel with episodic occupation, incipient chute cut-off
17.73	LB	Very low berm; substantial bank retreat post-1991, but minimal post-2018
17.55	LB	High berm with narrow inlet channel; within active channel 1991 & 2018. incipient chute cutoff
17.10	RB	Incipiently active channel, inlet has LWD accumulation, substantial bank migration post-1991 and post-2018
16.62	LB	Active inlet within 2018 active channel. Outside of bend, rapid bank retreat post-1991.
16.60	RB	Low berm with low channels ~200 feet beyond, inside of bend, part of 1991 and 2018 active channel; incipient chute cutoff
16.49	LB	Part of active side-channel complex across low floodplain; location makes occupation somewhat less likely than other adjacent channels
16.33	LB	Active inlet within 1991 active channel; outside of bend, rapid bank retreat post-1991; log jam at inlet but unlikely to preclude occupation

Inlet RM	Bank	Comments
16.21	LB	Active inlet; outside of bend, rapid bank retreat post-1991
16.12	LB	Active inlet within 1991 active channel; outside of bend, rapid bank retreat post-1991
15.15	RB	Narrow, moderately high berm, open channel beyond part of 1991 active channel; just off end of riprapped bank
15.05	RB	Narrow, moderately high berm, open channel beyond part of 1991 active channel; inlet adjacent to recently deposited island
14.79	LB	Broad, 200-ft long high berm in 2018, eroded by 2020 on outside of bend; low open channel beyond
14.10	LB SC	Alternate side channel for pathway @ RM 14.79
14.07	LB	Straight reach, low berm with narrow inlet channel, bank retreat post-1991 but minimal post-2018; behind flood fencing
14.04	LB SC	Branch off of the RM 14.07 pathway
5.03	RB	Low berm, active side channel; outside of bend
1.15	LB	Low bank, straight reach off of secondary channel, migration post-1991 but not post-2018

5.1.2 Encouragement of active channel-migration processes

The Channel Migration Zones (CMZs) identified in Cardno (2020) make only limited distinction in the magnitude of hazard over a 100-year period within the designated CMZ. Even if not further discriminated by the CMZ methodology, logic suggests that the risk is higher in areas of the river valley that are close to the most rapidly migrating channels. These are also the areas where geomorphic processes are most dynamic at the present time, and thus where removing existing or potential future constraints to those processes will be most immediately ecologically beneficial.

Zones of recent and relatively rapid bank erosion (and resulting channel migration) constitute areas where these processes should be encouraged, and any non-compatible activities on the adjacent floodplain in these areas should be limited if at all possible (Table 5-3). Although two localities have experienced more than 200 feet of migration in the two years 2018–2020, nearly all sites have migration rates under 200 feet per decade when averaged over a period of 10 years or longer. Only four exceptions to this limit have been identified; of these, two are continuing to migrate as of 2020 (at RM 16.5–16.4 and RM 0.45) and two have not experienced further bank retreat in the last three years.

Table 5-3 Localities of rapid, recent channel migration (i.e., post-1990). Migration rates greater than 200 feet per decade, when averaged over 10 years or more, are shaded. SC = side channel; all others are mainstem locations.

RM	Subreach	Bank	2018–2020 expansion, ft	Comments	Decadal trends
21.05	7	RB SC	31	On LB of RB side channel	350’ expansion 1991–2018
20.92	7	LB SC	0	On LB of LB side channel	103’ expansion 2006–2013; static thereafter
20.69	7	RB	38		50’ narrowing 1991–2018
19.39	7	RB	0	Same bend as 19.33	214’ expansion 2006–2017; static thereafter
19.33	7	RB	39		250’ expansion 1991–2018
18.05	6	RB	25		300’ expansion 1991–2015; 147’ expansion 2015–2018
17.59	6	LB	26		Transition zone, expansion to narrowing 1991–2018
17.10	6	RB	44		150’ expansion 1990–1991; additional 100’ expansion thereafter

RM	Subreach	Bank	2018–2020 expansion, ft	Comments	Decadal trends
16.50	6	LB	42	Same bend as 16.41	335’ expansion 1990–1991; additional 962’ expansion 1991–2018
16.41	6	LB	204		Transition zone, expansion to narrowing 1991–2018
16.05	6	LB	42		Up to 350’ narrowing 1991–2018
15.57	6	LB SC	39	On LB of LB side channel	Infill of 1991 channel
15.43	6	LB	43		Infill of 1991 channel
15.31	6	LB SC	31	On RB of LB side channel	Infill of 1991 channel
14.97	6	LB SC	27	On LB of LB side channel	Up to 400’ expansion 1991–2018
14.75	6	LB	143		<20’ expansion 1991–2018
12.12	4	RB	0		141’ expansion 1991–2009; static thereafter
11.49	4	RB	0		214’ expansion 1991–2009; static thereafter
11.20	4	RB SC	340	On RB of RB side channel	Up to 190’ expansion 1991–2018
10.49	4	RB SC	118	On LB of RB side channel	Up to 320’ expansion 1991–2018
10.32	4	LB	35		33’ narrowing 1991–2018
10.30	4	RB	46		45’ expansion 1991–2018
10.17	4	RB SC	0	On RB of RB side channel	206’ expansion 1990–2018
10.18	4	RB	74		58’ expansion 1991–2018
9.16	3	RB	0	On RB of RB side channel	114’ expansion 1990–2006; additional 67’ expansion 2006–2018
8.93	3	LB	24		57’ narrowing 1991–2018
7.71	3	LB	57		No change 1991–2018
7.40	3	LB SC	24	On LB of LB side channel	<20’ narrowing 1991–2018
7.10	3	LB SC	38	On LB of LB side channel	<20’ expansion 1991–2018
6.42	3	RB	30		59’ narrowing 1991–2018
5.43	2	LB	0		115’ expansion 1991–2009; static thereafter
4.89	2	RB	34		150’ expansion 1991–2018
4.32	2	RB	0		221’ expansion 2006–2016; static thereafter
3.50	2	LB	32		60’ expansion 1991–2018
3.37	2	LB SC	30	On LB of LB side channel	155’ expansion 1991–2006; static 2006–2018
2.06	1	LB	42		No change 1991–2018
1.38	1	RB	33		46’ narrowing 1991–2018

RM	Subreach	Bank	2018–2020 expansion, ft	Comments	Decadal trends
0.75	1	RB SC	0	On RB of RB side channel	450’ expansion 2002–2017; static thereafter
0.71	1	RB SC	39	On LB of RB side channel	Network rearrangement 1991–2018
0.45	1	LB	101		738’ expansion 1990–2020
0.26	1	LB	53		58’ narrowing 1991–2018

Particularly in the zones of rapid recent migration (i.e., non-zero values in the “2018–2020 expansion” column), protection of this active riverine process should merit attention. Given the effectiveness of riprap and other bank armoring for suppressing channel migration, however, these zones do not provide any guidance for where riprap *removal* might result in significant habitat benefit. To identify potential opportunities for encouraging channel migration, every incidence of an armored bank was reviewed for its geomorphic position relative to likely channel-migration processes, the area of potential floodplain and/or side-channel habitat that could be reengaged if migration was to proceed unimpeded, and a coarse evaluation of the likely social constraints to such removal based on adjacent floodplain land use. Only a few major revetments, particularly those protecting the BNSF Railroad and US Highway 2, were omitted from this evaluation. This approach identifies a number of potential opportunities for further evaluation (shown on the Appendix A map folio as “Potential Floodplain Habitat Expansion”), particularly those in a favorable geomorphic position (i.e., at the outside of a meander bend where migration is typically most active) and with limited upland land-use constraints (Table 5-4).

Table 5-4 Active-channel expansion opportunities, based on revetments whose removal could significantly increase potentially accessible floodplain habitat.

Also includes qualitative ratings of the likelihood, constraints, and benefits (rated only by area, not inferred habitat quality) of future channel occupation into the now-protected floodplain area. Shaded entries highlight some of the most promising removal candidates that merit further evaluation.

RM of bank armor	Bank	Area of potential floodplain accessed (acres)	Likelihood of occupation[1]	Land-use compatibilty[2]	Potential habitat area	Notes
15.32–15.15	RB	16.7	H	H	L	Forested strip between river and RR.
14.06–14.05	LB	12.9	H	M	H	Remove flood fence to encourage reoccupation, and create flood-flow passage under Mann Road. Opens 4900' of side channel, crosses field, forest.
14.02–13.75	RB	6.6	M	H	L	1 revetment @ 13.8 + short segment of another @14.0; reoccupied side channel.
13.45–13.31	RB	158.2	H	M	H	Sultan levee; blocks extensive side channel area, fields, 1 major structure.
13.31–13.20	RB	4.4	H	H	M	500' revetment to open side channel blocked post-1991. Opens ~600 ' of side channel
12.95–12.65	LB	28.5	H	M	M	Revetment protects field on outside bend.

RM of bank armor	Bank	Area of potential floodplain accessed (acres)	Likelihood of occupation[1]	Land-use compatibilty[2]	Potential habitat area	Notes
12.11–11.80	RB	59.8	H	M	H	Revetment protects field on outside of bend; large 1936 channel beyond.
11.40–11.25	RB	9.3	M	M	L	Revetment protects field. Relict scroll bar lies 1,200 behind on floodplain, but downstream (unarmored) bank erosion more likely for future reoccupation.
11.27–11.02	LB	34.4	H	M	M	Revetment protects forest and field; outside of bend.
10.30–10.21	RB SC	5.7	H	M	L	Revetment and flood fencing protect field.
8.01–7.83	RB	50.1	H	H	H	Fern Bluff levee protects forest, plus access to extensive 8700-foot-long 1939 side channel.
7.61–7.44	LB	8.6	M	M	L	Blocks fields, outlets of old side channels.
7.20–7.03	RB	28.3	L	H	M	Cutoff chute complex; needs additional berm removal set back from channel.
5.95–5.78	LB	83.9	H	M	H	Blocks access to Haskell Slough, 12,000 ft; no structures in direct path but risk of overtopping, erosion into developed land.
4.73–4.69	RB	63.7	M	H	H	Blocks access to forested Al Borlin Park, and 1921 and 1938 side channel.

[1] H=outside of bend or active migration zone, L=inside of bend, M=other channel position. This rating does not include the potential for engineered in-channel structures to intentionally divert flow as part of the design for revetment removal.
[2] H=forested land cover, M=agricultural fields; areas with structures and/or roads were omitted from this compilation.

An additional restoration-based rationale for the removal of revetments is the spatial association of salmonid spawning activity with armor-free channel segments (Section 3.1.4). Independent of any additional floodplain engagement that might occur following removal of bank armoring, potential in-channel benefits to spawning may prove to be locally significant in reaches of the river that might otherwise provide suitable spawning habitat in the absence of revetments.

5.1.3 Modification to existing levees and revetments

Although regulatory instruments such as Channel Migration Zone designations presume that only publicly maintained levees and revetments are sufficiently robust to protect the land behind them from encroachment by the river, the empirical evidence from the Lower Skykomish River indicates that even the non-public, “informal” revetments have been largely successful at restraining channel dynamics for the 50+ years that most of them have be present. From a geomorphic (only) perspective, their modification or removal would provide a net benefit to river functions and processes regardless of their location.

In nearly all localities, however, these channel-restraining structures were constructed for a reason, and their removal may not be feasible or socially/economically justifiable. Modifications to roughen their faces and provide a (somewhat) more ecologically hospitable and heterogeneous flow field, with the potential for local habitats of value to aquatic organisms, should be explored. The use of woody material and live plantings, commonly implemented in the Pacific Northwest and elsewhere for several decades, would constitute a worthwhile restoration approach. Because these actions do not significantly address in-channel processes, however, they can offer only limited long-term effects.

One action that may provide a more systemic benefit, however, is the redirection of the active flow from the face of extensive levees. As discussed above and illustrated in Figure 3-12, once channels engage a revetment or levee face they tend to “stick” to that face, depressing active channel dynamics not only along the armored bank itself but also downstream and across the valley. Thus, flow redirection is likely to have significant systemic benefits to in-channel processes, if successful.

One example along the Lower Skykomish River provides some encouragement for the potential effectiveness of this approach. As described for subreach 6, a set of 5 rock groins were built out into the channel sometime between 1990 and 2005 (RM 15.3–15.2), projecting into the flow between 30 and 40 feet perpendicular to the bank. As of 2005 they directly engaged the main flow of the river (Figure 5-1), but over time they may have influenced the growth of a large bar immediately upstream, which in turn has encouraged some shifting of the main channel away from the revetment and subsequent side-channel occupation along the opposite bank. A more detailed evaluation of the local flow hydraulics than presently available from the full-river model (WSE 2020) would be necessary, however, to show any causal relationship worth pursuing elsewhere.



Figure 5-1 Five constructed groins along the BNSF Railroad levee at RM 15.3–15.2.
The main channel directly engaged them in the first years after construction (2007, top), but by 2018 (bottom) the zone of primary channel activity had shifted across the floodplain. Downstream-most groin indicated by arrow. Images from Google Earth; flow is right to left.

Many of the levees and revetments along the river might provide benefit from this approach, because in most instances they are confining only one bank of the river, with the opportunity for active-channel expansion beyond the opposite bank into undeveloped floodplain. These opportunities appear particularly promising along the BNSF Railroad levee (RMs 20.4–19.6, 16.0–15.6, 5.3–5.0), the Startup training levee (RM 17.4–17.1), the Groeneveld levee 2 (RM 13.4–13.2), and various unnamed levees at RM 14.6–14.1, 12.9–12.7, 12.1–11.8, 7.6–7.5, 3.3–3.1, 2.8–2.4, 2.3–1.5, and 1.4–0.9.

5.1.4 Engineered vs. informal channel modifications

Several examples of “informal” channel modifications are present along the Lower Skykomish River. As previously noted, bank-armor installations (whether recorded as a public maintenance obligation or simply observed in the course of floating down-river) have generally been quite effective at restraining subsequent channel migration. Other structures, however, have been more variable in their success at their intended tasks. A subset of previously installed flood fences (short piles driven into a bar or the bed of the river to catch floating logs, induce sedimentation, and reduce bank erosion) were encountered during field work for this study (three examples are shown in Figure 5-2). Many were constructed over the years 2009-2011; others predate reliable records. For the recent set of projects, some have exerted local influence in the accumulation of LWD to form jams over the subsequent decade, and some have increased bar aggradation or contributed to erosion along the opposite bank (or other channel adjustments). Other arrays have elicited a localized response with limited significance, and still others have either seen some failure to achieve their intended outcome or no response. They are all examples of Roni et al.’s (2002) third category of restoration actions, recommended only after restoring natural processes or where short-term improvements in habitat are desired and warranted.



Figure 5-2 Flood fence examples from recent field work.
Top, RM 21.4 with piles now nearly buried by gravel at the inlet of this active side channel. The upstream-most piles have trapped some LWD (right edge of picture). Middle, extensive LWD accumulation as of 2020 triggered by 2009 flood fence construction. Bottom, flood fence along the secondary channel opposite RM 10.4, with minimal engagement of woody material but asociated with 130 feet of lateral post-construction bar expansion.

The lesson from these examples is that even small-scale floodplain or in-channel structures will commonly require engineered design if they are to persist and exert the intended nature and magnitude of long-term benefits for habitat and channel form (for guidance see Chapter 6 in USBR and ERDC 2016). Conversely, even informal bank armoring can be nearly as effective at restraining channel movement as named, publicly maintained facilities. Thus, constructing any such new structures should be approached cautiously, and evaluating the effects of existing restraining structures requires a comprehensive inventory of *all* such features regardless of their origin or pedigree.

5.1.5 Improving simplified instream habitat

Of the channel processes most impaired by human activity and most amenable to restoration with long-term sustainability and effectiveness, the reestablishment of a dynamic riparian zone is probably of highest priority. The actions most needed to accomplish this (removal of bank armoring, side-channel reconnection, flow redirection away from existing hardened banks) have already been addressed above. In addition to the physical changes to the channel planform that these actions could induce, they can also enhance another in-channel process: the recruitment and retention of LWD. Subreaches 7, 6, and to a lesser extent (but also lesser benefit) 1 display zones of active recruitment, primarily by bank erosion into forested floodplain. Not only do the other reaches lack recruitment, however, but also they lack zones for LWD retention. Future acquisition and restoration projects need to enhance these interrelated processes. The greatest need, however, appears to be the protection and enhancement of sites that could act as natural zones of wood accumulation with minimal additional intervention (and a corresponding avoidance of active LWD removal).

Along the Lower Skykomish River, the three dominant geomorphic settings for LWD accumulations are at the outside of unconstrained meander bends, particularly with side-channel inlets (see Figure 2-11); the head and crest of point bars (Figure 2-12); and the apex of mid-channel islands. The first two environments are best-expressed in subreach 6 on both sides of the river around the meander bend at RM 16.5 (Figure 5-3). Islands are not common along the river, but one of the largest jams has formed at the apex of the largest such island at RM 11.4 (see Figure 2-21). Facilitating more such accumulations will be best accomplished by supporting the processes that create these geomorphic settings: meander migration by removal of constraints and flow splitting through the (re)opening of side channels and avulsion pathways; and by an avoidance of the linear river-training structures that discourage a more diverse channel form and offer no opportunities for LWD retention themselves.

An additional geomorphic setting where increased wood accumulation and retention could be achieved through construction of engineered wood-retention structures is in those areas where ongoing channel migration (Table 5-3) or potential management-induced migration (i.e., by future revetment removal) (Table 5-4) would encroach on non-forested floodplain. Potential opportunities for future, managed migration into non-forested land, however, are more numerous. Although they are limited to single areas in each of subreaches 6 and 2, multiple such localities are present in subreaches 4, 3, and 1. Similarly, any potential avulsion pathways that were to become occupied or reoccupied by levee removal or natural processes (Tables 5-1, Table 5-2) would be worthwhile candidates for evaluating installations of large wood to support more rapid habitat formation.



Figure 5-3 Reach with the greatest concentration of LWD jams (highlighted by red circles). These accumulations occupy the head and crest of the point bar at RM 16.5, and at the inlets of multiple side channels on the outside of the bend. Flow is from right to upper left. Four of these LWD jams on the point bar formed at locations of vertical log arrays constructed in 2011.

5.2 Flood and Geomorphic Hazards in the Lower Skykomish River Valley

Hazards to people, structures, roadways, and other infrastructure in the Lower Skykomish River Valley have been expressed over many decades, with a wealth of experience and understanding of these hazards gained through multiple high-water events over the last century. These hazards can be broadly categorized into (1) frequent and/or deep and fast-flowing floodwaters; (2) progressive channel migration into adjacent upland areas; (3) abrupt avulsion into previously unoccupied (or minimally occupied) flow paths; and (4) failure of existing flood-protection facilities, allowing previously protected areas of the valley to be exposed to the active flow of the river (see Cardno 2021 for the present-day assessment of these facilities). These hazards are interrelated, and so their discrimination into separate categories is in part artificial—channel migration can expose certain avulsion-path inlets, previously inactive, to the full flow of the river; high floodwaters can accelerate the rate of channel migration and threaten facility failure as well as simply inundating low-lying land. Similarly, “hazards” and “resources” are commonly two sides of the same coin, in that a dynamic channel can not only threaten developed property but also create new (or rejuvenate previously existing) aquatic habitat. Thus, a geomorphic analysis alone is insufficient to guide the mitigation of flood hazards, no more than it is adequate to guide restoration activities. It can, however, highlight those areas of a river valley where the risks are highest, and where consideration of competing needs and interests must be weighed most carefully.

A map folio displaying the distribution of these hazard areas accompanies this report as Appendix B.

5.2.1 Areas of deep and fast-flowing floodwaters

Areas of flood hazard are well known from the history of past flooding events along the Skykomish River. The three largest recorded flows (1990, 2006, 2015) have all occurred within recent memory, inundating a pattern of residential and agricultural land uses that is slowly, but still unevenly, adapting to episodic high flows. It is beyond the scope of this geomorphic assessment to systematically inventory all areas of frequent deep floodwaters, but review of modeled flow depths during a 10-year flood (about 76,000 cfs) provides a useful discrimination of hazard areas (2-year floods extend little outside of established channels; 100-year floods inundate virtually the entire floodplain).

The 10-year flood shows widespread floodplain inundation, particularly in subreaches 6 and 5 but with depths generally less than 3 feet except where associated with past channel positions or avulsion channel networks. Farther upstream in subreach 7, even the 10-year flood is largely confined to the main channel and a few discrete side channels. Subreach 4 hosts the greatest extent of floodplain inundated with 4 or more feet of water, virtually of which are agricultural fields or forest. Shallow floodwaters cover nearly all of the subreach 3 floodplain, but with structures almost entirely located above floodwaters, along the margins of the floodplain on higher terraces or alluvial fans. Flows are more channelized in subreach 2, particularly along Haskell Slough, but more structures are located on the floodplain itself and thus subject to greater potential for inundation than farther upstream. Floodwaters spread out into the multiple relict channels of the Skykomish–Snoqualmie confluence area of subreach 1, but structures are generally set well back from the low-elevation areas of prior river occupation and so avoid significant 10-year inundation.

As presented on the map folio of Appendix B, the areas of deep and fast flow ("DFF") during a 10-year flood are discriminated into High Risk and "Judgment" (i.e., Medium Risk) zones for an adult, as defined by USBR (1988) (Figure 5-4), with flow conditions as modeled by WSE (2020). USBR's "Low Danger Zone" is not shown on the maps, and so the full area of inundation by the 10-year flood is not displayed.

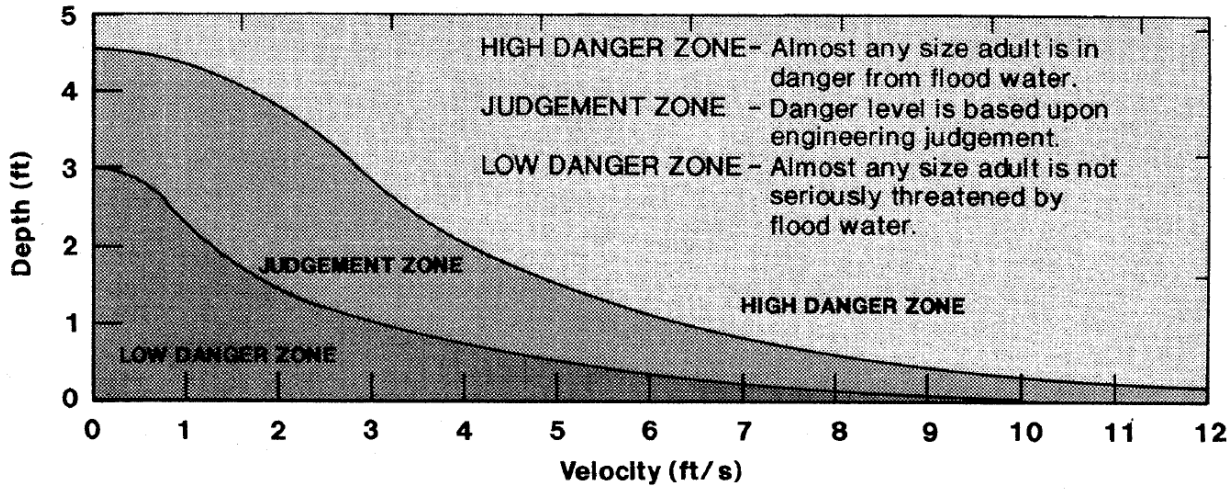


Figure 5-4 Danger zones related to floodwater depth and velocity. The "High" and "Judgment" (I.e., Medium) zones are plotted on the map folio of Appendix B (from USBR 1988, their Figure 5).

5.2.2 Areas of rapid channel migration and future migration risk

As embodied in the designation of channel migration zones (Cardno 2020), channel encroachment into all areas within the area of recognized past channel locations (i.e., the "Historical Migration Zone" of Cardno 2020) should be anticipated over a sufficiently long period of management concern. For shorter planning periods, however, the recent behavior of the river is obviously of greatest relevance. Table 5-1 highlights the areas of rapid, recent channel migration along the Lower Skykomish River over the last three decades. Even within this more limited time frame, however, several localities stand out by virtue of their recent level of activity (Table 5-5). All such areas with at least 20 feet of bank erosion between the 2018

and 2020 airphotos have been identified, with the map folio of Appendix B showing potential areas of future expansion projected over the next two decades at current rates ("Future Migration Risk Areas").

Table 5-5 Localities of greatest channel expansion between 2018 and 2020.

RM	Subreach	Bank	2018–2020 bank erosion, ft	Comments
16.41	6	LB	204	Further migration may be constrained by sharpening bend, but multiple side-channel inlets may be activated by existing or future migration.
14.75	6	LB	143	Recent activation of previously stable bank position.
11.20	4	RB SC	340	Recent acceleration of migration along RB of the RB side channel.
10.49	4	RB SC	118	Significant channel realignment along the RB side channel, with potential to alter future erosion rates along the mainstem LB.
0.45	1	LB	101	Continuation of long-term migration and channel realignment within the confluence zone.

5.2.3 Areas of high avulsion potential and potential consequences

As part of the Channel Migration Zone development (Cardno 2020), all potential avulsion pathways off of the active channels of the Skykomish River were identified and mapped. These pathways were further discriminated, however, by the condition of their blocking berm, highlighting those with the lowest (and, typically, also the narrowest) separation from the modern (2020) channel (see Table 5-2 above; also shown on the map folio of Appendix B as "Avulsion Pathway Zones"). A further discrimination can be made based on the intensity of land-use activities that potentially could be affected should the avulsion pathway be reoccupied, considering only pathways not presently blocked by existing infrastructure. This subset of potentially active channels comprising high-potential *and* high-consequence avulsion pathways falls into four geographical zones as listed in Table 5-6.

In Appendix B, the inlets to the mapped avulsion pathways are marked, and they are discriminated as to their current (2020) condition. Those labeled "Active" are already occupied to some degree by active flow, and their pathway are included in the outline of the 2018 active channel. Those labeled "Eroding" are not presently blocking a mapped active side channel, but erosion along the adjacent channel margins raise concern that the inlet berm blocking the potential avulsion pathway could be removed in the future.

Table 5-6 Avulsion pathway zones with a high potential for future reoccupation and with downstream land uses potentially incompatible with channel reactivation (compare Table 5-4).

Inlet RM	Bank	Notes
Upper subreach 6 pre-1938 channel complex, eroding bend (RM 18.1–17.4)		
17.92	RB	High bank <100 ft wide separates channel from main channel; active bank retreat upstream and aggradation downstream, post-1991; existing structure to southwest
17.89	RB	Active channel with episodic occupation, incipient chute cut-off; existing structure (see RM 17.92 avulsion channel) to northeast
Upper subreach 6 1938 active channel zone, eroding bend (RM 17.75–17.35)		
17.73	LB	Very low berm; substantial bank retreat post-1991, but minimal post-2018; pathway adjacent to low-elevation residential development along 157th Place SE
Mid-subreach 6 1938 mainstem channel, South Slough inlet zone, eroding bend (RM 16.7–16.1)		
16.62	LB	Active inlet within 2018 active channel. Outside of bend, rapid bank retreat post-1991
16.49	LB	Part of South Slough complex across low floodplain; location makes occupation somewhat less likely than other adjacent channels
16.33	LB	Part of South Slough complex across low floodplain; outside of bend, rapid bank retreat post-1991; log jam at inlet but unlikely to preclude occupation
16.21	LB	Part of South Slough complex across low floodplain; outside of bend, rapid bank retreat post-1991
Mid-subreach 5 1938 side channels, Shinglebolt–Sky River Slough inlets		
14.79	LB	Broad, 200-ft long high berm in 2018, eroded by 2020 on outside of bend; low open channel beyond
14.10	LB SC	Alternate side channel for pathway @ RM 14.79
14.07	LB	Straight reach, low berm with narrow inlet channel, bank retreat post-1991 but minimal post-2018; behind flood fencing

5.2.4 Flood-protection infrastructure at risk

Within this geomorphic assessment, hazards have been assessed under current conditions, which include about five miles of existing revetments, levees, and other forms of bank armoring and flood protection along the Lower Skykomish River. These facilities will not all provide equivalent levels of protection, however, in a future large flood event. In acknowledgment that *any* loss of protection could have significant geomorphic (and, also, economic) consequences, a companion set of "infrastructure assessments" is being prepared in parallel with this geomorphic report to explore those potential consequences (key facilities tabulated in Table 5-7, with their associated areas at risk should facility failure ever occur shown on the map folio of Appendix B).

Table 5-7 Flood-protection infrastructure judged to be at potential risk of future failure, with relative hazard ratings based on facility condition and downstream land uses.

Facility	Location	Hazard rating (from Cardno 2021)
Startup levee	RM 19.0–17.7 (right bank)	Low
Startup training levee	RM 17.7–17.1	Medium
Groeneveld levee 1 and 311th Plug levee	RM 14.0–13.8 (left bank)	Medium
Groeneveld levee 2 (Groeneveld Dam)	RM 13.2–13.1 (right floodplain)	Low
Sultan training levee	RM 13.45–13.20 (right bank)	Very High
Fern Bluff levee	RM 8.0–7.8 (right bank)	Low
Haskell Slough levee	RM 5.94–5.78 (left bank)	Medium (as of repairs completed November 2020)
Park Place levee	Rm 3.6–3.2 (right floodplain)	Low
Hansen levee	RM 2.9–2.4 (right bank)	Low
Schlamp levee	RM 1.7–1.5 (left bank)	Medium

Two facilities stand out by virtue of both their present condition and the potential geomorphic response to any future loss of function. The Sultan training levee (RM 13.45–13.20) presently limits the reoccupation of a cut-off chute that extends from RM 13.3 to 12.0 (right bank) and was last a dynamic side channel as of the 1965 airphoto. It has continued to receive modest flow inputs from inlets at RMs 13.17 and 12.95, but these inlets are both along straight river segments and/or inside bends with stable-to-aggrading channel margins, and so they are unlikely to expand given a continuation of existing conditions. Were the levee to fail at RM 13.3, however, a third, now-blocked inlet would likely see dramatically increased flow into the side channel, with the potential for a several-fold increase in the current side-channel width to a size commensurate with that not experienced here since 1965.

The inlet to Haskell Slough (RM 5.94–5.78) is presently blocked by a 1930s-era post-and-rock levee that is experiencing both structural degradation and overtopping in large floods (and has been repaired on an emergency basis by Snohomish County in 2020). Consequences of any future intended or unintentional reoccupation of Haskell Slough would depend on the magnitude of reintroduced flows. The inlet lies on the outside of a gentle outside bend with relatively modest, recent (1991–2018) erosion of the adjacent bank at rates of about 30 feet per decade. There is no evidence that the full flow of the Skykomish River has ever followed this pathway in the last century (or more), even pre-blockage. However, the topographic form of the slough is generally more than 150 feet wide and is encroached by several crossings that could be impacted by any significant increase in flows. Existing structures are generally set back 100 feet (or more) from the slough channel's top-of-bank, and so even moderate reintroduction of flows would be unlikely to create a risk of structure-threatening bank erosion. Imposing any limit on future flows through the slough, however, will require some form of facility at the inlet, since unconstrained geomorphic evolution along this part of the river would likely allow future flows to significantly exceed the capacity of the present-day channel.

A third facility, the Startup training levee, has a somewhat indeterminate area of risk in the event of failure (see the circular area depicted in Appendix B, page 6, immediately west of the town of Startup), given the geographical limits of the hydraulic modeling and limited topographic relief in this area. It is not considered to have a high potential for failure, and so this uncertainty is not judged to be significant at this time.

Two other facilities merit comment. The Startup levee and Startup training levee were both evaluated by the US Army Corps of Engineers, who produced 2020 Routine Inspection Reports for both. Review of these reports, together with the Cardno river raft-based low-flow visual inspection of the Startup training levee on September 2, 2020, were used to determine the area of risk and to assign relative level of risk for these facilities. The Startup training levee has a robust riprap revetment and toe, but since the mainstem river channel currently impacts the levee at nearly 90 degrees, it was deemed a moderate risk; based on current conditions, the Startup levee was assigned low risk. Were a breach of the Startup levee to occur, however, the dambreak flood wave would flow northwest through the BNSF railroad bridge over the Wallace River at Startup (River Mile 17.5) and dissipate radially until the depth and velocity were no longer hazardous. This semi-circular area of hazard, as shown in the map folio of Appendix B, represents an estimate of the potential zone of risk.

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6 Summary of Key Findings

1. The Lower Skykomish River expresses three distinct geomorphic zones, with particular relevance to both the river's past history and its potential opportunities for restoration:
   - Subreaches 7, 6, and 5, commonly referenced as "the braided reach," is characterized by a broad floodplain with multiple active and recently active channels, particularly downstream of RM 19.6 as the river emerges from its confinement by high terraces and the BNSF Railroad revetement along the City of Gold Bar.
   - Subreaches 4, 3, and 2 express progressively greater confinement between bounding terraces, with few active side channels and much less overall sinuosity than farther upstream.
   - Subreach 1 is almost deltaic in form, with a broad low-relief floodplain and multiple abandoned scroll bars testifying to a long history of interaction with the Snoqualmie River.
2. Across all reaches, the zones of channel activity and floodplain occupation have generally shrunk in area over the last century. Changes in flood regime or sediment input cannot explain this temporal trend; most likely, early 20th-century gravel mining and early/mid-century construction of levees and revetments have systemically dampened the river's response to high flows.
3. The dynamic nature of the river in subreaches 7–5 downstream of RM 19.6, and the relative absence of artificial constraints, render these six miles of river the most promising for ecological restoration and/or protection, consistent with the prior synoptic assessment of restoration potential along the tributaries of the entire Snohomish Basin (Tulalip Tribes, n.d.).
4. These same subreaches also host the localities at greatest risk from future channel avulsions. Although land uses are generally less intense in this upper part of the study area, the dynamic character of the river and its potential for extremely rapid changes in flow direction and magnitude require careful consideration of land uses throughout the floodplain that are incompatible with deep, fast-flowing water.
5. Active channel migration along many unarmored reaches demonstrate the river's continuing capacity both to create new aquatic habitats and to pose ongoing risk to human activity and infrastructure on the adjacent floodplain. Such zones of both opportunity and hazard commonly coincide, making the need to balance these potentially competing needs particularly important along the Lower Skykomish River.

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