AN OVERVIEW OF THE GEOLOGY AND GEOMORPHOLOGY OF THE SNOQUALMIE RIVER WATERSHED

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April 2004

King County
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Water and Land Resources Division
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Table of Contents

1.0 Introduction 1

1.1. Purpose and Scope of this Report 1
1.2. Overview of the Snoqualmie River Watershed 1

2.0 Factors Controlling Fluvial Geomorphology 4

3.0 Bedrock Geology in the Snoqualmie River Watershed 7

4.0 Glacial History 12

4.1. Glacial Deposits 12
4.2. Glacial Erosion 21
4.3. Drainage Patterns During Most Recent Glaciations 21

5.0 Post-Glacial History 27

5.1. Incision of Post-Glacial Drainage System 27
5.2. Active Fluvial Geomorphic Processes in the Snoqualmie Valley 27
5.2.1. Valley Scale 27
5.2.2. Reach Scale 29
5.2.3. Local Processes 34
5.3. Post-Glacial Deposits 48
5.3.1. Alluvial Valley Fill 48
5.3.2. Alluvial Fan Deposits 50
5.3.3. Landslide Deposits 50

6.0 Description of Specific Reaches and Tributaries 51

6.1. Upper Snoqualmie Basin 51
6.1.1. North Fork Snoqualmie River 51
6.1.2. Middle Fork Snoqualmie River 54
6.1.3. South Fork Snoqualmie River 54
6.1.4. Upper Mainstem 57
6.2. Snoqualmie Falls 58
6.3. Lower Snoqualmie Watershed 58
6.3.1. Lower Mainstem 58
6.3.2. Tributaries to Lower Mainstem 63

7.0 Human Influence on Geomorphic Processes 75

7.1. Logging 75
7.2. Levee and Revetment Construction 77
7.3. Dams 77
7.4. Floodplain Clearing and Drainage 77
7.5. Land Development 78

8.0 Suggested Further Investigations 81

9.0 Conclusion 82

10.0 References 83

11.0 Glossary 86

List of Figures

Figure 1: Vicinity Map 2
Figure 2: Factors that Control the Size and Shape of Stream Channels 6
Figure 3: Generalized Geologic Map of the Snoqualmie Watershed 8
Figure 4: Geologic Map of the Snoqualmie Watershed 9
Figure 5: Cirque Lakes in the North Fork Snoqualmie Watershed 14
Figure 6: Glacially Sculpted Till Surfaces 19
Figure 7: Alpental, a Glacially Sculpted Alpine Valley 23
Figure 8: Channelways in the Headwater Area of Griffin Creek 24
Figure 9: Major Glacial Outwash Channels Draining Glacial Lake Snoqualmie 25
Figure 10: Alluvial Fans in the Taylor River Drainage 28
Figure 11: Common Landslide Types in the Snoqualmie Watershed 40
Figure 12: Lidar Image of the Tolt Valley Showing Massive Slumps 43
Figure 13: Step Jam 45
Figure 14: Bar-Apex Jam 46
Figure 15: Meander Jam 47
Figure 16: Wetlands Developed in Glacially Sculpted Depressions 49
Figure 17: Subbasin Boundaries in the Snoqualmie Watershed 52
Figure 18: Longitudinal Profiles of the Snoqualmie River and its Major Tributaries 53
Figure 19: Levees and Revetments along the Snoqualmie River and its Tributaries 55
Figure 20: Lidar Image Showing Relict Channels Near the Three Forks Confluence 56
Figure 21: Streambed Texture along the Mainstem Snoqualmie River 60
Figure 22: Historical Cross Sections of the Lower Raging River 66
Figure 23: Patterson Creek in a Glacial Meltwater Channel 67
Figure 24: Shaded Relief Drawing Showing the Original and Current Alignment of Lower Cherry Creek 73
Figure 25: Comparison of Historical and Modern Maps Showing Draining of the Snoqualmie River Floodplain 79

List of Photos

Photo 1: Transitional Beds Exposed in Tuck Creek 15
Photo 2: Vashon Advance Outwash near Carnation 16
Photo 3: Vashon Till Near Duvall 17
Photo 4: Ice-Contact Stratified Drift Near Duvall 18
Photo 5: Vashon Recessional Outwash Near Duvall 20
Photo 6: Glacial Striations Near Stossel Creek 22
Photo 7: Step-Pool Morphology on a Tributary to the Middle Fork Snoqualmie 31
Photo 8: A Cascade on Peoples Creek 32
Photo 9: A Step-Pool Reach on Tuck Creek 33
Photo 10: Plain Bed Morphology on the Raging River 36
Photo 11: A Braided Reach on the Tolt River 37
Photo 12: Pool-Riffle Morphology on the Middle Fork Snoqualmie River 38
Photo 13: Ripple Marks in the Mainstem Snoqualmie River Near Duvall 39
Photo 14: Rock Fall on the West Face of Mt. Si 42
Photo 15: A Boulder Derived from Rock Fall on the West Face of Mt. Si 42
Photo 16: A Step Jam on Peoples Creek 45
Photo 17: A Bar-Apex Jam on the North Fork Tolt River 46

Photo 18: A Meander Jam on the North Fork Tolt River 47
Photo 19: Natural Levees along the Snoqualmie River Near Duvall..... 61
Photo 20: South Fork Tolt Dam and Reservoir 69
Photo 21: A Bedrock Canyon on the North Fork Tolt River 70
Photo 22: Logging Clearcuts in the Tolt Drainage 76
Photo 23: Severe Erosion on the West Wall of the Snoqualmie Valley Near Carnation..... 80

List of Tables

Table 1: ..... Summary of the Channel Classification System Proposed by Montgomery and Buffington (1997)..... 30

1.0 Introduction

1.1. Purpose and Scope of this Report

The purpose of this report is to summarize current knowledge on the geology and geomorphology of the Snoqualmie River Watershed, with emphasis on how this information relates to land use and aquatic habitat issues in the watershed. This report was prepared in support of the Snohomish River Basin Salmon Conservation Plan. The report is specifically intended to:

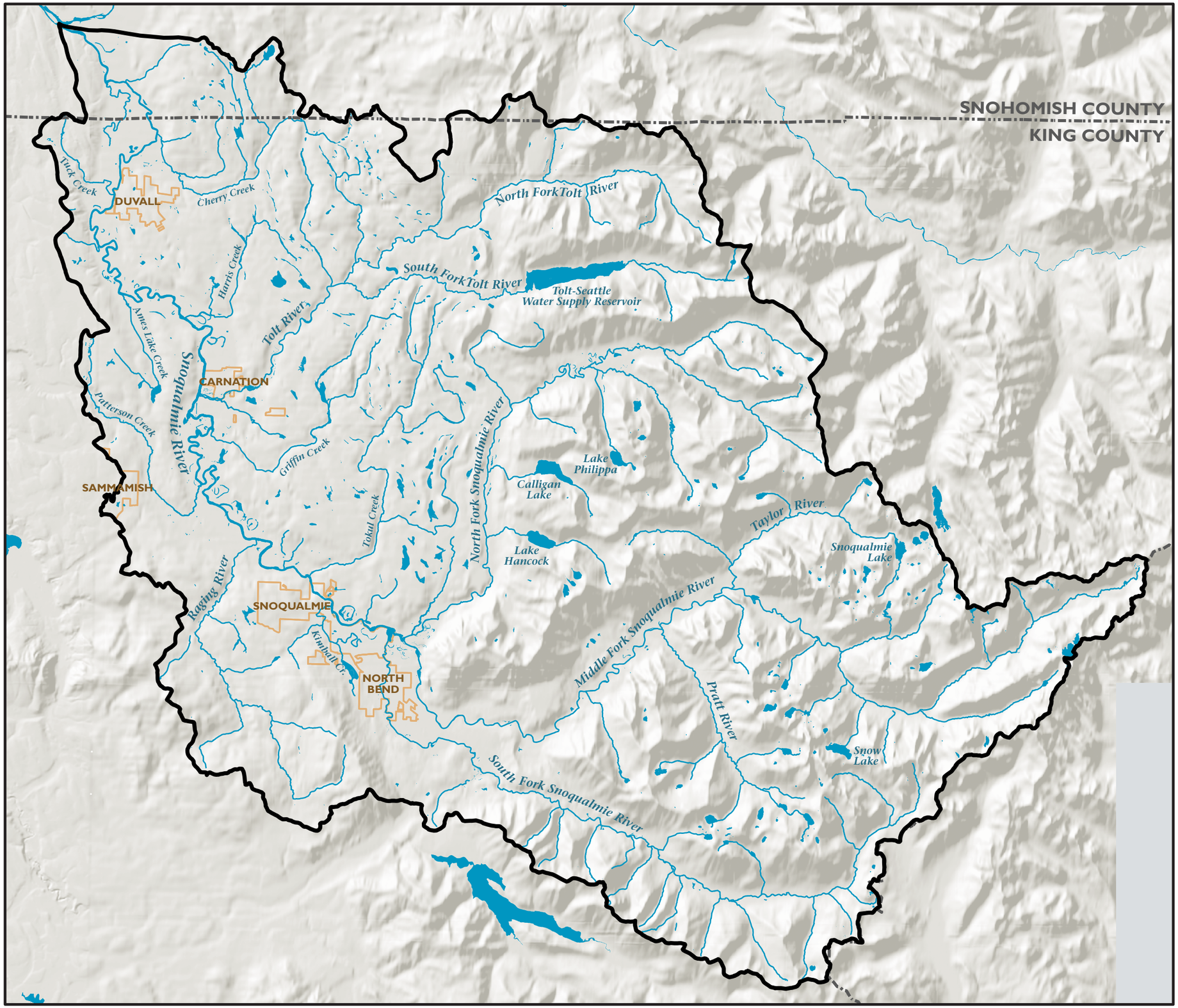
- Characterize the geologic history and active geomorphic processes in the Snoqualmie River valley;
- Provide a basis for assessing the role of active geomorphic processes in development of high-quality aquatic and riparian habitat;
- Identify circumstances in the watershed where geologic conditions or fluvial geomorphic processes pose a risk to existing or likely future land use; and
- Identify gaps in our present understanding of geologic conditions or geomorphic processes in the Snoqualmie River watershed as they relate to development of aquatic habitat or hazards to land use.

1.2. Overview of the Snoqualmie River Watershed

The Snoqualmie River originates as west-flowing drainage from the central Washington Cascade Mountains. Its various headwater tributaries join to form the mainstem river in the vicinity of the city of North Bend. The mainstem river continues flowing westward over Snoqualmie Falls. Below the Falls the river turns north into a glacially sculpted trough that it follows for 40 miles (64 kilometers) until reaching the confluence with the Skykomish River near the city of Monroe (Figure 1). The combined discharge of the Snoqualmie and Skykomish Rivers flows generally westward as the Snohomish River, reaching Puget Sound at the city of Everett.

The Snoqualmie River has a drainage area of 693 square miles (1794 square kilometers) at its confluence with the Skykomish River, and ranges in elevation from 7492 feet (2283 meters) on Mount Hinman on the Cascade Crest to 15 feet (4.6 meters) at the confluence with the Skykomish. Rainfall in the watershed ranges from 40 inches (1000 millimeters) in the lower valley up to 160 inches (4000 millimeters) near the Cascade Crest. At Carnation (the lowest gauged station in the watershed), the two-year discharge is 30,200 cubic feet per second (855 cubic meters per second); the one-hundred-year discharge is 79,700 cubic feet per second (2257 cubic meters per second). The Carnation gauge includes flow from 87 percent of the watershed area.

The Snoqualmie River watershed includes parts of two major physiographic provinces, the Puget Lowland and the Middle Cascade Range (Buffington et al., 2003). For the purposes of this report, these will be referred to as the “lowland” and “alpine” portions of the watershed.



SNOQUALMIE WATERSHED

Figure 1

VICINITY MAP

Watershed Boundary

Stream

Lake/River

Incorporated Areas

N

0 2 4 Miles

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In the lowland portion of the watershed, geology and topography are primarily products of repeated continental glaciations. In the alpine area, much of the ground surface (except in valley bottoms) is directly underlain by bedrock, and the topography is primarily a result of erosion and sediment deposition by repeated alpine glaciations.

Land use in the Snoqualmie watershed is strongly related to elevation and topography. The highest portions of the watershed in the high Cascades are set aside in the Alpine Lakes Wilderness Area; 112 square miles (289 square kilometers) or 16 percent of the watershed are inside the Wilderness Area boundaries. With a few minor deviations, all of the land in the watershed starting in Township 10 and east to the Cascade Crest (including the wilderness area) is in the Mount Baker-Snoqualmie National Forest. The lower slopes of the Cascades and the foothills areas are in mixed public/private ownership in many locations, preserving the “checkerboard” ownership pattern reflecting early railroad and public school land grants. Much of this land is in forest production. The alluvial valley bottoms have a long and continuing history of agriculture. Urban land uses and densities characterize communities in the watershed, including the cities of Snoqualmie, North Bend, Carnation, and Duvall, and the unincorporated towns of Preston and Fall City. Suburban residential development is the dominant land use in the portion of the watershed west of the lower valley and is expanding in other areas of low to moderate elevation.

2.0 Factors Controlling Fluvial Geomorphology

The physical characteristics of a stream channel result from the integration of a number of controlling factors. The relationship between these factors is complex and in some cases only qualitatively understood. In spite of this uncertainty, it is critical to base stream management actions (whether for habitat enhancement or hazard mitigation) on the clearest possible understanding of active geomorphic processes and relationships in the action area.

Precipitation falling on the landscape is the ultimate source of stream flow. Rain (or snowmelt) can flow a variety of paths between falling to earth and reaching a stream channel. Precipitation that falls on a typical undisturbed Pacific Northwest hillside soaks directly into the ground without flowing on the surface at all. This water, moving as shallow or deep groundwater, flows downslope and emerges as seeps or springs that feed stream flow. This process attenuates discharge from intense precipitation events, decreasing peak flows and increasing stream base flow. In contrast, precipitation that falls on impervious surface (bedrock or asphalt) flows quickly downslope into the receiving channel. This results in much higher peak discharges and lower base flow. From a hydrologic standpoint, the most significant change that occurs with land development is a dramatic increase in the percent area of impervious surface in the developed area.

Upon reaching a channel, water has potential energy related to its height above sea level. This potential energy is converted to kinetic energy as the water flows downhill. This kinetic energy provides the motive force for all fluvial geomorphic processes. The amount of energy available to do fluvial geomorphic work in a watershed is therefore a function of the ground surface topography (elevation), and the climate (precipitation). Geomorphic processes are continually flattening the landscape through erosion. The rate and pattern of this erosion is strongly controlled by the underlying geology. Tectonic movement raises areas of the earth's crust. The interplay between erosion and tectonic uplift ultimately controls the development of watershed topography.

The climate, topography, and substrate geology control the rate and routing of water flow from the land surface and through the drainage network. These drainage characteristics constitute the watershed hydrology. The hydrology in turn is one of the primary factors directly controlling fluvial processes. The character of the vegetative cover is largely controlled by the climate, and to a lesser extent by the substrate geology, hydrology, and topography. Vegetation in turn exerts a strong influence on hydrology by creating soil conditions that allow rapid infiltration. Live vegetation and organic detritus play an important role in many geomorphic processes. Canopy cover and organic soil horizons reduce surface erosion. Roots reinforce hillslopes and streambanks. In most environments the presence of vegetation inherently introduces fire to the landscape. Large woody debris (LWD) can strongly influence stream channel morphology.

Human actions alter geomorphic process in numerous and often dramatic ways. Human innovation creates new ways of modifying natural processes on an almost daily basis. Construction of roads and buildings changes natural runoff patterns. Grading, resource

extraction, and dam construction directly alter topography. Logging, agriculture, and landscaping can dramatically change vegetation patterns over large areas of the landscape. The web of interrelated factors that control fluvial geomorphic processes is summarized in Figure 2.

The physical character of a stream channel (including elements like cross-sectional shape, longitudinal profile, streambed texture, and sinuosity) is a result of integration of the controlling factors described above. Changing any of these factors will generally result in a change in the channel character. It is, however, often difficult to predict exactly how a channel will respond to a given change. For example, if a landslide suddenly introduces a large volume of sediment into a river, the channel may show a variety of responses. It may widen and become shallower, the streambed texture may become finer, the channel may become braided, and the sinuosity may increase. Fluvial geomorphic relationships suggest that any (or all) of these are possible channel responses to increased sediment supply. Predicting which of these responses is most likely and to what extent each will manifest itself is a substantially indeterminate problem. Much of the habitat degradation now seen in Pacific Northwest streams is a result of unanticipated responses to human alteration of the contributing watershed.

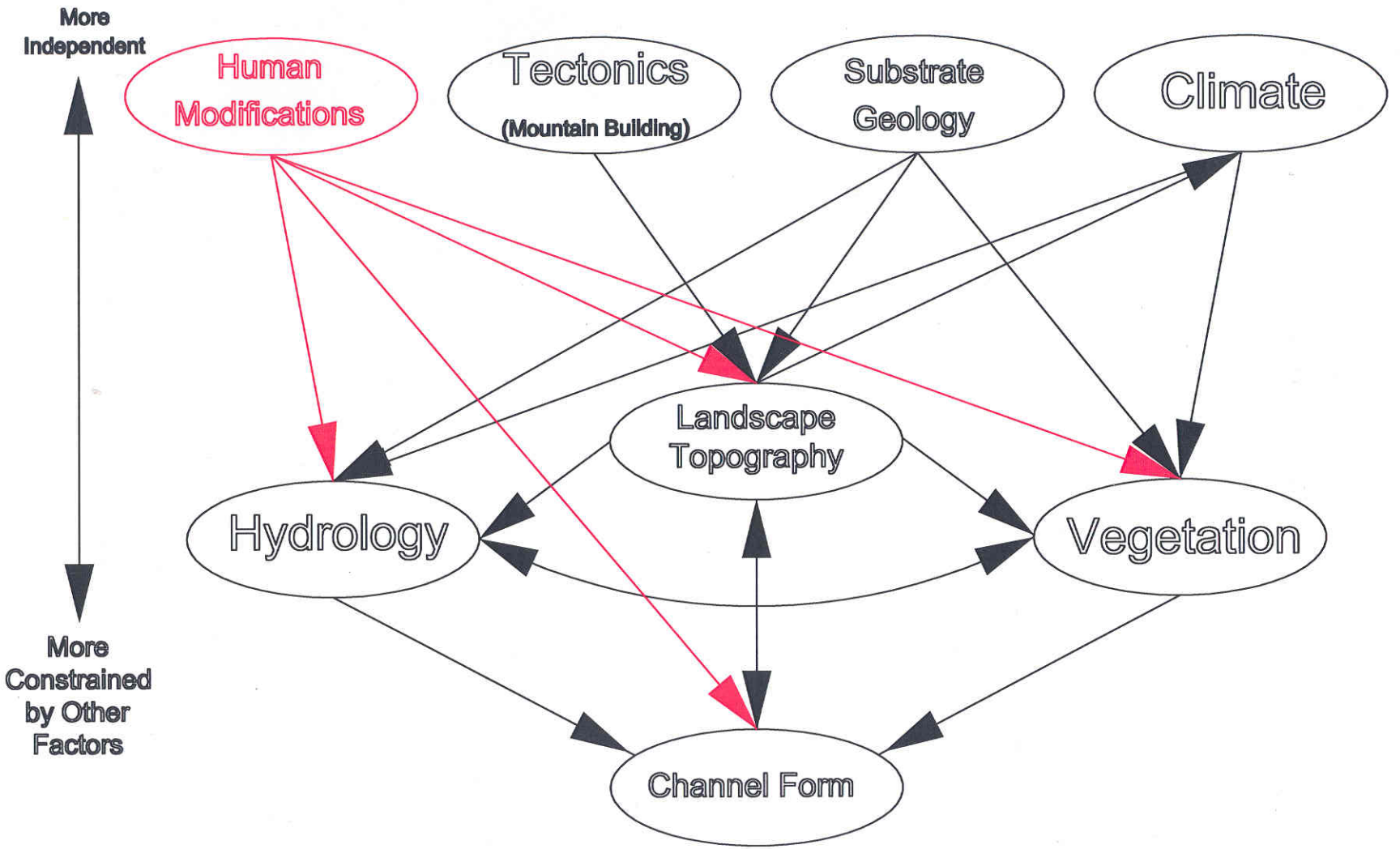


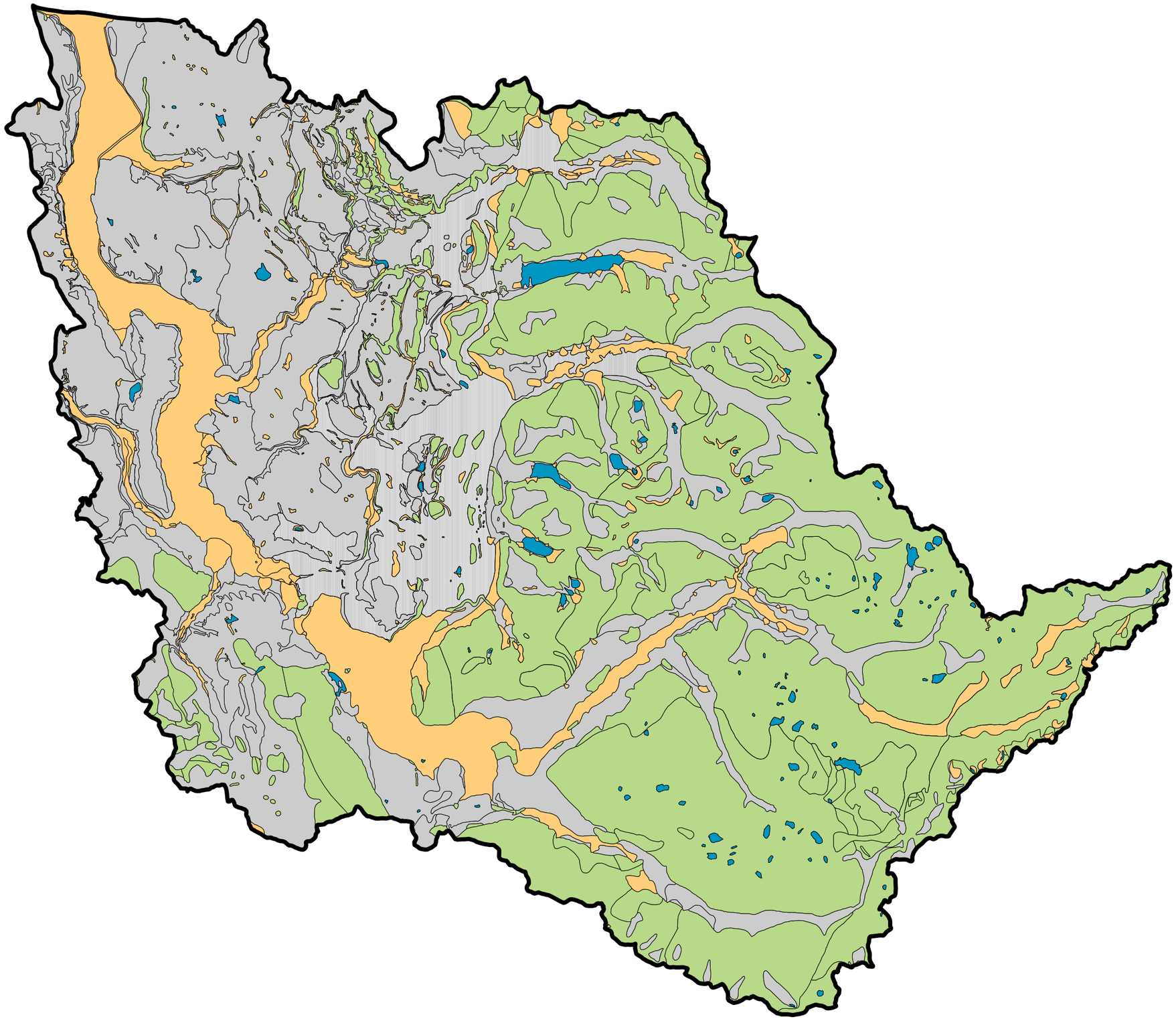
Figure 2: Factors that control the size and shape of stream channels

3.0 Bedrock Geology in the Snoqualmie River Watershed

Most of the headwater channels draining from the Cascade Mountains are underlain at shallow depth by bedrock (Figure 3). There are three primary bedrock assemblages exposed in the Snoqualmie River watershed (Tabor et al., 1993; Tabor et al., 2000) that form three irregular bands roughly paralleling the topographic expression of the Cascade Range. Along the core of the Cascade Range, intrusive igneous rocks of Tertiary age are extensively exposed. These consist primarily of light gray granite rocks. Most of the High Cascade peaks in the Snoqualmie River watershed are composed of these erosion-resistant rocks. These rocks are identified as unit Tst and Tsg on Figure 4, the geologic map of the Snoqualmie River watershed.

Generally bordering these tertiary rocks to the west is a band of pre-Tertiary rocks known as the western mélange belt. Mélange, a French word for mixture or medley, refers to a heterogeneous assemblage of rocks that has been intensively sheared and deformed. This deformation occurs as these rocks are “scraped” off the top surface of a crustal plate that is being subducted. These rocks record a period in between the early Cretaceous and middle Eocene (100 to 40 million years ago) when the study area was on the western edge of the North American continent (Tabor et al., 2000). These rocks consist of marine sedimentary and igneous rocks that have been subject to relatively low-grade metamorphic modification. For example, Mount Si is a large block of erosion resistant metamorphosed gabbro of the mélange unit. Rocks of this mélange unit are generally more friable and more readily weathered than the plutonic rocks to the east. The mélange rocks are identified as Tkwa on Figure 4.

Bordering the mélange rocks to the west are Eocene Age volcanic and sedimentary rocks 45 to 37 million years ago) (Tabor et al., 1993). Weathered andesite of this unit is widely exposed in the foothills and lower, western peaks of the Cascades. Snoqualmie Falls are located where the Snoqualmie River flows over an outcrop of these rocks. These rocks are identified as Trr and Tmp on Figure 4.



SNOQUALMIE WATERSHED

Figure 3

GENERALIZED GEOLOGY

Watershed Boundary

Recent

Glacial

Bedrock

Water

N

0 2 4 Miles

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SNOQUALMIE WATERSHED

Figure 4

GEOLOGY

Watershed Boundary

See next two pages for detailed geology legend

N

0 2 4 Miles

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SNOQUALMIE WATERSHED

Figure 4 (continued)

GEOLOGIC MAP DESCRIPTIONS

Quaternary

POSTGLACIAL DEPOSITS

gl **Glaciers and permanent snowfields**

m **Modified land (Holocene)**—Sand and gravel as fill or extensively graded natural deposits that obscure or substantially alter the original geologic deposit.

Wetland deposits (Holocene)—Peat and alluvium, poorly drained and intermittently wet annually. Grades into unit **Qyal** (unlabeled for map clarity)

Qf **Alluvial fan deposits (Holocene)**—Boulders, cobbles, and sand deposited in lobate form where streams emerge from confining valleys and reduced gradients cause sediment loads to be deposited

Qyal **Younger alluvium (Holocene)**—Moderately sorted deposits of cobble gravel, pebbly sand, and sandy silt along major rivers and stream channels; some fan material similar to that included in unit Qt. Includes deposits mapped on certain earlier geologic maps as Qa or Qal

Qoal **Older alluvium (Holocene and Pleistocene)**—Texturally equivalent to unit Qyal but deposits lie at higher elevations and typically have greater relief than younger alluvium. Deposits may be late recessional outwash but cannot be unequivocally assigned a pre-Holocene origin

Landslide deposits (Holocene and Pleistocene)— Divided into:

Qls **Landslide**—Diamicton of angular clasts of bedrock and surficial deposits derived from upslope. Includes areas of irregular, hummocky topography. Equivalent to deposits mapped on some earlier geologic maps as Ql and includes deposits mapped on the Skykomish River 1:100,000 quadrangle as incipient blockslides (Qib)

Qmw **Mass-wastage deposits (Holocene and Pleistocene)**— Colluvium, soil, or landslide debris with indistinct morphology, mapped where sufficiently continuous and thick to obscure underlying material. Unit is gradational with landslide deposits (Qls) and alluvium (Qyal). Numerous unmapped areas of mass-wastage deposits occur elsewhere on map in equivalent topographic and geologic settings but are too discontinuous or too poorly exposed to show at map scale. Deposits, both mapped and unmapped, include abundant discrete landslides 1-10 m in lateral extent

Qt **Talus deposits (Holocene and Pleistocene)**—Nonsorted angular boulder gravel to boulder diamicton. Where low on hillslopes may be gradational with alluvium (Qyal). At higher altitudes, includes small rock-avalanche deposits as well as some Holocene moraine, rock glacier, and protalus rampart deposits that lack characteristic morphology. Generally unvegetated

GLACIAL AND NONGLACIAL DEPOSITS

Qgt **Glacial and talus deposits (Holocene and Pleistocene)**— Material similar to unit Qt but having distinct morainal form that indicates deposition at terminus of small glacier or permanent snowfield. Includes deposits in mountainous areas mapped on certain previous quadrangles as Qgp or Qagt

Qag **Alpine glacial deposits (Pleistocene)**—Glacial deposits ranging from boulder till in uplands and upvalley to gravel or sand outwash on broad valley floors. On valley sides and uplands includes areas veneered with drift but also includes bedrock, alluvial fans, colluvium, or talus deposits. On valley floors also includes small fans, bogs, and modern stream alluvium. Areas of thin, sparse drift not distinguished from bedrock. In headward reaches of high alpine streams, grades into unit Qgt

Deposits of Vashon stade of Fraser glaciation of Armstrong and others (1965) of Cordilleran ice sheet (Pleistocene)— Divided into:

Qvr **Recessional outwash deposits**—Stratified sand and gravel, moderately to well sorted, and well-bedded silty sand to silty clay deposited in proglacial and ice-marginal environments. Locally subdivided into sand-dominated deposits (Qvrs), gravel-dominated deposits (Qvrg), silt-dominated lowland lacustrine deposits (Qvrl), and ice-marginal glaciolacustrine deposits (Qvrm) present in many of the lower mountain valleys consisting of bedded silt and clay containing sand lenses and sparse dropstones. Equivalent to units Qsr, Qpo, Qpv, and Qpd on early 1:24,000-scale maps of western King County. Recessional outwash deposits are subdivided on the basis of location and altitude into multiple stages of deposition indicated by subscripts, with I being the oldest and V being the youngest

Qvi **Ice-contact deposits**—Stratified water-laid sand and gravel, silt, clay, and minor till with abrupt grain-size changes and collapse features indicating deposition adjacent to active or stagnant ice. Locally divided into ice-contact morainal embankments (Qvim) (Booth, 1986), present as valley plugs at the mouths of many of the lower mountain valleys. Subscripts follow the same convention as for unit Qvr and indicate probable ice-marginal zones during deposition of corresponding recessional outwash deposit. Equivalent to units Qik, Qit, Qiv, and Qis on early 1:24,000-scale maps of western King County

Qvt **Till**—Compact diamict containing subrounded to well-rounded clasts, glacially transported and deposited. Includes minor stratified fluvial deposits. Generally forms an undulating surface a few meters to a few tens of meters thick. In ice-marginal areas and where covered by thin layer of recessional outwash, contact with recessional-outwash or ice-contact deposits (Qvr or Qvi) is gradational. Equivalent to unit Qgt on early 1:24,000-scale maps of western King County

Qva **Advance outwash deposits**—Well-bedded sand and gravel deposited by streams and rivers issuing from the front of the advancing ice sheet. Generally unoxidized; almost devoid of silt or clay, except near the base of the unit and as discontinuous beds. Equivalent to unit Qsa on early 1:24,000-scale maps of western King County, and also includes deposits previously mapped as Colvos Sand (Qc) on Vashon Island

Qvu **Vashon Drift, undivided**

Qtb **Transitional beds (Pleistocene)**—Laminated to massive silt, clayey silt, and silty clay deposited in lowland or proglacial lakes. Marks transition from nonglacial to glacial time; unequivocal evidence for glacial or nonglacial origin rarely present

Qpf **Sedimentary deposits of pre-Fraser glaciation age (Pleistocene)**—Weakly oxidized to moderately oxidized sand and gravel, lacustrine sediments containing local peat layers, and moderately oxidized to strongly oxidized diamict composed of silty matrix and rounded gravel clasts. Individual layers too small to display at map scale. Evidence of strong in-place weathering throughout exposures, includes oxidation, weathering rinds, and clay-mineral replacement. On Vashon Island, locally subdivided into fine-grained deposits (Qpff), coarse-grained deposits (Qpfc), and mixed-grain-size deposits (Qpfm); also locally subdivided across map area into deposits of inferred nonglacial origin (Qpfn) on the basis of organic material and abundant volcanic sediment of presumed Mt. Rainier origin

Qob **Olympia beds (Pleistocene)**—Locally oxidized, stratified fluvial sand and gravel, deposited immediately prior to the Vashon glaciation during interglacial conditions. Gravel lithologies are almost exclusively volcanic

Qdu **Drift, undivided (Pleistocene)**

Qtu **Till, undivided (Pleistocene)**

Open Water

Continued on next page

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SNOQUALMIE WATERSHED

Figure 4 (continued)

GEOLOGIC MAP DESCRIPTIONS

Pre-Quaternary

BEDROCK

ROCKS WEST OF THE STRAIGHT CREEK FAULT

Ts **Sandstone (Miocene and Oligocene)**—Sandstone, conglomerate, mudstone, and shale. Mapped by Minard (1985) in the north part of the map area and Mullineaux (1965) in the south part of the map area in similar stratigraphic positions; however, these separate areas of outcrops may not be strictly correlative

Rocks of Snoqualmie batholith—Divided into:

Tsg **Tonalite and granodiorite, southern phase (Miocene)**—Hornblende-biotite granodiorite and tonalite, medium grained, mostly equigranular with hypidiomorphic texture, locally with clinopyroxene. Southern phase of pluton is overall slightly more K-feldspar rich than northern phase (Tst) and mostly light colored and coarsely jointed. Equivalent to unit Tsgs on the Snoqualmie Pass 1:100,000 quadrangle and also includes rocks mapped there as fine-grained monzonite (Tsgf) and mafic diorite and gabbro (Tsm)

Tst **Tonalite and granodiorite, northern phase (Miocene and Oligocene)**—Biotite-hornblende granodiorite and tonalite, medium grained, mostly equigranular, with hypidiomorphic texture; locally with clinopyroxene. Mostly light-colored, coarsely jointed rock. Includes rocks on the Snoqualmie Pass and Skykomish River 1:100,000 quadrangles mapped as granodiorite and granite (Tsgg or Tsg) and breccia (Tsb)

Ti **Intrusive rocks (Miocene, Oligocene, and Eocene)**—Includes rocks on the Snoqualmie Pass and Skykomish River 1:100,000 quadrangles mapped as pyroxene andesite porphyry (Tip), tonalite (Tit), dacite porphyry (Tidp), altered porphyry (Tiap), and the Fuller Mountain plug (Tfm)

Tv **Volcanic rocks (Oligocene)**—Mostly dacite and minor andesite and rhyolite in breccia, tuffs, ash-flow tuffs, and rare flows. Mapped on Garfield Mountain and near east edge of map, where unit may include some rocks belonging to underlying Naches Formation

Tig **Index batholith (Oligocene)**—Mostly biotite-hornblende and hornblende-biotite granodiorite and tonalite but locally ranges from quartz diorite and quartz monzonite to rare granite. Includes rocks mapped on the Skykomish River 1:100,000 quadrangle as granodiorite of the Goblin Creek stock (Tigg) and granodiorite and granite of the Sunday Creek stock (Tigs)

To **Ohanapecosh Formation (Oligocene)**—Well-bedded, multicolored, volcanic- and crystal-lithic andesitic tuff and breccia and volcaniclastic sedimentary rocks alternating with massive tuff breccia, subordinate basalt and andesite flows and flow breccia, and minor rhyolite tuff. Characteristically light green, but also pistachio-green, light-bluish green, purplish, black, brown, or white. Includes rocks mapped on the Snoqualmie Pass 1:100,000 quadrangle as the tuff member of Lake Keechelus (Tolk)

gb **Gabbro (age uncertain)**—On Money Creek, hypersthene-clinopyroxene gabbro, medium-grained, subophitic to locally uralitic. Commonly layered containing well-aligned calcic plagioclase. On Palmer Mountain, medium-grained uralitic gabbro and quartz gabbro composed of tightly packed calcic plagioclase with uralite patches and uralite pseudomorphous after subophitic pyroxene(?). On Middle Fork of Snoqualmie River, heterogeneous, uralitized pyroxene gabbro to mafic biotite-hornblende tonalite; strongly thermally metamorphosed

Tn **Naches Formation (early Oligocene? to middle Eocene)**—Rhyolite, andesite, and basalt flows, tuff, and breccia with interbeds of feldspathic subquartzose sandstone and siltstone as well as rare coal. Interbedded sedimentary rocks are white to light-tan or gray, coarse-grained micaceous feldspathic sandstones, exhibiting crossbeds and graded bedding, and black argillite and laminated siltstone. Includes rocks mapped on the Skykomish River and Snoqualmie Pass 1:100,000 quadrangles as volcanic rocks and minor sandstone (Tnv), Mount Catherine rhyolite member (Tnmc), rhyolite (Tnr), feldspathic sandstone and volcanic rocks (Tns), glomeroporphyritic basalt (Tnbg), Guye sedimentary member (Tng), and basalt (Tnb)

Tmp **Volcanic rocks of Mount Persis (late? Eocene)**—Mostly gray to black, locally reddish, porphyritic two-pyroxene andesite lava and breccia. Phenocrysts and glomerocrysts of plagioclase, clinopyroxene, hypersthene, and opaque minerals in devitrified groundmass. Mostly highly altered. Massive to blocky joints. Flow layering obscure. Includes rocks mapped on the Skykomish River and Snoqualmie Pass 1:100,000 quadrangles as hornblende dacite breccia (Tphb) and pyroxene andesite porphyry (Tpp)

Tp **Puget Group (late and middle Eocene)**—Micaceous feldspathic subquartzose sandstone, siltstone, claystone, and coal. Tabular beds of sandstone are massive to cross bedded and occasionally exhibit channel cut-and-fill structures. Light to dark siltstones form poor outcrops, are commonly thinly laminated, and contain organic matter. Coal beds are as thick as 5 m

Locally divided into:

Tpt **Tukwila Formation (late and middle Eocene)**—Volcanic breccia, conglomerate, sandstone, and flows with intercalated feldspathic sandstone and impure coal beds. Tuff and breccia with clasts of porphyritic andesite and dacite and polymictic volcanic conglomerate appear to predominate, but flow rocks (in part sills or dikes?) form resistant layers

Tptm **Tiger Mountain Formation (middle Eocene)**—Light-colored, medium-grained, micaceous feldspathic subquartzose sandstone interbedded with siltstone, minor pebble conglomerate, and coal beds

Trr **Raging River Formation (middle Eocene)**—Shallow marine and alluvial volcanic-rich sandstone, siltstone, shale, and minor conglomerate. Locally highly fossiliferous; plant remains common. Minor conglomerate predominantly consists of volcanic clasts but locally contains chert pebbles

ROCKS EAST OF THE STRAIGHT CREEK FAULT

Swauk Formation (middle and early Eocene)—Divided into:

Tss **Sandstone**—Predominantly feldspathic subquartzose sandstone and conglomerate, fluviatile, light-colored, medium-grained, and minor interbeds of siltstone and shale. Thin to very thick bedded, poorly sorted, locally crossbedded, and with lesser interbeds of carbonaceous siltstone and shale, pebbly sandstone, and conglomerate. Includes rocks subdivided on the Skykomish River and Snoqualmie Pass 1:100,000 quadrangles as Silver Pass Volcanic Member (Tssp)

ROCKS SOUTHWEST OF DARRINGTON-DEVILS MOUNTAIN FAULT ZONE

Rocks of the western melange belt (middle Eocene and [or] Late Cretaceous)—Divided into:

TKwa **Argillite and graywacke**—Well-bedded marine sandstone and argillite and subordinate pervasively sheared argillite. Purplish, reddish, gray and black, fine- to coarse-grained and pebbly lithofeldspathic and volcanolithic subquartzose sandstone interbedded with black argillite. Sandstone commonly is mixed type containing clasts of mostly plagioclase, chert, volcanic rocks, and quartz, as well as sandstone, siltstone, phyllite, biotite, muscovite, and epidote. Locally cut by greenstone (metadiabase) dikes. Also includes rocks mapped on the Skykomish River and Snoqualmie Pass 1:100,000 quadrangles as chert (TKwc); marble (TKwm); slate, phyllite, and semischist (TKws); and potassium-feldspar-bearing sandstone (TKwk)

TKwv **Metavolcanic rocks**—Greenstone, greenstone breccia, and metadiabase, with minor metagabbro, argillite, and sandstone; includes boudinaged metaquartz porphyry dikes. Also includes rocks mapped on the Skykomish River and Snoqualmie Pass 1:100,000 quadrangles as phyllitic greenstone (TKwp)

TKwg **Metagabbro**—Massive to foliated, fine- to medium-grained metagabbro. Many outcrops sheared at all scales. Metamorphic minerals include uralite, chlorite, sphene, and calcite. Unit includes rare hornblende metatonalite and well-recrystallized amphibolite. Also includes rocks mapped on the Skykomish River and Snoqualmie Pass 1:100,000 quadrangles as ultramafic rocks (TKwu), metatonalite (Tkwt), and metadiabase (TKwd)

Rocks of the eastern melange belt (middle Eocene and (or) Late Cretaceous)—Divided into:

TKe **Chert, mafic metavolcanic rock, amphibolite, argillite, graywacke, and marble**—Highly deformed chert and medium- to fine-grained banded purplish biotite quartzite (metachert) intimately mixed with tectonized greenstone, greenstone breccia, and marble. Includes hornblende schist and muscovite, biotite quartz schist and dikes of metadiorite and metagabbro. Original sedimentary and volcanic textures largely obscured by penetrative deformation and static thermal metamorphism. Also includes rocks mapped on the Skykomish River and Snoqualmie Pass 1:100,000 quadrangles as marble (TKem), chert and metachert (TKec), migmatitic gneiss (TKeg), matadiabase (TKed), metatonalite (TKet), and ultramafic rocks (TKeu)

TKev **Mafic metavolcanic rocks, chert, argillite, and graywacke**—Greenstone and greenschist (metabasalt and meta-andesite), with minor metagraywacke, chert-rich metagrit, and metaconglomerate, mostly massive and rarely bedded. Also includes rocks mapped on the Snoqualmie Pass 1:100,000 quadrangle as marble (TKem)

Easton Metamorphic Suite (Early Cretaceous)—Divided into:

Ked **Darrington Phyllite**—Mostly black to gray graphitic chlorite-sericite-quartz phyllite with minor albite (?), and opaque minerals. Phyllite is commonly highly crinkled and contains quartz segregation lenses and veins that are commonly ptygmatically folded. Phyllite predominates and is locally interbedded with greenschist and blueschist

King County
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Water and Land Resources Division

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4.0 Glacial History

The Snoqualmie River watershed has been subject to two distinctly separate (although substantially contemporaneous) types of glacial activity. Continental glaciers originating in the highlands of the Canadian Coast Range and Vancouver Island merge and flow south forming the Puget lobe of the Cordilleran Ice Sheet. The Cordilleran Ice Sheet has advanced and retreated multiple times during the Pleistocene Era (between two million and ten thousand years ago). The most recent of these advances has been named the Vashon stade of the Fraser glaciation. This continental glacial advance filled the Puget Lowland from the Cascade Mountains to the Olympic Mountains, and extended south as far as the vicinity of the present-day city of Olympia. It reached its maximum extent approximately 14,000 years before present (bp). In the vicinity of the Snoqualmie River watershed, continental glacial ice reached an elevation of 2400 to 3300 feet (750 to 990 meters) on the Cascade Mountains (Thorson, 1979). Sediments deposited by continental glacial advances underlie most of the ground surface in the Snoqualmie River watershed west of the Cascade foothills.

The climatic conditions that lead to growth of continental glaciers also caused mountain, or alpine glaciers to develop and expand. Alpine glaciers from the high Cascades extended down mountain valleys to the Cascade foothills. The most recent major alpine glaciation was the Evans Creek stade of the Fraser glaciation. This advance reached a maximum approximately 20,000 years bp, and these glaciers had retreated significantly by the time of the Vashon continental maximum 6000 years later. In the Snoqualmie watershed, major alpine glaciers developed in the valleys of each of the three forks of the Snoqualmie River, both forks of the Tolt River, and in many of the tributaries to these rivers. Most of the Alpine lakes in the Snoqualmie watershed are cirque lakes, scoured by glacial erosion at the heads of these alpine glaciers (Figure 5). Reconstruction of the alpine glacier profile indicates that the maximum ice thickness in the Middle Fork Snoqualmie Valley was 2100 feet (645 meters) (Williams, 1971). Sediment deposited by the subsequent Vashon advance into the Puget Lowland covered the down-valley deposits of the Evans Creek alpine advance. For that reason, glacial deposits marking the maximum down-valley extent of these alpine glaciers are not exposed to the modern ground surface.

4.1. Glacial Deposits

Over the course of a glacial advance and retreat, a variety of sediments is deposited in and near the glacier. Many of these distinct glacial deposits are present in the Snoqualmie watershed. Their extent and geometry provide a rich record of glacial history. The properties of these deposits strongly influence modern geomorphic processes in the watershed.

Transitional beds: When the Puget lobe of the Cordilleran Ice Sheet advanced into the Puget Lowland, the lobe blocked drainage from the Puget Lowland to the Strait of Juan de Fuca. With blockage of sea-level drainage to the north, a freshwater proglacial lake formed in the Puget Lowland and rose until it spilled south into the Chehalis Valley. The earliest sediments deposited during a glacial advance into the Puget Lowland are lake-bottom

sediments deposited in this proglacial lake. These deposits are typically horizontally laminated silts and clays (Photo 1). They are referred to as transitional beds because they mark the transition from non-glacial to glacial conditions. At a given point in the Puget Lowland, transitional beds are the first, and therefore stratigraphically the lowest sediments marking a glacial sequence. Transitional beds are identified as Qtb on Figure 4.

Advance outwash: Glacial outwash is fluvial sediment deposited by streams flowing from the glacier, or by streams diverted by the glacier. Outwash can be deposited during glacial advance and retreat. Outwash deposits laid down during the glacial advance and subsequently overridden by glacial ice are called advance outwash. As the glacier advanced southward into the ice-dammed lake, a wedge of coarser sediment was deposited immediately in front of the advancing ice. Most of this sediment was probably carried in or on the glacial ice and released by melting at the snout of the glacier. These deposits are generally gravelly sand, crudely stratified, often showing cross-bedding (Photo 2). Advance outwash can contain lenses of coarse, well-sorted sediment, probably indicating relict channels, and lenses of very poorly sorted sediment, probably recording mass-waste events as the sediment was being deposited. In the Puget Lowland, advance outwash is often the thickest unit in the Vashon stratigraphic section, and makes up most of the volume of constructional glacial landscapes (Booth, 1994). Advance outwash is identified as Qva on Figure 4.

Glacial till: Glacial till is a sediment deposited directly at the base of a glacier. In the Puget Lowland, till generally occurs as dense silty, gravelly sand. Gravel clasts in glacial till are typically not in contact, but are supported by the finer-grained matrix (Photo 3). A layer of glacial till a few tens of feet (several meters) thick directly underlies much of the ground surface on the rolling glacial uplands of the lower Snoqualmie Valley. The distinctive streamlined “Art Deco” topography typical of glacially sculpted till uplands is clearly evident in many parts of the lower Snoqualmie Valley (Figure 6). Glacial till is identified as Qvt on Figure 4.

Ice-contact deposits: The lower Snoqualmie Valley is a glacially scoured trough that was occupied by a lobe of ice during late deglaciation. Locally, wedges of sediment accumulated between this ice lobe and the adjacent valley walls. These wedges now form ice-contact or “kame” deposits seen as irregular terraces along the lower valley walls. A kame terrace is especially well-developed and continuous on the east side of the lower valley between Carnation and Fall City. Ice-contact deposits have a heterogeneous texture, but most often are composed of loose to medium dense gravelly silty sand with crude, discontinuous stratification (Photo 4). On Figure 4, ice-contact deposits are labeled Qvi.

Glacial recessional outwash: Recessional outwash is fluvial sediment deposited during the glacial maximum, and during glacial retreat. Recessional outwash is present in relict outwash channels and deltas throughout the Snoqualmie watershed. These deposits are typically stratified gravelly sand and are often mined for sand and gravel (Photo 5). Recessional outwash is identified as Qvr on Figure 4.

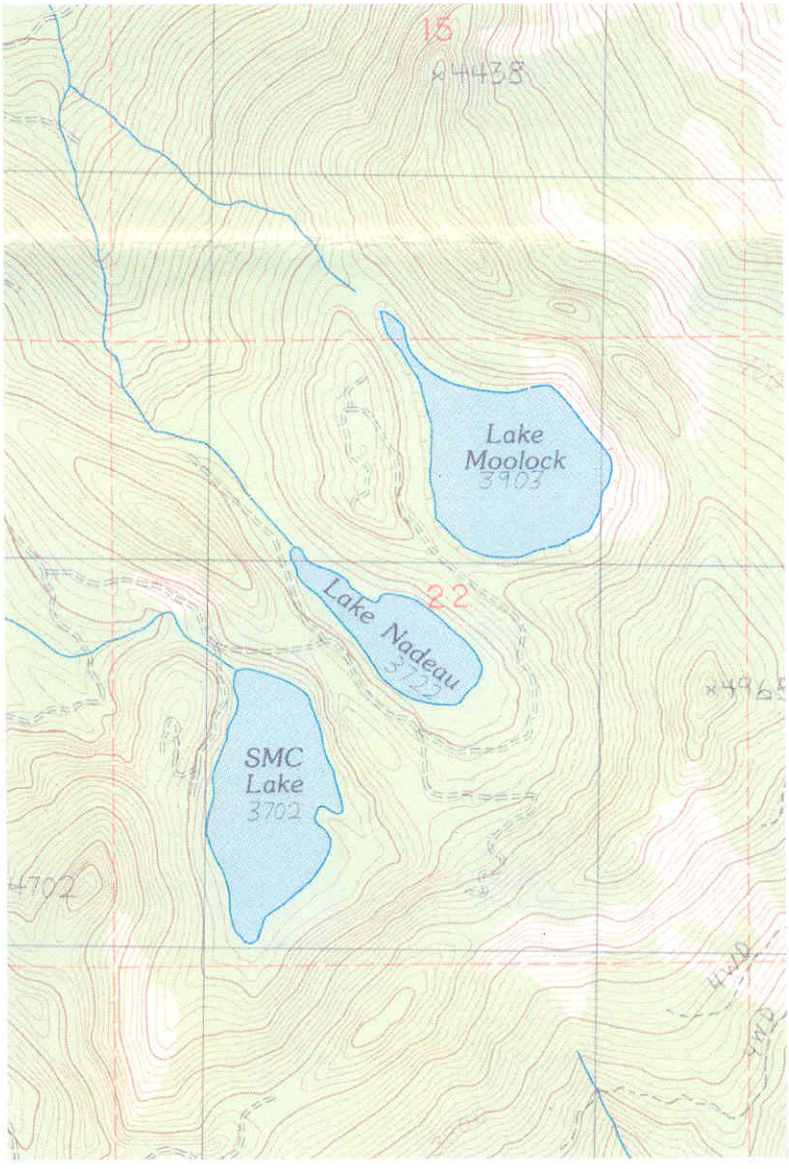


Figure 5: Cirque lakes in the North Fork Snoqualmie Watershed

Photo 1: Transitional beds (Qtb) exposed in Tuck Creek. The outcrop of this unit is associated with widespread landsliding in the Tuck Creek ravine.

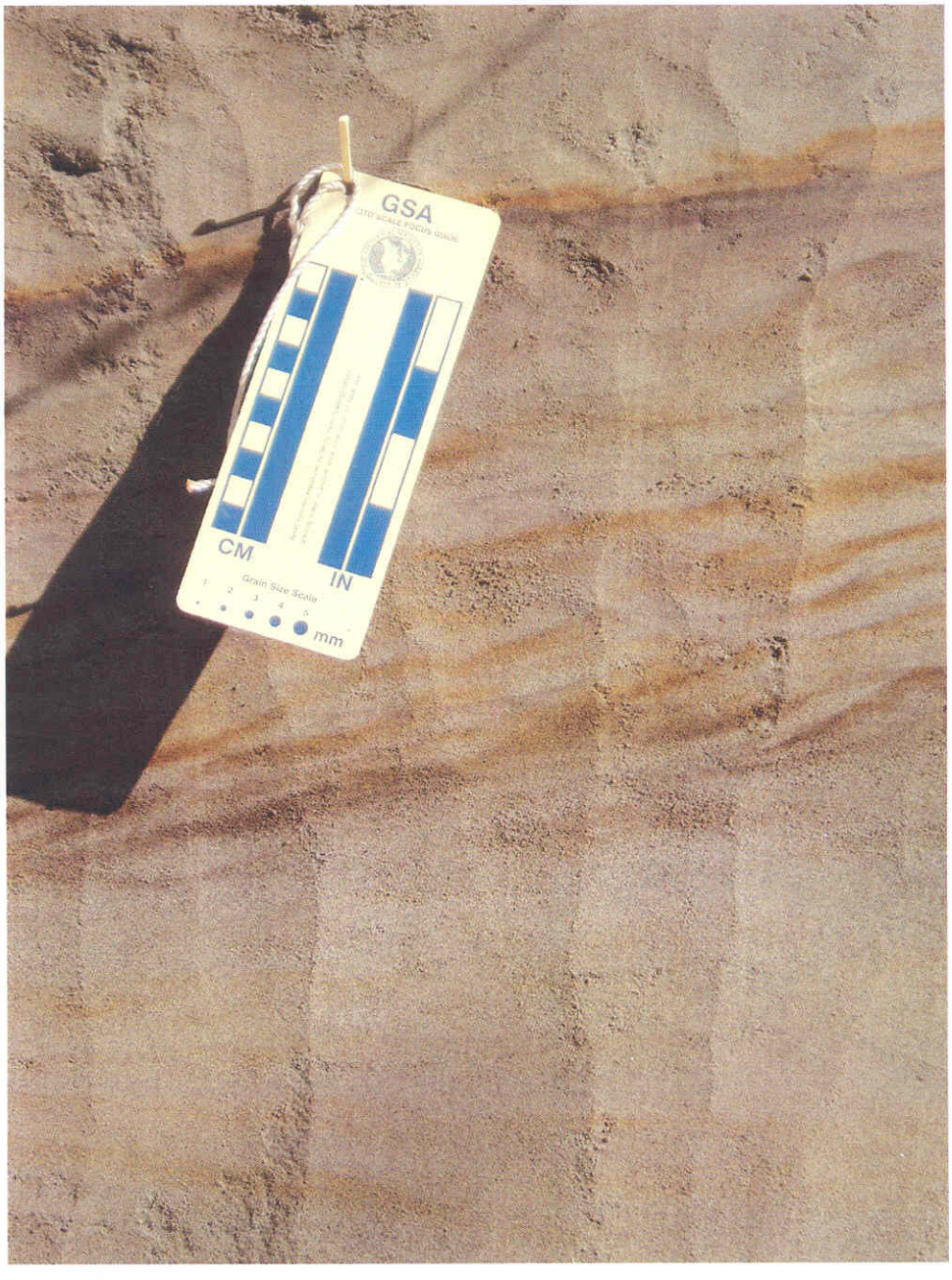


Photo 2: Vashon advance outwash (Qva), in the vicinity of Carnation. Note uniform sandy texture and cross-bedding.

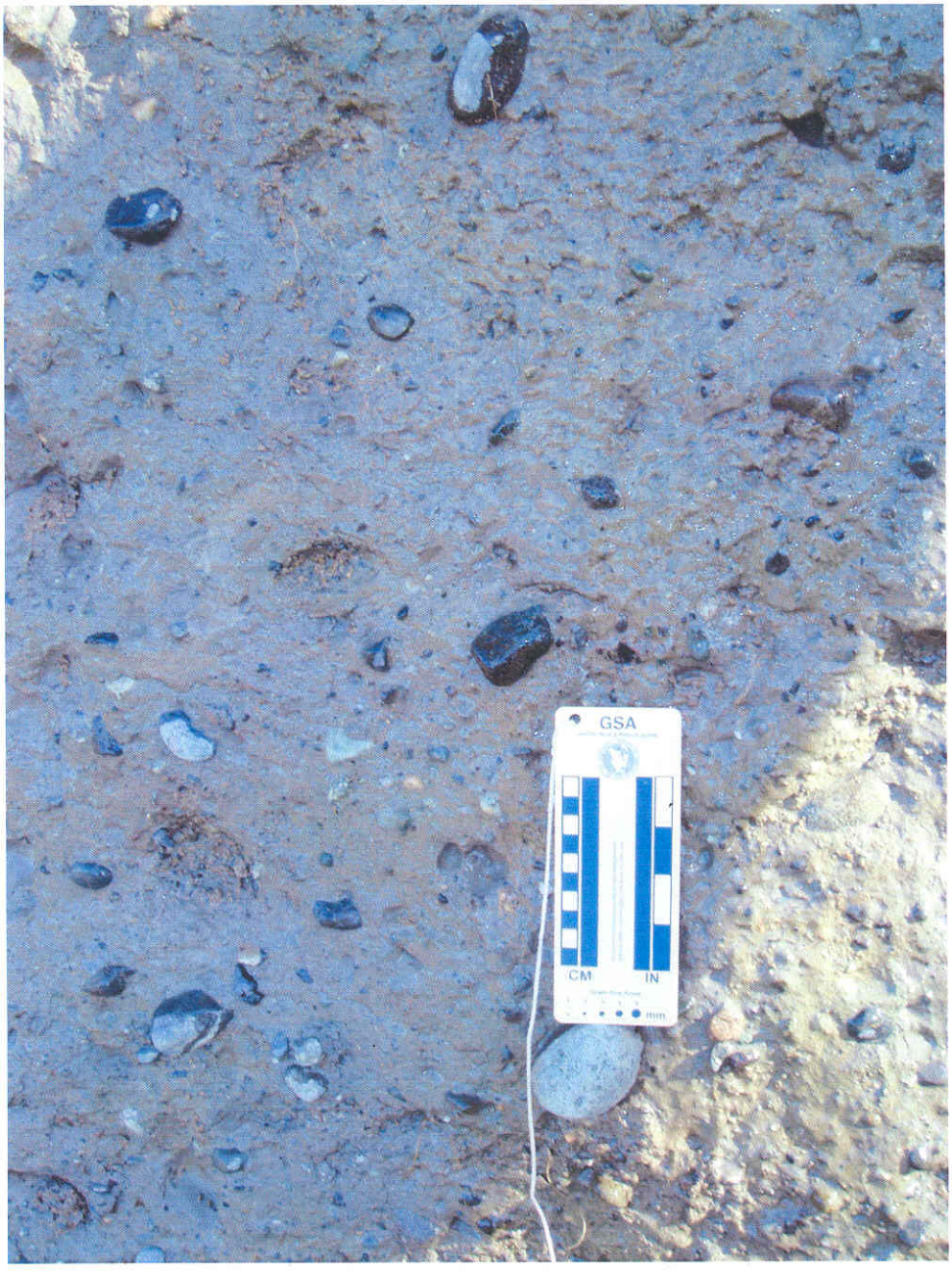
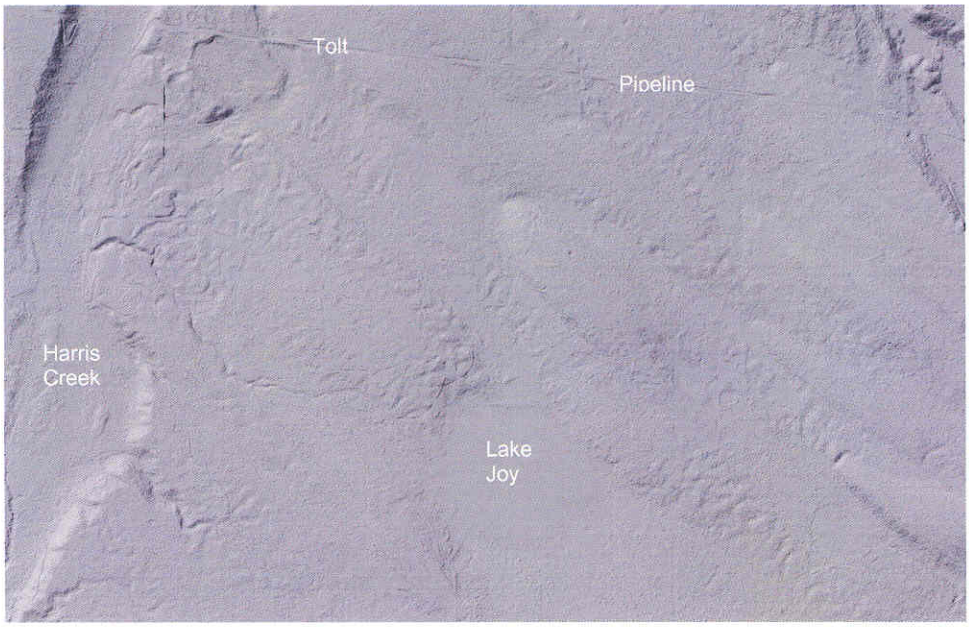
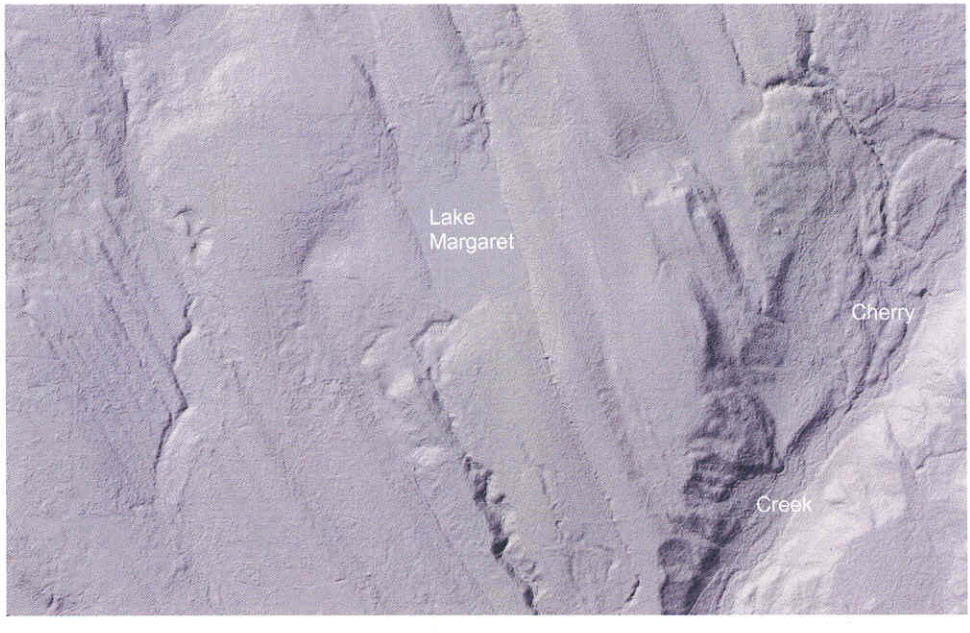


Photo 3: Vashon till (Qvt) exposed in the vicinity of Duvall

Photo 4: Ice-contact stratified drift (Qvi) exposed in an abandoned gravel pit west of Duvall.



6a: Lake Joy area



6b: Lake Margaret area

Figure 6: Lidar images showing glacially sculpted till surface with characteristic "art deco" topography.

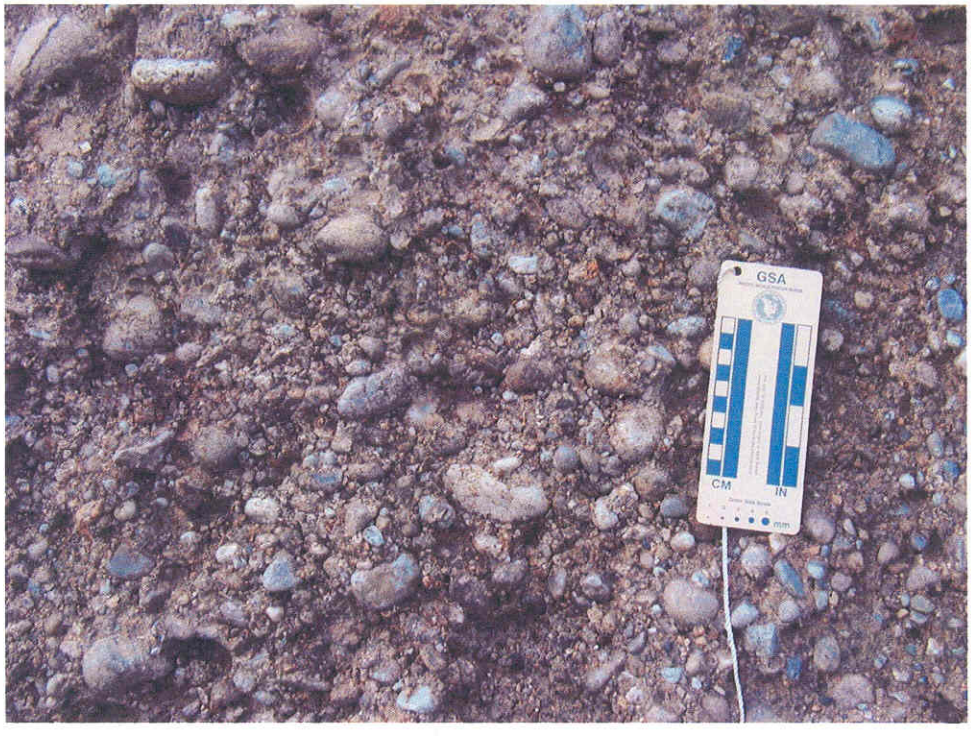


Photo 5: Vashon recessional outwash (Qvr), in the vicinity of Duvall. Note the coarse texture of this deposit. Vashon recessional deposits are the most widely mined source of commercial sand and gravel in the Puget Lowland.

4.2. Glacial Erosion

In addition to depositing large volumes of sediment, the continental ice sheet and associated processes were responsible for extensive erosion in the Puget Lowland. The most obvious mechanism of glacial erosion is ice scour; there is clear evidence of ice scour in the Snoqualmie Valley. Photo 6 shows well-developed glacial striations on a bedrock exposure near Stossel Creek. These striations are a direct product of erosion by sliding glacier ice. The effects of ice scour are also evident in the numerous cirque lakes (Figure 5) and glacially carved valleys (Figure 7) in the Cascade Mountains.

However, the bulk of glacial erosion was not due to ice scour but was rather erosion by water flowing in meltwater channels underneath the active glacier (Booth and Hallet, 1993). Such subglacial fluvial erosion is responsible for excavation of the large north-south trending troughs that dominate Puget Lowland topography. Puget Sound, Lake Washington, and Lake Sammamish occupy such troughs; the lower Snoqualmie Valley is the easternmost of these major troughs.

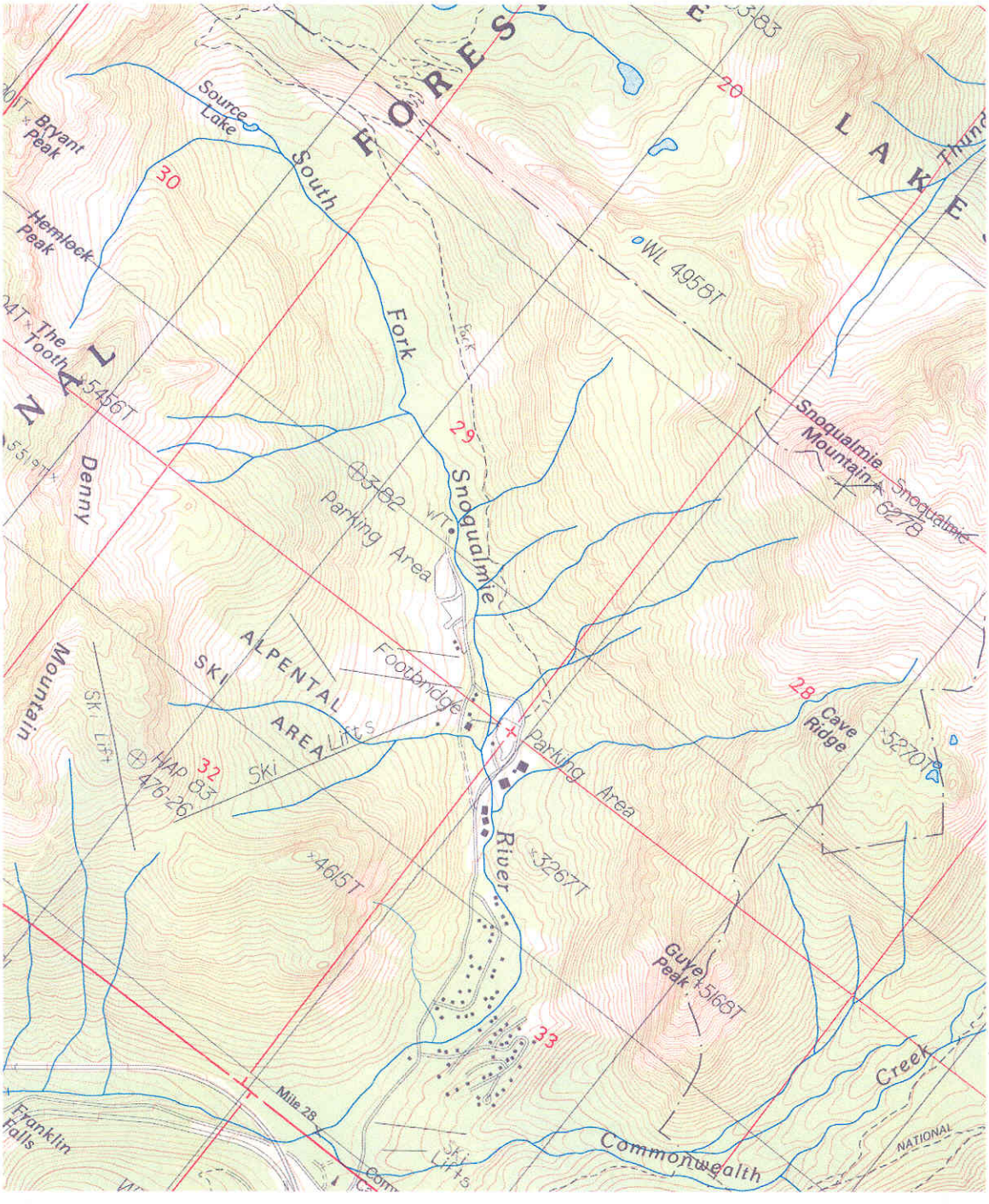
In addition to scouring these large troughs, erosion by subglacial meltwater streams is responsible for eroding a network of smaller channels that are prominent topographic features in the area east of the Lower Snoqualmie Valley and west of the Cascade Mountains. These distinctive features, termed “channelways” by Booth (1990), are steep-sided and often eroded into bedrock. The longitudinal profile along the center of these features is typically quite flat and often has reaches with adverse gradient. As a result, many of these channelways contain wetlands or open water lakes. Many of the modern streams draining this portion of the Snoqualmie watershed occupy portions of these channelways. Figure 8 shows a series of these channelways now occupied by Tokul Creek and its tributaries.

4.3. Drainage Patterns During Most Recent Glaciations

When the Puget lobe of the Cordilleran ice sheet reached its maximum lateral extent in the Puget Lowland, it also reached its highest elevation on the flanks of the Cascade Range. The glacier blocked preglacial drainage courses which flowed northwest from the Snoqualmie watershed, as they do today. During the ice maximum, meltwater from the glacier as well as streams from the Cascade Range were diverted to the south, along and beneath the margin between the glacier and the Cascade Range. As the glacier retreated from the Snoqualmie watershed, a series of progressively lower drainage divides became exposed, and each one for a time acted as the primary outlet for the Snoqualmie watershed area. Booth (1990) numbered these various outlets in order to simplify correlation between the various outlet locations and the associated outwash deposits. Figure 9 shows the location of each of these drainage channels and their associated drainage interval.

Photo 6: Striations indicating glacial scour of a bedrock outcrop in the Stossel Creek drainage.

Figure 7: Alpental, a Glacially Sculpted Alpine Valley



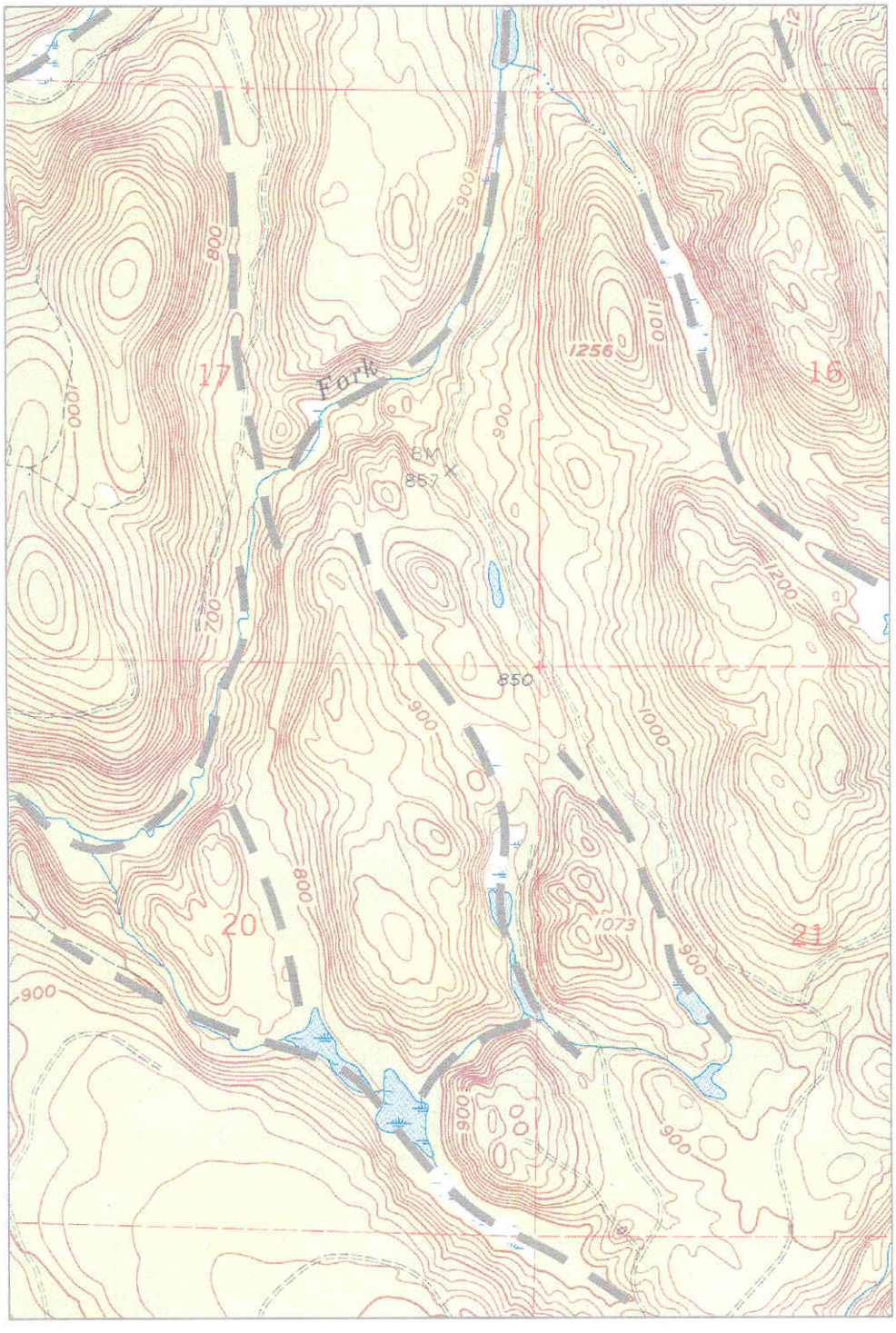
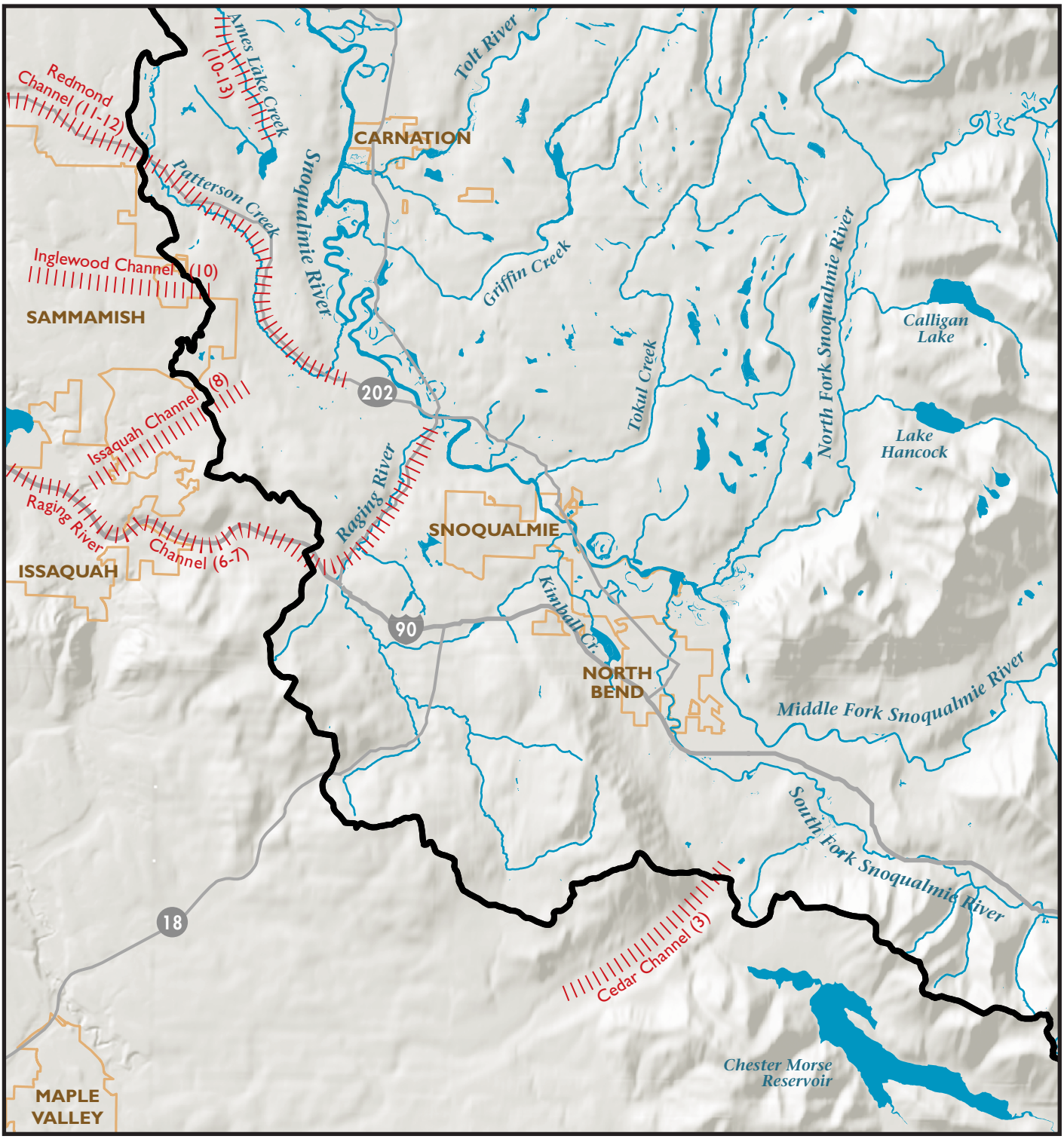


Figure 8: Channelways in the headwater area of Griffin Creek. Gray dashed lines indicate channelway alignments.



SNOQUALMIE WATERSHED

Figure 9

GLACIAL MELTWATER CHANNELS

||| (3) Glacial Meltwater Channels Draining Glacial Lake Snoqualmie*

Watershed Boundary

Stream

Lake/River

Incorporated Areas

* Number refers to vashon recessional interval, per Booth (1990)

N

0 2 4 Miles

April 2004

King County

Department of Natural Resources and Parks
Water and Land Resources Division

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Data Sources: King County Datasets, Hand-drawn Channels
File Name: 0312snoGEOLriverFACIL.ai wgab
Prepared by: King County DNRP/WLR GIS and Visual Communications & Web Unit

5.0 Post-Glacial History

5.1. Incision of Post-Glacial Drainage System

As glaciers retreated from the Puget Lowland, they left a landscape highly susceptible to a variety of non-glacial erosional processes. This susceptibility was due to a number of characteristics of this post-glacial landscape. These include:

- The lack of vegetative cover;
- The lack of surficial organic soil horizons, and
- A drainage network developed to convey subglacial and ice marginal runoff, and thus largely out of equilibrium with the post-glacial topography and climate.

In a geomorphic context, this was a quintessential "youthful" landscape. Under these circumstances, a period of rapid erosion was inevitable. This erosion occurred through a variety of geomorphic processes. Where runoff collected in swales or depressions in the post-glacial topography and discharged over steep slopes, ravines were quickly incised. Alluvial fans formed at the base of these steep slopes (Figure 10). Steep slopes, previously buttressed by glacial ice or undercut by rapid stream incision, failed in massive landslides. Closed depressions at all scales in the glacial landscape filled progressively with water, organic detritus, and sediment, forming lakes, wetlands, and alluvial lowlands. From a geologic standpoint, the Snoqualmie watershed remains a youthful landscape. Most of the area underlain by glacial substrate (Figure 3) has undergone little post-glacial geomorphic modification. Much of the active geomorphic activity in the Snoqualmie watershed consists of equilibrating this recently glacial landscape to the current, temperate, non-glacial conditions.

5.2. Active Fluvial Geomorphic Processes in the Snoqualmie Valley

Modern geomorphic activity is being expressed at a variety of scales across the modern landscape.

5.2.1. Valley Scale

The gross topography of the Snoqualmie watershed is dominated by a series of large valleys, now largely occupied by rivers. In the upper watershed, these valleys are scoured in bedrock, and bedrock is still exposed on the valley walls and intervening ridges. These valleys record a long history of both glacial and non-glacial erosion. The gross geomorphic activity in these valleys consists of gradual erosion of bedrock uplands and transport of the resulting sediment down valley.

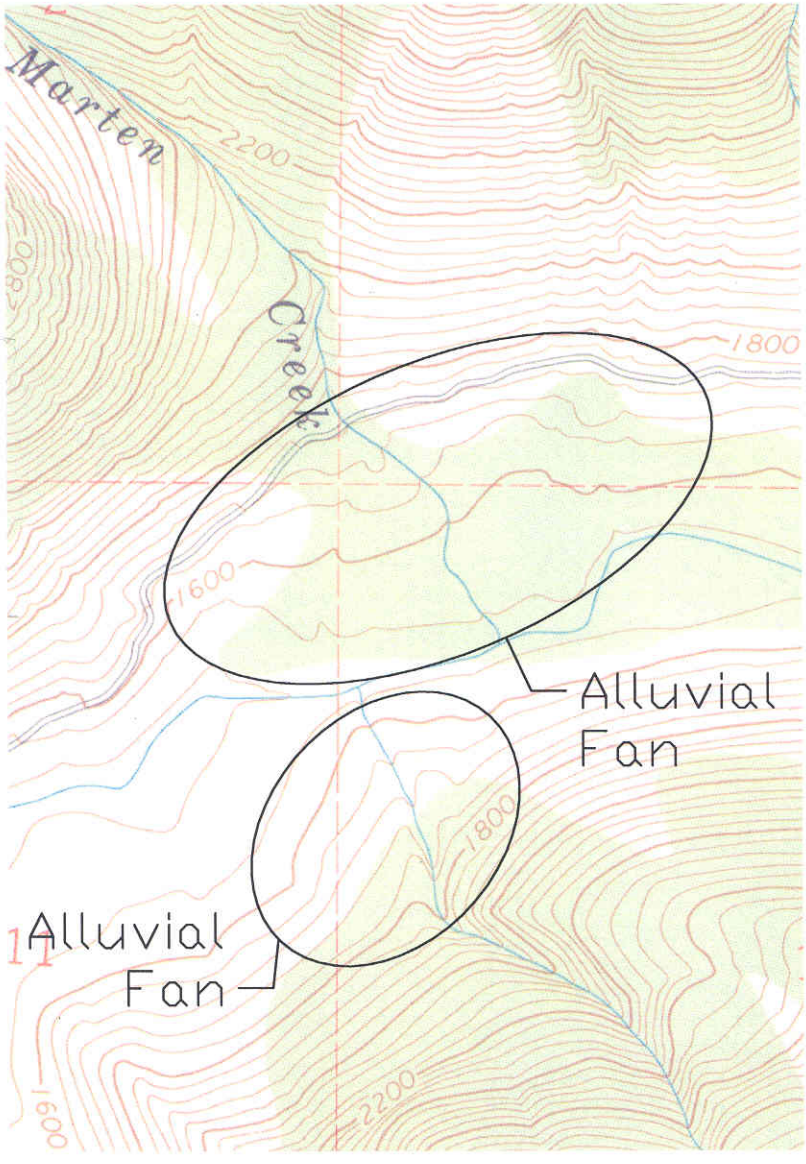


Figure 10. Alluvial Fans at the mouth of Marten Creek and an unnamed tributary on the Taylor River

In the lower portions of the watershed, these valleys are troughs that are largely relict glacial features. The geometry of these troughs was largely a product of subglacial erosion, and the modern rivers occupying these valleys are generally significantly underfit. Examples of these relict valleys include the Snoqualmie Valley from the Three Forks area downstream to Snoqualmie Falls, the lower Snoqualmie mainstem from the vicinity of Fall City downstream to its confluence with the Skykomish River, lower Cherry Creek, and lower Patterson Creek. Immediately following deglaciation, it is likely that lakes were present in portions of these troughs (features presumably similar to Lakes Washington and Sammamish to the west). Any such closed depressions have been subsequently filled with sediment, but the watercourses in these valleys are still incompetent to transport the coarse sediment supplied by tributary streams. As a result, these valleys are gradually but inevitably filling with sediment. Because these watercourses are unable to transport the supplied bedload, they are also subject to being displaced within their broad valleys by alluvial fans from tributary streams. Examples include the Snoqualmie River at the confluence with the Tolt and Raging Rivers, and the confluence of the North Fork and mainstem of Cherry Creek.

5.2.2. Reach Scale

At the reach scale, the various geomorphic processes (Section 2) interact to create channels with distinctive attributes. A variety of classification schemes has been developed to group and summarize the range of channel character. The classification scheme proposed by Montgomery and Buffington (1997) was developed in the Pacific Northwest and encompasses the range of channel types present in the Snoqualmie watershed. The key elements of this classification are summarized in Table 1. In general, the Montgomery and Buffington classification is organized based on a typical down-valley progression of channel types as encountered in mountainous terrain and in a temperate climate.

Table 1: Summary of the Channel Classification System Proposed by Montgomery and Buffington (1997)

	Dune ripple	Pool riffle	Plane bed	Step pool	Cascade	Bedrock	Colluvial
Typical Bed Material	Sand	Gravel	Gravel-Cobble	Cobble-Boulder	Boulder	Rock	Variable
Dominant Roughness Elements	Sinuosity, bedforms (dunes, ripples, bars), grains, banks	Bedforms (bars, pools), grains, banks	Grains, banks	Bedforms (steps, pools), grains, banks	Grains, banks	Bed and banks	Grains
Typical Confinement	Unconfined	Unconfined	Variable	Confined	Confined	Confined	Confined
Typical Pool Spacing (in channel widths)	5 to 7	5 to 7	None	1 to 4	<1	Variable	
Typical Slopes		<0.015	0.015 – 0.03	0.03 – 0.065	>0.065		

Typically, small headwater streams in the alpine portion of the watershed are cascade and step-pool channels. These tributaries are characterized by steep gradients and coarse channel substrate. Sediment delivery to these channels commonly occurs by debris flows. Photo 7 shows a step-pool channel reach on a small, unnamed tributary to the Middle Fork Snoqualmie River. Cascade and step-pool channels of more limited extent are also found in the lowland portions of the watershed. Here they are often present in steep channel reaches where modern channels descend from rolling glacial uplands or relict glacial channels down to modern river valley bottoms. Bedrock is occasionally encountered in these channels, but frequently they are entirely underlain by glacial sediments. The presence of abundant cobble- and boulder-sized clasts in the glacial substrate and/or effective LWD in the channel are critical to the stability of these channels. Most small lowland tributaries to the Snoqualmie River include this type of steep channel morphology somewhere along their profile. Typical examples include Tokul Creek, upper Patterson Creek, Tuck Creek, and Peoples Creek.

Photo 8 shows cascade morphology on Peoples Creek. Photo 9 shows a step-pool channel formed with a combination of boulders and LWD in Tuck Creek.

Photo 7: Step-pool morphology on an unnamed tributary to the Middle Fork Snoqualmie River.

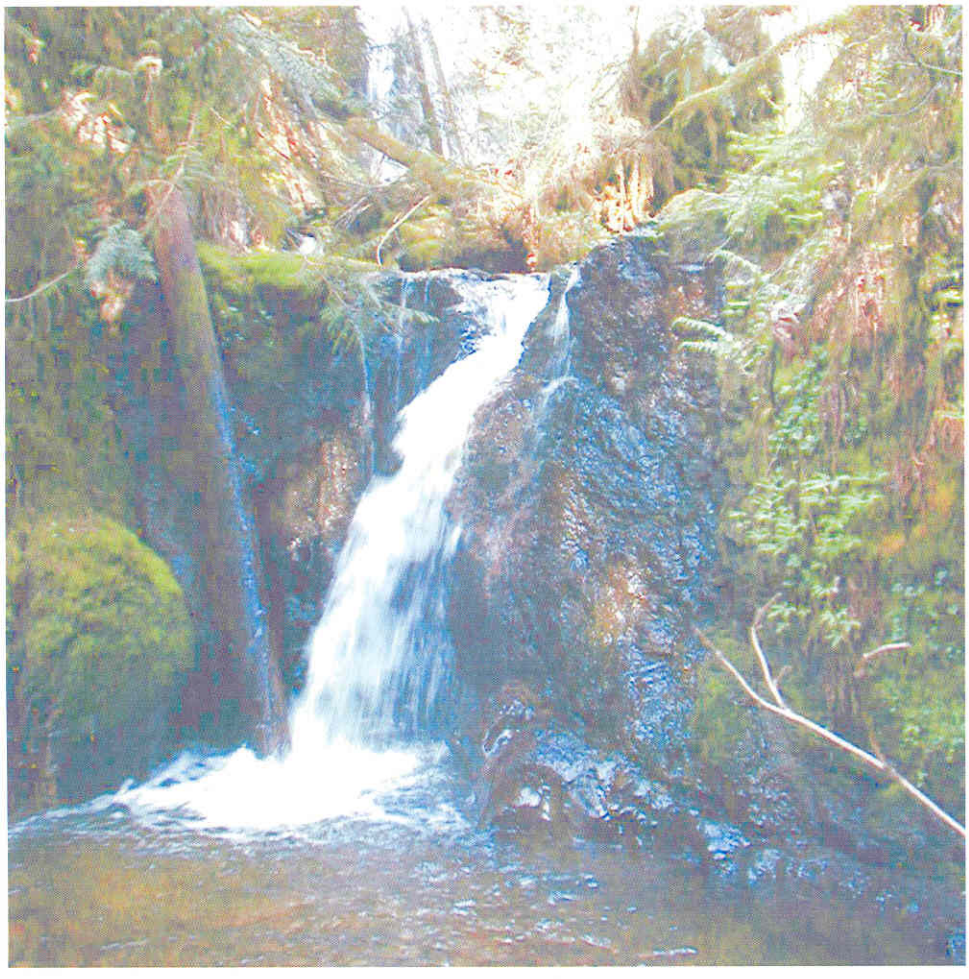


Photo 8: A cascade in an area where Peoples Creek flows over an exposure of Tertiary bedrock

Photo 9: A step-pool reach on Tuck Creek. Note that steps in this channel are formed by a combination of woody debris and boulders.

Lower gradient channels in bedrock or post-glacially incised valleys often form plane-bed channels. Some portions of mainstem rivers in the alpine portions of the watershed have a plane-bed morphology. This morphology is also common in lowland channels. It is likely that many lowland channels that now have plane-bed morphology were step-pool channels under pristine conditions. Human activities have removed wood from these channels or removed the source of LWD from riparian zones. In many such streams, boulders and cobbles are absent, and LWD formed the primary step-forming element in the channel. Without LWD, step formation was not possible, and these streams then transitioned to the plane-bed character evident today. Photo 10 shows plane-bed morphology in the Raging River.

In gravel-bedded channel reaches where the quantity of bedload supplied to the channel exceeds the channel's ability to move it, there is net sediment accumulation. Reaches of this type are common in the alpine portion of the watershed, notably in areas where a rapid downstream decrease in channel gradient reduces the local sediment transporting capacity. Typically in these areas, the channel develops a braided character with multiple active channels and rapid migration of the channels and intervening bars (Photo 11). Braided morphology is locally present on all three forks of the Snoqualmie, and on both forks of the Tolt.

Moving downstream, both channel gradient and valley confinement typically decrease and channels develop a pool-riffle pattern. Pool-riffle channels typically occur in valleys with relatively well-developed floodplains. Typically, these channels have little contact with valley walls and are therefore not strongly affected by fluvial or mass-wasting processes originating from outside the channel perimeter. Pool-riffle channels, which are common in both the alpine and lowland portions of the watershed, are characterized by a well-developed meandering pattern in map view (Photo 12).

The lowest gradient channel types found in the Snoqualmie Valley show a dune-ripple morphology. These channels are generally incompetent to transport bedload larger than sand. Flow resistance in these channels comes from channel geometry, and also from ripples and dunes formed on the streambed. Dune-ripple channels typically show a well-developed meander pattern. Much of the Snoqualmie River mainstem in the lower valley has a dune-ripple character. Photo 13 shows dune-ripple morphology on the lower Snoqualmie River in the vicinity of the city of Duvall.

5.2.3. Local Processes

Some geomorphic phenomena occur at discrete locations with relatively limited horizontal extent. These phenomena are a result of a specific local combination of topographic, geologic, and hydrologic factors. Examples of these types of processes in the Snoqualmie Valley include landsliding and alluvial fan construction.

5.2.3.1. Landslides

Various styles of landsliding occur in the Snoqualmie watershed. Collectively, they represent one of the most important mechanisms supplying sediment to the fluvial system. The style of landsliding that occurs at a given location depends on local geologic, topographic, and hydrologic conditions. Figure 11 shows diagrams of several styles of slope failure common to the Snoqualmie watershed.

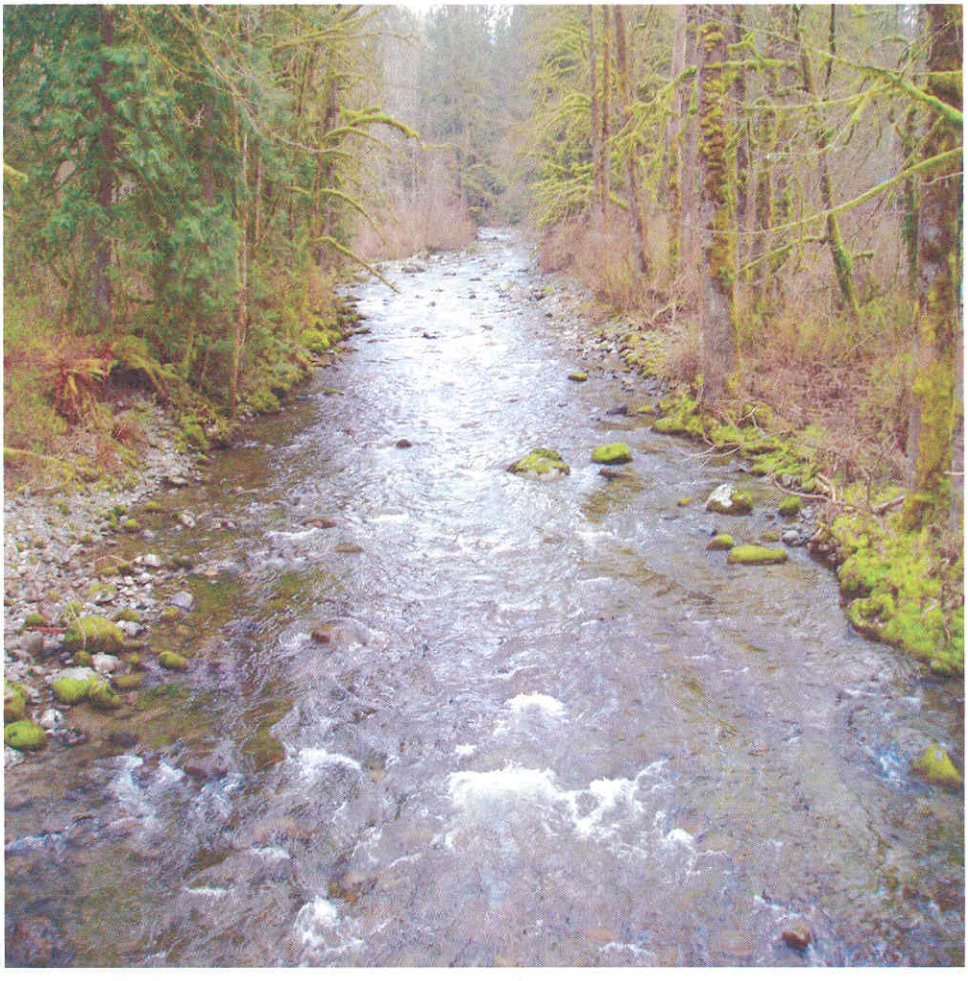


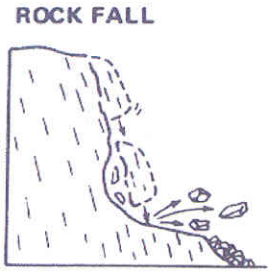
Photo 10: Plane-bed morphology on the Raging River between Preston and Fall City.

Photo 11: A braided reach on the Tolt River a short distance upstream of Carnation at approximately river mile 2.

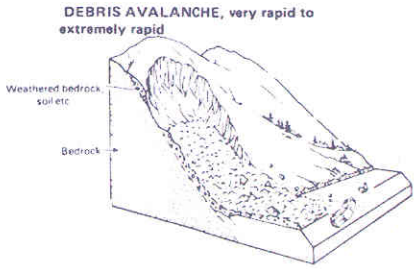
Photo 12: Pool-riffle morphology on the Middle Fork Snoqualmie River.

Photo 13: Ripple marks in fine sand on the bed of the Snoqualmie River in the vicinity of Duvall. Such ripple marks are an indication of dune ripple morphology on this reach of the river.

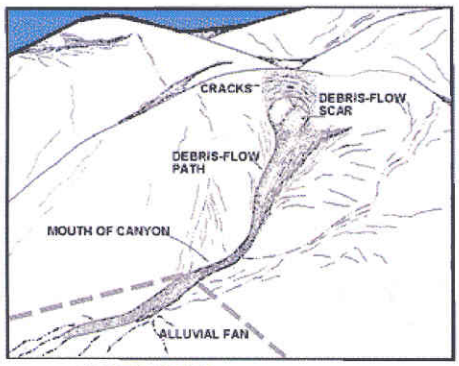
Figure 11: Common Landslide Types in the Snoqualmie Valley Watershed



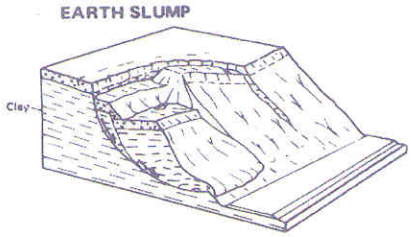
Rock Fall: (Varnes, 1978)



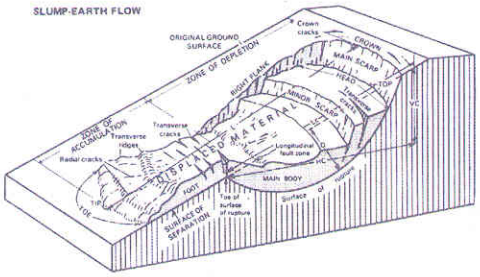
Debris Avalanche (Varnes, 1978)



Debris Flow (U.S. Geological Survey Open-File Report 83-635)



Earth Slumps (Varnes, 1978)



Slump-Earth Flow (Varnes, 1978)

In the high Cascades, rock fall is a common mass-wastage process in glacially sculpted peaks and ridges. Areas of active or recent rock fall activity are often indicated by the accumulation of a talus at the base of the slope (Photo 14). Rock fall can also be indicated by a more diffuse scattering of angular boulders near the base of a bedrock cliff. A field of such boulders is present along the Moon Valley Road along the base of the northwest face of Mount Si (Photo 15).

On steep slopes in the alpine portions of the watershed, landsliding is dominated by shallow debris avalanches. This type of failure occurs when a shallow layer of soil overlying bedrock becomes saturated and slides downslope. These types of failures often occur in swales or hollows on steep slopes. Debris avalanches are often seen where fill slopes and landings on logging roads are located on steep, alpine hillslopes. As the detached soil layer slides, it often disaggregates into a fluid mass that accelerates downslope as a debris flow. This mechanism creates the characteristic spoon-shaped scars common in steep alpine valleys. Debris flows typically erode more soil and incorporate downed wood or standing trees as they move downslope. These flows are a major source of both sediment and LWD in alpine stream channels.

Debris avalanches are also common in lowland portions of the watershed. In these features, the surficial soil layer typically slides over consolidated glacial sediments rather than bedrock, but the mechanism is identical. Because slopes are generally shorter and less steep, it is less common for slumps in lowland settings to transition into debris flows. Larger deep-seated landslides are also common in the lowland portion of the Snoqualmie Valley. These slides are typically located on valley walls often in areas where the valley wall is underlain by fine-grained glacial units (Figure 12). Most of these larger landslides are prehistoric features, some probably dating back to immediately post-glacial time. Although old, many of these landslides remain marginally stable and could be reactivated by periods of wet weather, seismic activity, or human modification.

5.2.3.2. Alluvial Fan Construction

Alluvial fans are a common feature throughout the Snoqualmie watershed, and most of these fans are still active and growing. Alluvial fans form where high-energy streams with the ability to transport relatively coarse sediment discharge into a low-energy environment with insufficient stream energy to transport this sediment. Progressive accumulation of immobile sediment at these locations results in relatively frequent changes in channel location, leading to the development of the characteristic fan-shaped deposit in map view.

Photo 14: Rockfall from cliffs on the west face of Mt. Si has created the taluses seen here. Note areas of lighter gray on the cliff, suggesting active spalling of the cliff face.

Photo 15: A boulder derived from rockfall on the west face of Mt. Si. This boulder and others like it are located along Moon Valley Road, an area of residential development outside of North Bend.

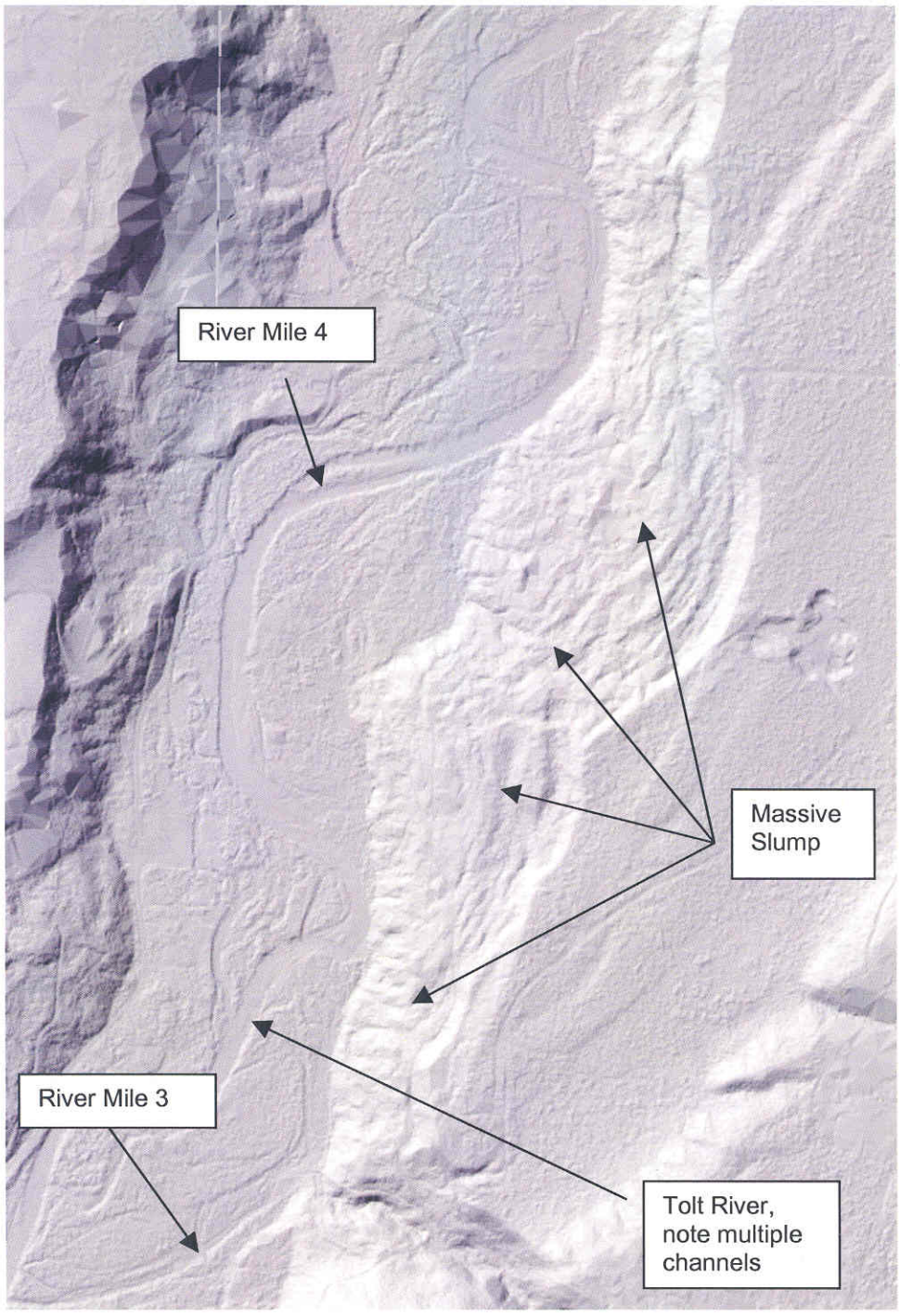


Figure 12: Lidar image of the Tolt Valley showing a massive slump on the south valley wall. This slump is likely prehistoric but it is also likely to be active or marginally stable and subject to reactivation if disturbed. Note braided character of adjacent Tolt River.

Alluvial fans form at a variety of scales, from features below the resolution of available mapping up to features like the Tolt River fan at Carnation, which covers an area of approximately 2 square miles (5 square kilometers). Figure 10 shows examples of several alluvial fans in the Snoqualmie watershed.

5.2.3.3. LWD Recruitment and Incorporation

An extensive body of recent geomorphic literature has identified the critical role that LWD plays in the function of Pacific Northwest streams and rivers (Bilby and Ward, 1989). LWD interacts with stream channels in a variety of ways, in settings ranging from steep ephemeral headwater swales to large, low gradient mainstem river channels.

Woody debris that falls into small, steep headwater channels is often too large for the stream to move. Wood can play a primary role in stabilizing these channels. Stems and rootwads often constitute the largest structural elements in these steep channels and limit channel erosion by creating “hard points” that directly limit channel incision or widening. In addition, these woody elements, often in association with boulders, constitute the primary roughness elements in small steep channels. By increasing channel roughness, these elements help dissipate the kinetic energy of stream flow through increased turbulence, thereby decreasing the energy available for channel or bank erosion.

As stream size increases, the character, abundance, and distribution of LWD continues to be a controlling factor in fluvial geomorphic processes, but the nature of the interaction changes between the wood component and channel form changes. Most significantly, as channel size increases, progressively larger wood pieces become increasing mobile. In mainstem rivers, flood flows are typically capable of moving the largest pieces of supplied woody debris. Stable LWD structures can still form, but these now consist of multiple logs that achieve their stability not only because of the size of individual pieces but also because of the architecture of the entire assemblage. A number of common debris jam types have been identified by Abbe et al. (2003) (Figures 13, 14, and 15; Photos 16, 17, and 18). Debris jams can obstruct and deflect flow, leading to increased channel migration. Jams can sometimes persist for centuries, remaining as stable features in the floodplain as the channel migrates around them (Abbe et al., 2003).

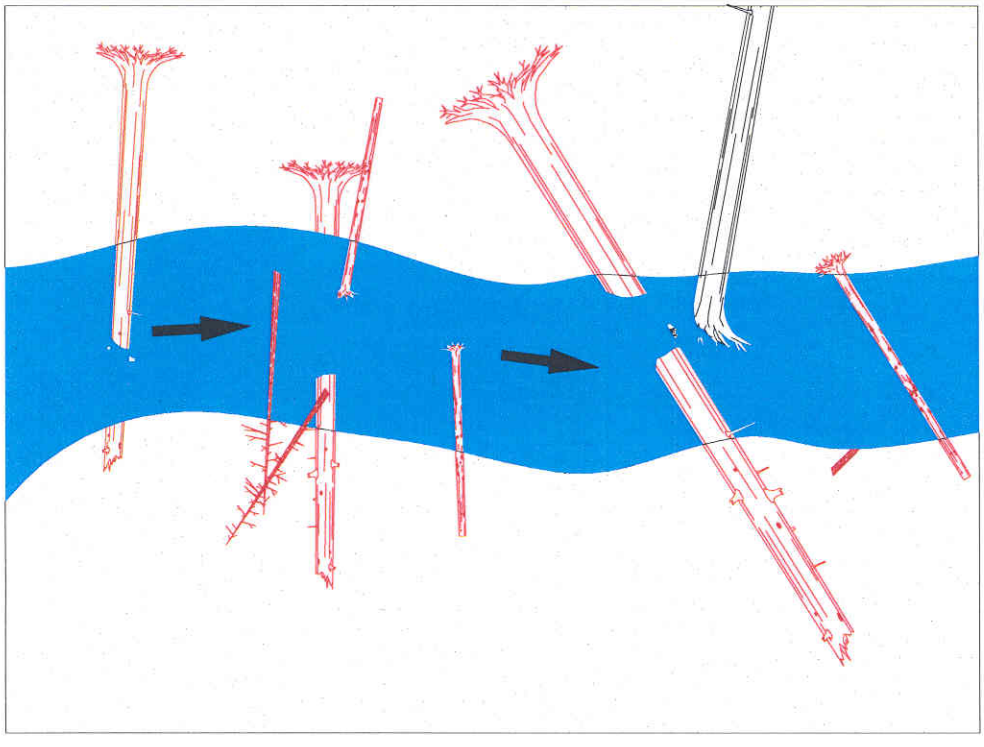


Figure 13: Step jam (after Abbe et al. (2003))

Photo 16: Step jam on Peoples Creek

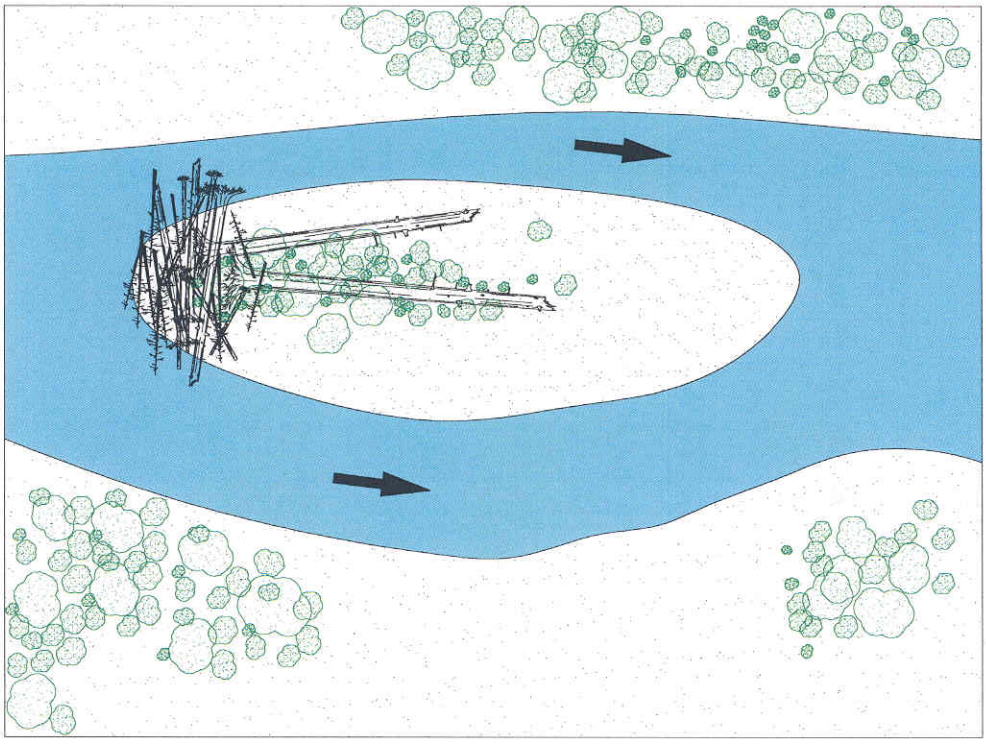


Figure 14: Bar-apex jam (after Abbe et al., 2000)

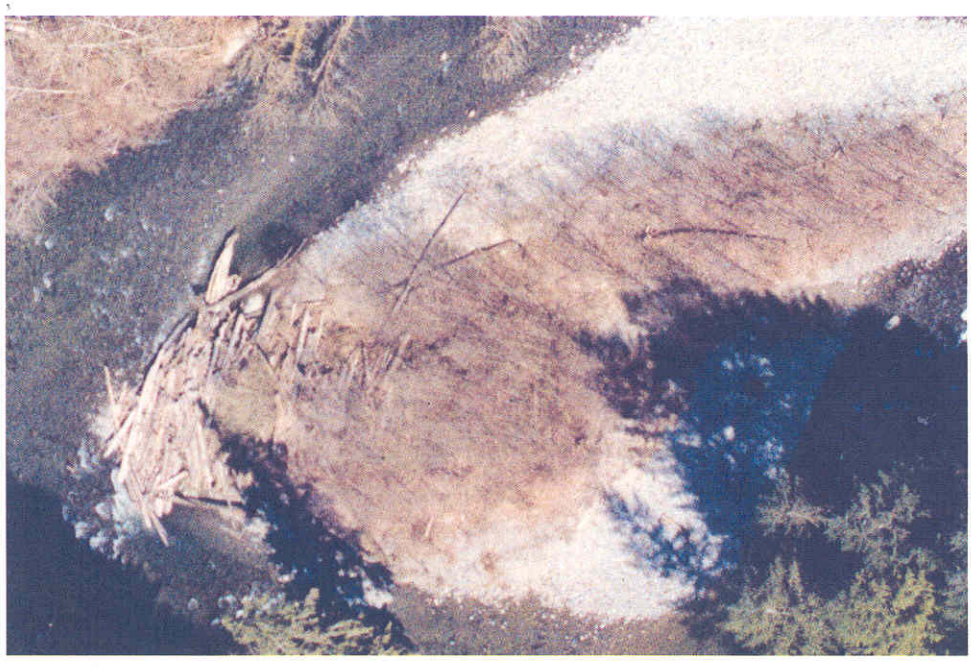


Photo 17: Mature bar-apex jam on North Fork, Tolt River

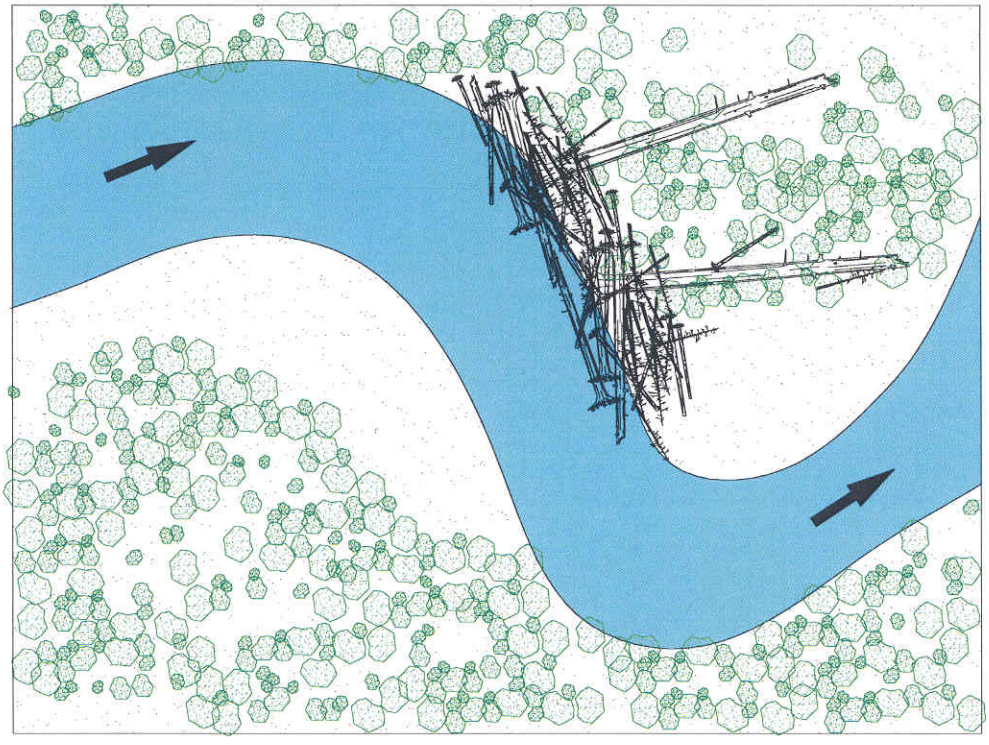


Figure 15: Meander jam (after Abbe et al. 2002)

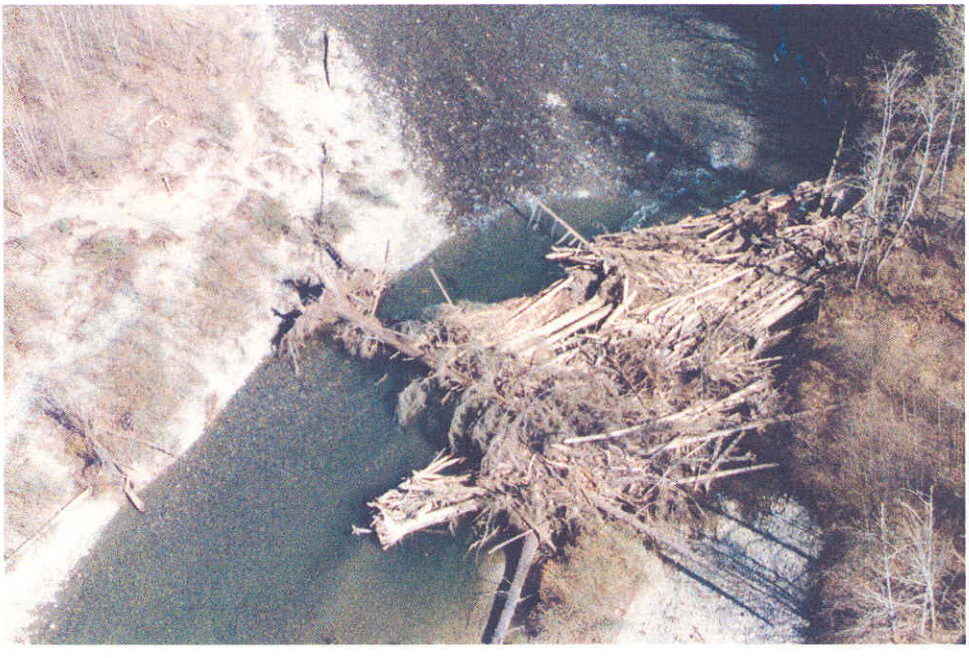


Photo 18: Meander jam on the North Fork, Tolt River

Wood can be supplied to channels in a variety of ways. Trees adjacent to steep headwater swales may be fallen as a result of landslides, avalanches, or windthrow. These woody pieces may remain in these steep swales until debris flows move them downslope into larger tributary or mainstem channels. In larger channels, the primary local source of LWD is streamside trees that fall directly into the channel as a result of lateral channel migration, intense weather events, or beaver activity. Regardless of location in the watershed, the quantity and character of the natural LWD input depends on the areal extent, stem density, species distribution, and maturity of the forested riparian zone.

LWD jams in the lower Snoqualmie River are less common than in other Puget Lowland rivers. This is, in part, a result of the drastic reduction in the extent of riparian forest and armoring of channel banks that limits lateral erosion. However, there is some evidence based on historical accounts that the lower Snoqualmie had a relatively low LWD loading even before non-native human settlement. Collins et al. (2003) suggests that this comparatively low LWD abundance may be typical of Puget Lowland rivers that occupy relict glacial troughs. These rivers typically have low gradients and low confinement compared with rivers in self-formed valleys. As a result, these channels tend to have lower average boundary shear stress and therefore lower natural rates of channel migration. Lateral migration and undermining of riparian trees is an important source of LWD recruitment.

5.3. Post-Glacial Deposits

5.3.1. Alluvial Valley Fill

Following glacial retreat, the freshly exposed land surface was covered with a complex pattern of channels and depressions. Since deglaciation, sediment has progressively accumulated in these features. The character of the depression and its location in the post-glacial drainage network largely determine the character of the sediment that it collects. Where such features occur high in the drainage network, with little upstream sediment supply, they tend to fill gradually with organic sediments, with varying content of fine-grained mineral sediment. This type of sedimentation created wetlands like the ones shown in Figure 16. Where such depressions occur lower in the drainage network, they typically fill with sediment from the watershed upstream. This sediment may range from fine-grained lacustrine deposits through silty or sandy alluvium to gravelly fluvial deposits. Deposits of this type fill the major alluvial valley bottoms, including the upper mainstem valley from the Three Forks confluence to Snoqualmie Falls, the lower Snoqualmie Valley, and smaller valley segments on the lower Tolt River and Patterson Creek.

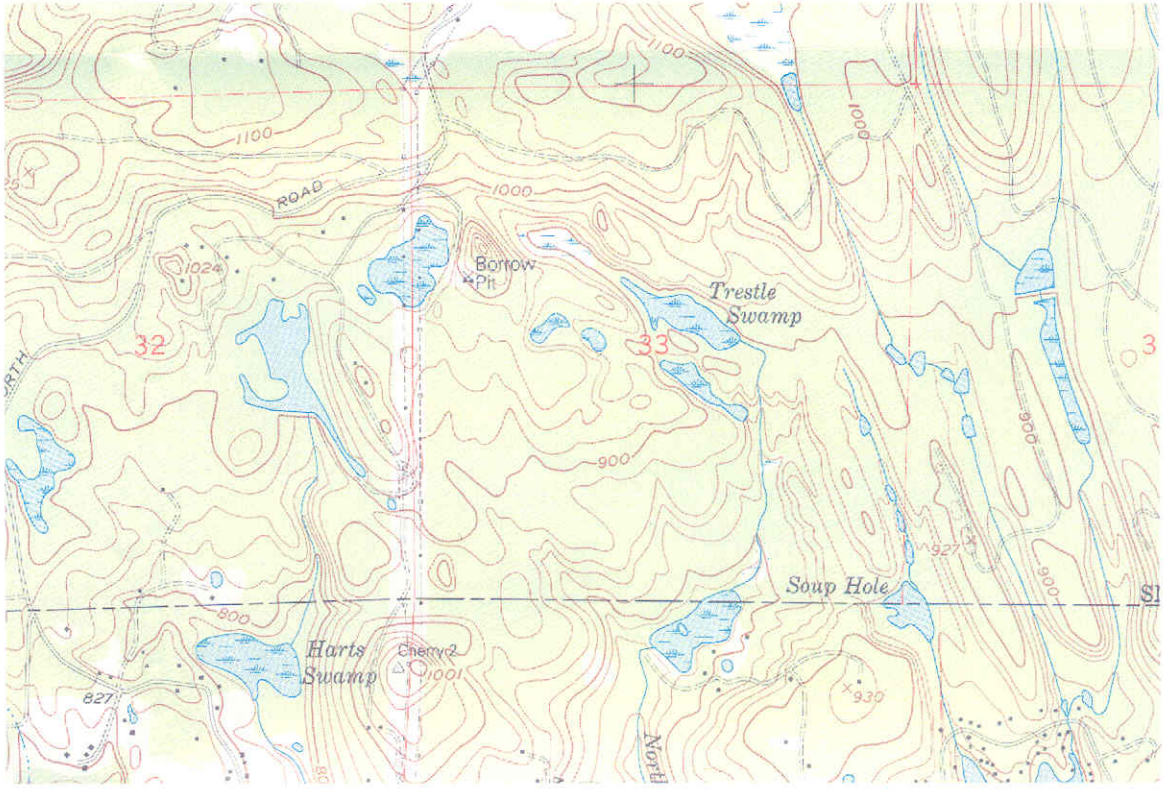


Figure 16: Wetlands developed in depressions in the glacial landscape in the Cherry Creek basin.

5.3.2. Alluvial Fan Deposits

Alluvial fan deposits are typically coarser than adjacent alluvial deposits. They are often gravelly with crude stratification. They may show surficial evidence of multiple abandoned channels. The pattern of patchy, multi-aged vegetative cover may indicate a history of repeated local disturbance due to frequent channel migration.

5.3.3. Landslide Deposits

Landslide deposits have variable textures depending on the geologic substrate from which they were derived. Depending on the style of landsliding, the debris can range from being slightly to completely disturbed. In the case of slumps, large blocks may appear relatively undisturbed, although they have moved and rotated during slide movement. Debris flow and debris avalanche deposits on the other hand are typically disaggregated. Because of their disturbance history, landslide debris is typically soft or loose. Landslide deposits are often most easily recognized based on their distinctive topography rather than on the nature of their constituent sediments. Such distinctive topography can include steep arcuate head scarps, mid-slope benches, stepped topography, lobate toes, and hummocky topography. Active landslides are often marked by bent or leaning trees.

6.0 Description of Specific Reaches and Tributaries

Figure 17 shows the basin boundaries of the major tributary streams in the Snoqualmie River watershed. Figure 18 shows the longitudinal profile of these tributaries.

6.1. Upper Snoqualmie Basin

The upper Snoqualmie Basin includes the entire watershed above Snoqualmie Falls. This includes 367 square miles (591 square kilometers) or 53 percent of the entire Snoqualmie watershed. Property ownership in the upper basin is divided among federal, state, and private owners. With small deviations, the U.S. Forest Service owns the entire upper basin, starting in Range 10 and extending east to the Cascade Crest. To the west of Range 10, land ownership shows the familiar checkerboard pattern of state and private ownership inherited from railroad and public school land grants. Most of the upper watershed has an alpine character, but the river immediately above Snoqualmie Falls, in the vicinity of Snoqualmie and North Bend, is similar in character to the river in the lower valley.

6.1.1. North Fork Snoqualmie River

The North Fork of the Snoqualmie River has a watershed area of 104 square miles (269 square kilometers). Elevation ranges from 410 feet (126 meters) at the Three Forks confluence to 5894 feet (1814 meters) on Lennox Mountain. The upper North Fork Snoqualmie River flows generally westerly from a drainage network in the central Cascades. If the North Fork continued west from its headwaters, it would join the mainstem Snoqualmie near the city of Carnation. Instead, after emerging from the Cascade massif, the North Fork turns south, following a glacial channelway along the base of the massif until reaching the confluence with the Middle and South forks. Major tributaries to the North Fork include Philippa Creek, Deep Creek, Lennox Creek, and Illinois Creek.

Two small areas in the upper watershed of the North Fork are located in the Alpine Lakes Wilderness area. Together, these make up approximately 10 percent of the watershed area. Virtually all of the remainder of the watershed is managed for timber production. There has been extensive prospecting in the upper North Fork valley, and deposits of gold, silver, copper, and molybdenite have been identified. However, no large-scale mining operations have ever been undertaken (Bethel, 1951; Johnson, 2004).

Tertiary volcanic and sedimentary rocks underlie the foothills bounding the North Fork Snoqualmie River Basin. Alpine glaciers occupied the upper North Fork valley, as well as its major tributaries, during the last Ice Age.

SNOQUALMIE WATERSHED

Figure 17

SUBBASINS

Subbasin Boundary

Watershed Boundary

Stream

Lake/River

Incorporated Areas

N

0 2 4 Miles

April 2004

King County

Department of Natural Resources and Parks
Water and Land Resources Division

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File Name: 0312snoGEOLsubbasins.ai wgab **Prepared by:** King County DNRP/WLR GIS and Visual Communications & Web Unit

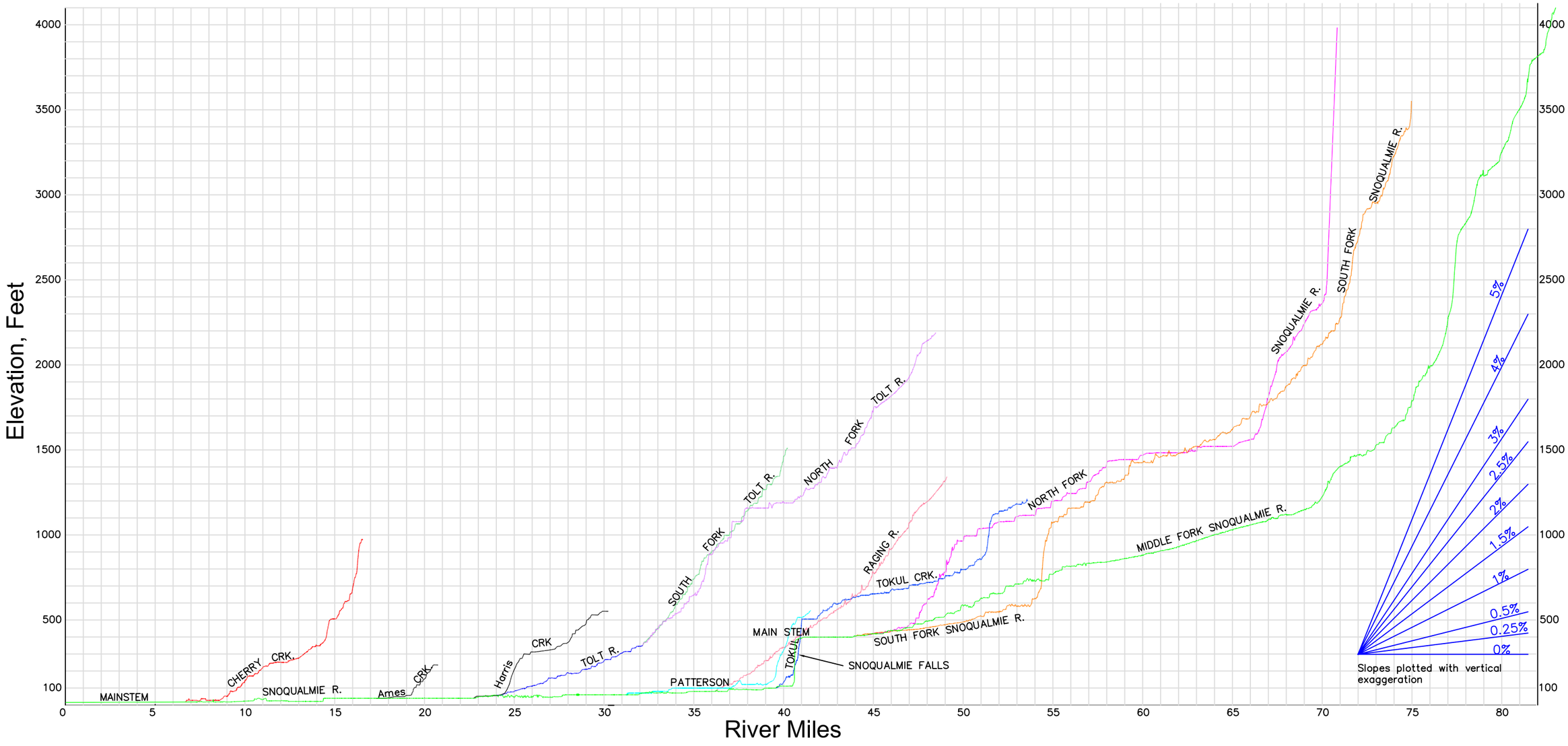


Figure 18: Longitudinal Profile of the Snoqualmie River and selected tributaries. Vertical exaggeration: 52.8:1 (1 mile horizontal = 100 feet vertical)

6.1.2. Middle Fork Snoqualmie River

The Middle Fork of the Snoqualmie River is the largest of the three forks, with a drainage area of 170 square miles. The Middle Fork includes Mount Hinman, the highest point in the Snoqualmie River watershed at 7492 feet (2283 meters). In the Middle Fork watershed, about 47 percent of the land is located within the Alpine Lakes Wilderness area. Outside of the Wilderness Area, land use in the watershed consists primarily of forest production and recreation on land with mixed public/private ownership.

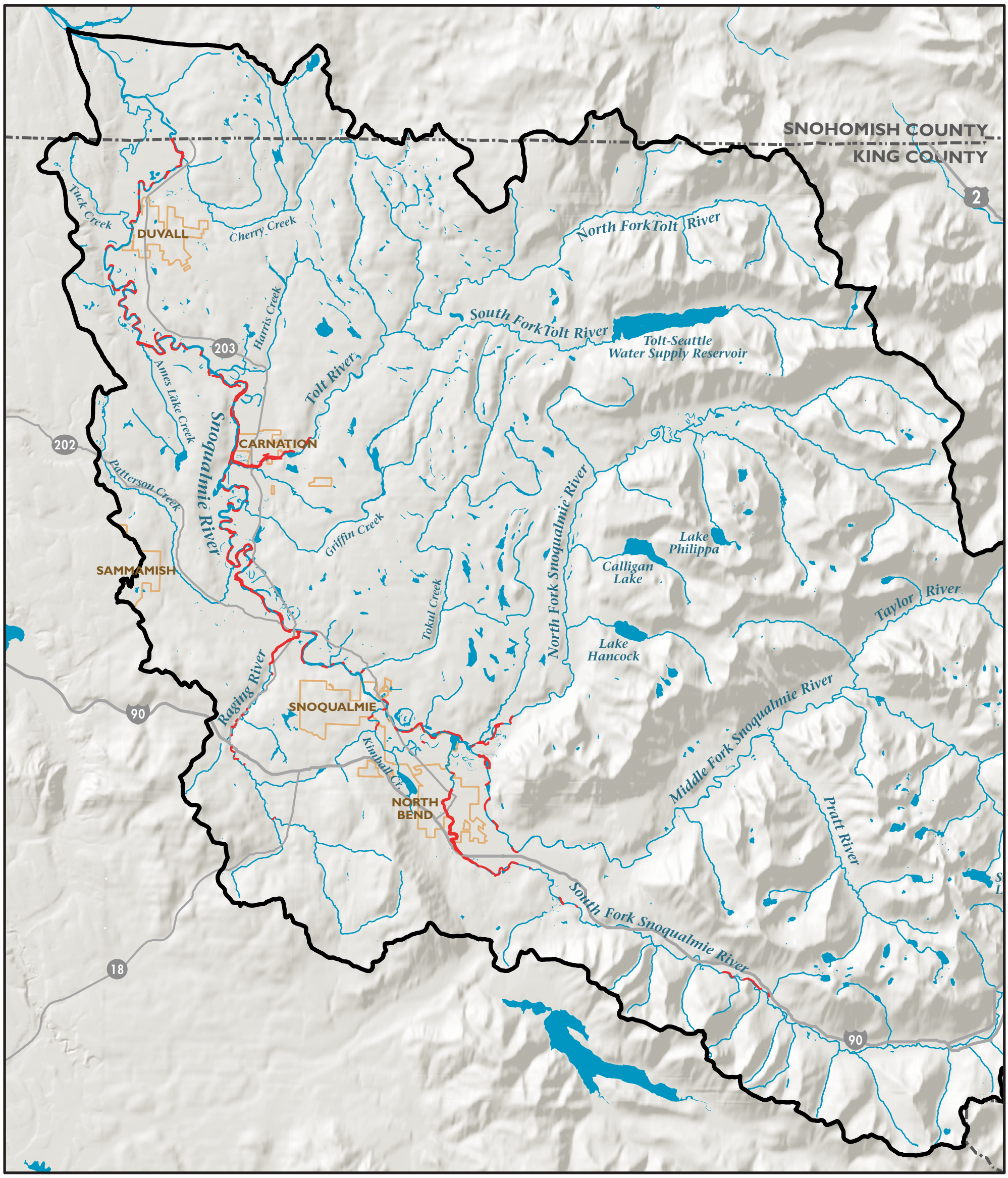
The upper 15 miles of the Middle Fork flows in a narrow bedrock-walled channel. The gradient ranges from 5 percent at the upstream end of this reach to 3 percent at the downstream end. The channel is relatively straight in map view and has a braided morphology. This is probably a result of a high rate of sediment delivery from numerous small, steep tributaries that drain the precipitous valley walls.

At a point approximately 15 miles (24 kilometers) downstream from the Cascade Crest and 20 miles (32 kilometers) upstream of the Three Forks confluence, the river character changes dramatically. The valley widens and the river gradient drops to approximately 0.5 percent. The channel meanders across the relatively broad valley bottom. Through this reach, the channel is relatively unconfined and exhibits pool-riffle morphology. Both the Pratt River and the Taylor River are tributaries to the Middle Fork in this reach.

For its last 5.5 miles (8.9 kilometers), the Middle Fork flows across the merged alluvial floodplain formed by the confluence of the Three Forks. The river maintains a 0.5 percent gradient and meandering plan form. This is the only section of the river with significant adjacent development, and there the banks have been locally armored and/or leveed in order to protect adjacent properties (Figure 19). The number of relict channel remnants increases approaching the confluence area, suggesting that this has been an area of active sediment deposition (Figure 20).

6.1.3. South Fork Snoqualmie River

The South Fork of the Snoqualmie River has a tributary area of 85 square miles (220 square kilometers) and therefore is the smallest of the three forks. Interstate 90 follows the South Fork from North Bend for 24 miles (39 kilometers) until the highway leaves the river to cross Snoqualmie Pass. Two small dams on the South Fork take advantage of natural waterfalls to provide hydraulic head for hydroelectric production. These are located at Weeks Falls at river mile 13 (river kilometer 21) and at Twin Falls at river mile 10 (river kilometer 16). The Weeks Falls dam incorporates an inflatable bladder that forms the crest of the dam. The bladder is deflated during high flows to allow bedload to pass through the dam site. The lowest section of the South Fork flows through the city of North Bend. The river is confined between constructed levees for virtually this entire section (Figure 19).



SNOQUALMIE WATERSHED

Figure 19

RIVER FACILITIES

- River Facility
- Watershed Boundary
- Stream
- Lake/River
- Incorporated Areas

N

0 2 4 Miles

April 2004

King County

Department of Natural Resources and Parks
Water and Land Resources Division

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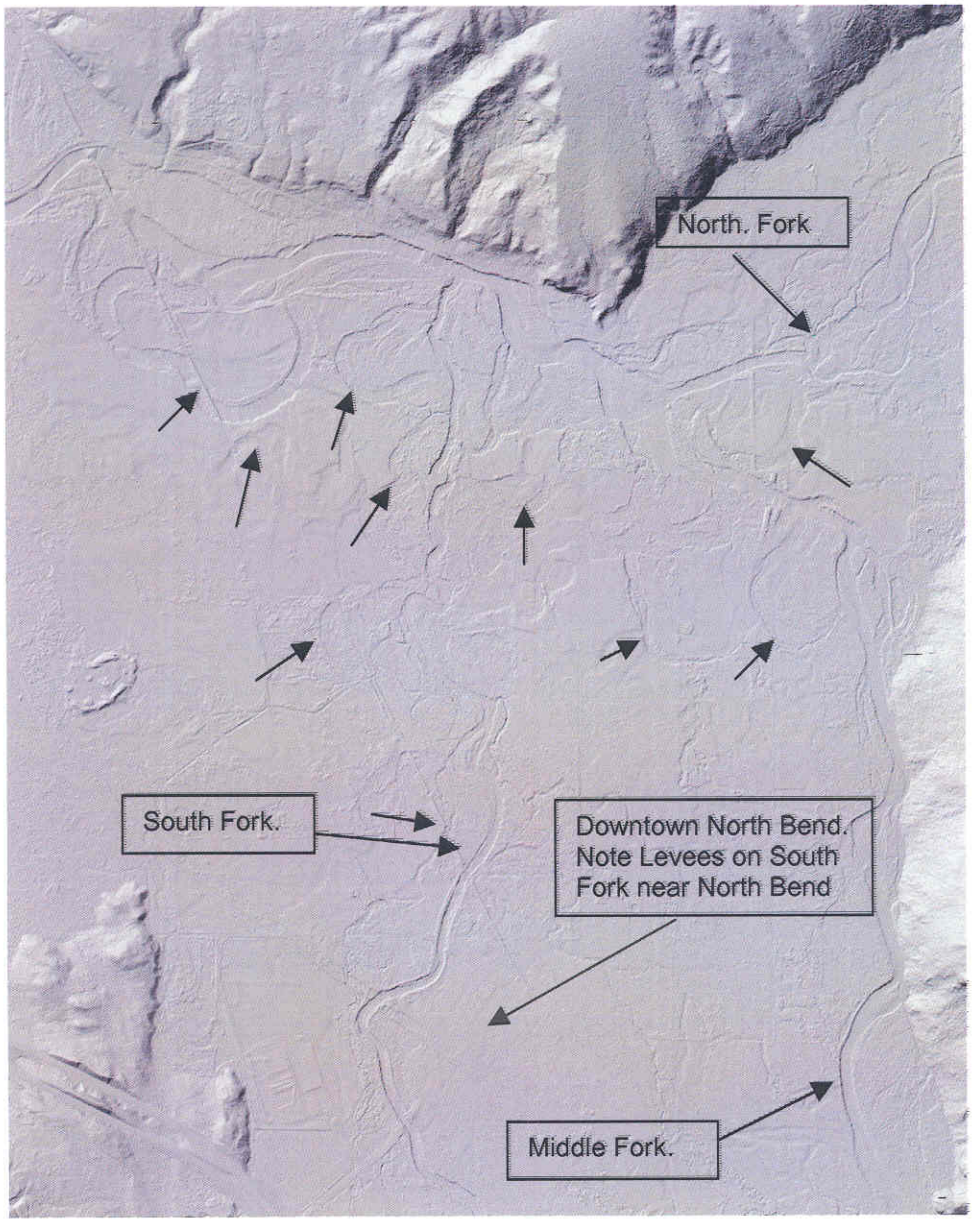

Figure 20: Lidar image showing multiple relict channels near the confluence of the North, Middle, and South Forks of the Snoqualmie River. Unlabeled arrows indict relict channels. Close inspection shows levees on the South Fork in the vicinity of North Bend.

The headwaters of the South Fork drain the Snoqualmie Pass area and the watershed boundary extends to the Cascade Crest. The watershed ranges in elevation from 6278 feet (1932 meters) on Snoqualmie Mountain down to 410 feet (125 meters) at the confluence with the Middle Fork Snoqualmie River. The South Fork has numerous, mostly high-gradient tributaries, including Denny Creek. Most of the ground surface in the South Fork basin is underlain by bedrock at shallow depth.

The upper valley of the South Fork was occupied and shaped by alpine glaciers, and it has the generally parabolic cross section typical of glaciated mountain valleys. The upper valley slopes are generally underlain by bedrock, and the valley floors by alpine glacial deposits and modern alluvium and colluvium. Near the Cascade Crest, the South Fork has a gradient of about 5 percent. Just above Twin Falls, the gradient has dropped to approximately 1 percent.

In its upper section, the South Fork Snoqualmie occupies a classic hanging valley. Twin Falls along with the steep channel sections above and below provide a vertical drop of approximately 600 feet (180 meters). Twin Falls marks the transition between topography sculpted by alpine glaciers upstream, and that created by erosion and deposition associated with the Puget lobe of the Cordilleran Ice Sheet below.

Below Twin Falls, the channel gradient decreases to 0.25 percent and natural valley confinement decreases dramatically. As a result, the river's ability to transport sediment is also dramatically decreased. The river deposits large volumes of sediment and begins to braid. Reid and Dunne (1996) report that the South Fork transports a mean annual bedload of 2600 tons (2400 metric tonnes), and that all of this sediment is deposited in the lower valley, upstream of the confluence with the mainstem. The floodplain in a broad area near the mouth of the South Fork shows remnants of numerous former channel locations (Figure 20), suggesting that the channel was highly mobile prior to human modification. An extensive levee system now constrains much of this channel's former mobility. Outside of this levee system, a significant area near the channel has been designated by King County as a channel migration hazard (Perkins, 1996).

6.1.4. Upper Mainstem

For the purposes of this report, the upper mainstem is the channel reach between the confluence of the Three Forks (river mile 45.0, river kilometer 72.4) and Snoqualmie Falls (river mile 40.3, river kilometer 64.8). This reach of channel is 3.4 miles (5.5 kilometers) long and flows through the City of Snoqualmie. Land use adjacent to this reach includes agriculture, scattered single-family residential housing, and higher density residential and commercial properties in the City of Snoqualmie.

The upper mainstem meanders through a broad, nearly level alluvial valley bottom originally known as the Salal Prairie. The character of this reach of river and of the surrounding alluvial fill is largely a result of the bed control provided by the bedrock shelf that forms Snoqualmie Falls.

The upper mainstem is a low-gradient channel with an average slope of 0.03 percent. Because of this low gradient, the channel moves almost no bedload through this reach. In marked contrast to the Three Forks area immediately upstream, the upper mainstem has no history and shows little evidence of active channel migration. This is also a reflection of its comparatively low-energy character, having neither competence to construct bars nor to erode banks. In the Montgomery and Buffington system, this reach of channel would be characterized as a dune-ripple channel. Kimball Creek is the largest tributary to the upper mainstem reach.

6.2. Snoqualmie Falls

Snoqualmie Falls is located on the Snoqualmie mainstem at river mile 40.3 (river kilometer 64.8). The Falls are 268 feet (82 meters) high, formed where the Snoqualmie River drops over a shelf of Tertiary volcanic rock. It is likely that, prior to the Vashon glacial advance, the Snoqualmie River flowed in a valley or canyon located south of its present location under the present Lake Alice Plateau. In the absence of the present bedrock control, the Snoqualmie River would presumably have a more continuous transition from alpine headwaters to the lower valley. The level alluvial valley now occupied by the Cities of Snoqualmie and North Bend would likely not exist, and the river would be located in a deep valley through this reach. The steeper gradient would have allowed bedload to move through this reach, filling and steepening the channel in the lower valley. In general, it is likely that, in the absence of Snoqualmie Falls, the overall character of the Snoqualmie Valley would be much more like that of the Skykomish Valley immediately to the north.

6.3. Lower Snoqualmie Watershed

6.3.1. Lower Mainstem

The lower mainstem of the Snoqualmie River extends from the base of Snoqualmie Falls at river mile 40.3 (river kilometer 64.8) downstream to the mouth of the Snoqualmie River. As shown on Figure 19, there has been extensive bank protection constructed on the lower Snoqualmie. A review of historical mapping revealed that the lower Snoqualmie showed relatively little evidence of channel movement, even prior to the construction of these armoring projects (Collins and Sheikh, 2002). These authors also evaluated the historical occurrence of LWD in the lower Snoqualmie. They concluded that LWD loadings were much higher under pristine conditions as compared with current conditions, but they also suggest that natural LWD loading in the Snoqualmie was lower than in some other Puget Lowland rivers. One possible explanation for this is the relatively low rate of channel migration in the lower valley. With less active channel migration, there would be less opportunity for trees in the riparian zone to be undermined by bank erosion and introduced into the river.

Booth et al. (1991) sampled streambed sediment, starting on the lower South Fork Snoqualmie and continuing down to the mainstem at its confluence with the Skykomish River. Figure 21 shows a clear and repeating pattern in which the streambed sediment coarsens abruptly at the confluence with high-gradient tributaries and then fines rapidly downstream. This pattern is evident below Tokul Creek, the Raging River, and the Tolt River. Booth et al. (1991) also evaluated how the sediment transport capability of the Snoqualmie River varies along the channel and found that for much of its length the lower Snoqualmie was largely incompetent to transport sediment larger than sand size. They concluded that larger sediments accumulate in relatively permanent fan and channel deposits, which are very slowly filling the lower Snoqualmie Valley.

The longitudinal profile of the lower mainstem (Figure 18) is notable primarily for its low gradient, in marked contrast to the profiles of its tributaries and upstream forks. In the vicinity of Fall City, the average gradient is approximately 0.07 percent. The lowest reach of the river, just above the confluence with the Skykomish, has an average gradient of approximately 0.01 percent. This low gradient reflects the origin of the lower Snoqualmie Valley as a slowly filling glacial trough.

Through most of the lower valley, the Snoqualmie River has developed significant natural levees. These levees are broad elevated berms that parallel the river channel (Photo 19). Such levees form over the course of numerous floods as sand and silt are deposited on the floodplain immediately adjacent to the channel. Natural levees are a common characteristic of dune-ripple channels. Because of the elevation of these levees, the riverbanks in the lower valley are often significantly higher than areas of the floodplain farther from the river. As a result, large areas of the floodplain have very poor natural drainage. This circumstance accounts for the large areas of wetland that occupied the floodplain prior to non-native settlement (Collins and Sheikh, 2002).

Collins and Sheikh (2002) divide the lower Snoqualmie into seven reaches based on channel characteristics. These divisions are adopted with slight modifications for this discussion and are described from upstream to downstream.

6.3.1.1. Falls Reach: RM 39.5 – 40.3 (RK 63.6 - 64.8)

The upstream end of this short reach begins at Snoqualmie Falls and ends in the vicinity at the confluence with Tokul Creek. This section is relatively steep and sediment-starved because nearly all of the coarse sediment from the upper watershed is deposited in the low gradient channel reach immediately above the Falls. Much of the streambed in this reach is composed of gravel. Near the Falls, the streambed is composed of blocks of bedrock from the cliff face at the Falls.

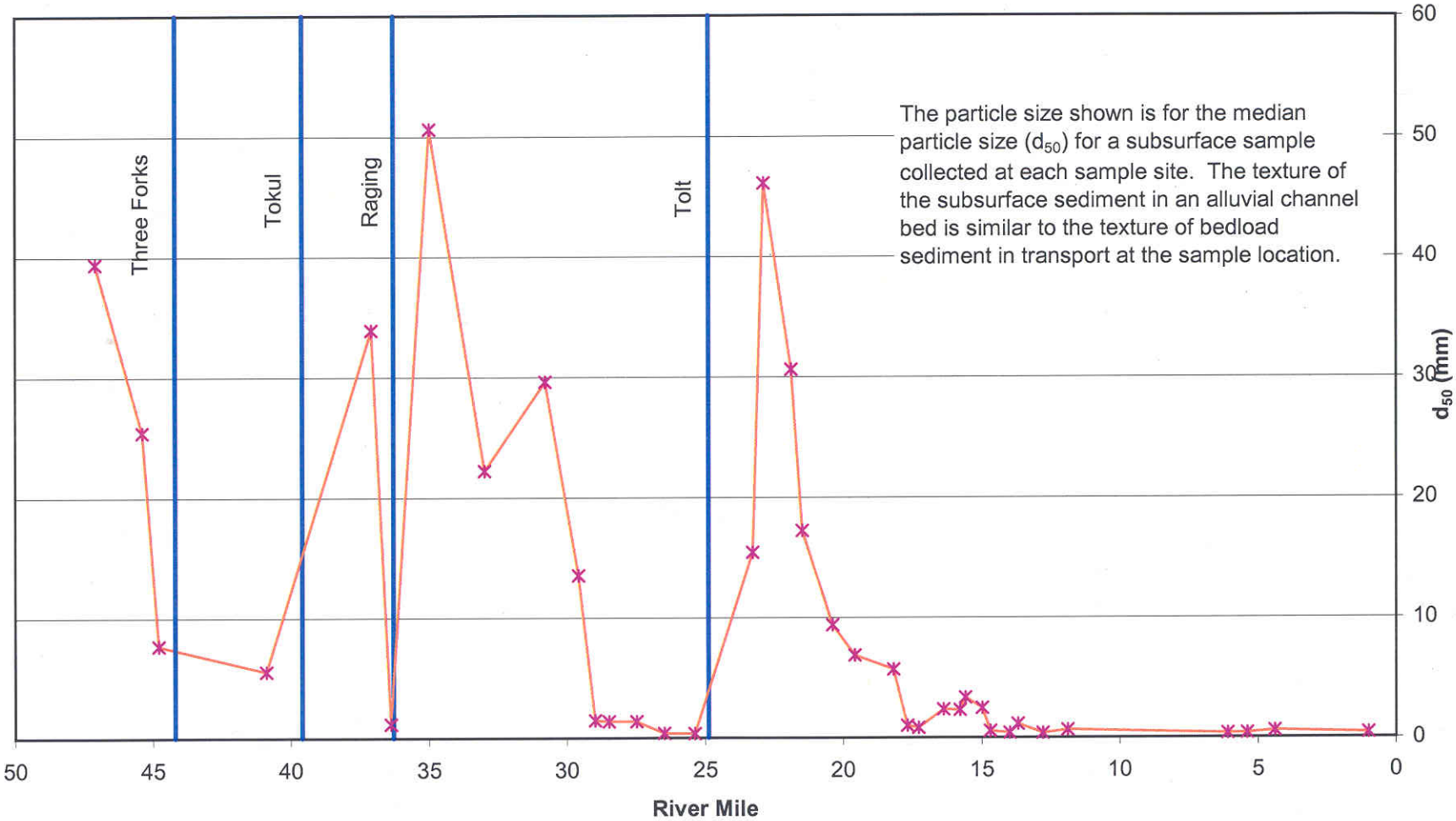

Figure 21: Snoqualmie Streambed Sediment Texture (Booth et al. 1991)

Photo19: Natural levees along the lower Snoqualmie River downstream of Duvall. Floodwaters cover the entire floodplain except for artificially constructed berms and the natural levees immediately adjacent to the channel.

6.3.1.2. Upper Fan Reach: RM 36 – 39.5 (RK 58 – 63.6)

Through this reach, the channel is relatively straight and confined by the Tokul Creek alluvial fan on the north side at the upstream end of the reach, and the Raging River fan on the south side at the downstream end.

6.3.1.3. Upper Meandering Reach: RM 27 – 36 (RK 43.5 – 58)

In this reach, the Snoqualmie exhibits a strongly meandering character, with a sinuosity of 2.0. At the upper end of this reach, the channel bed is gravelly as a result of the gravel supplied by the Raging River. Booth et al. (1991) documented a pronounced downstream fining of the streambed texture through this reach (Figure 21). Near the upstream end, immediately downstream of the Raging River confluence, the d_{50} of mobile streambed sediment was 77 mm (cobble). At the downstream end, just above the confluence with the Tolt, the d_{50} has dropped to 0.34 mm (medium sand). Numerous abandoned channels on the floodplain adjacent to this reach testify to a geomorphic history of active channel migration.

6.3.1.4. Tolt Fan Reach from RM 23 to 27 (RK 37 to 43.5)

In the vicinity of the city of Carnation, the Snoqualmie River flows in a distinctly straight channel immediately at the base of the west wall of the Snoqualmie Valley. The west valley wall adjacent to this reach shows evidence of oversteepened slopes and active instability. Both of these circumstances are atypical of the Lower Snoqualmie River and valley. This reach has a sinuosity of 1.06 and an average gradient of 0.04 percent. These characteristics are a result of displacement of the Snoqualmie River against the west valley wall by the fan constructed by the Tolt River. Immediately above the confluence, the Tolt has a gradient of approximately 0.5 percent, roughly 10 times steeper than the Snoqualmie in this reach. Because of the gradient differential, the Tolt drops sediment on its fan that the Snoqualmie is unable to move. As a result, the Snoqualmie is forced around the perimeter of the fan. The fan deposits now extend all the way across the floodplain, and the Snoqualmie River is trapped between the right bank fan deposits and the left bank valley wall. Leftward displacement of the Snoqualmie channel into the toe of the valley wall has resulted in the oversteepening and instability evident here.

6.3.1.5. Lower Meandering Reach: RM 12-23 (RK 19.3-37)

The upstream end of the lower reach begins at a prominent meander known as Chinook Bend. Beginning at this point, the valley bottom shows evidence of multiple abandoned meanders, suggesting that this has been an area of relatively active channel migration compared with much of the lower valley. It appears that the channel mobility evident in this reach is a consequence of reduced channel confinement and decreased gradient as the

river leaves the confining influence of the Tolt fan. The decreased gradient and decreased confinement mean that average basal shear stress and therefore the sediment transport capacity decrease significantly, moving from the Tolt Fan Reach to the Lower Meandering Reach. The increased rate of channel migration in this reach is presumably a result of the increased sediment deposition. The rate of channel migration appears to decrease downstream. This reach has a sinuosity of 1.8 and exhibits pool-riffle morphology near the upstream end where the streambed is gravelly and transitions to a dune-ripple morphology downstream.

6.3.1.6. Duvall Reach: RM 3 – 12 (RK 4.8 – 19.3)

Through this reach, the Snoqualmie River shows a less pronounced meandering pattern with a sinuosity of 1.6. With no high gradient tributary supplying coarse sediment, the streambed remains sandy and the channel retains a dune-ripple morphology through this reach. Tributaries in this reach include Tuck Creek and Cherry Creek.

6.3.1.7. Lower River: RM 0 – 3 (RK 0 – 4.8)

In the 3 miles (4.8 kilometers) of river immediately upstream from the confluence with the Skykomish River, the Snoqualmie River is again forced against the left (west) valley wall, this time by the sediment deposition from the steeper and more energetic Skykomish River. Abandoned channels on the wedge of floodplain separating the two rivers indicate that the location of the confluence changes over time. Tributaries to this reach include Peoples Creek and Ricci Creek.

6.3.2. Tributaries to Lower Mainstem

6.3.2.1. Tokul Creek

Tokul Creek is the first major tributary entering the Snoqualmie downstream of Snoqualmie Falls. It has a watershed area of 34 square miles (88 square kilometers) and ranges in elevation from 1722 feet (525 meters) to 105 feet (32 meters) at the confluence with the Snoqualmie River. Most of the land area in the Tokul Creek watershed is in timber production. There are a few scattered residences along the lower 1.5 miles (2.4 kilometers) of the river. The Tokul Creek hatchery is located a short distance upstream of the mouth of the creek.

Tokul Creek drains an elongated, relatively low gradient watershed. Between river mile 1.5 and 11.5 (river kilometer 2.4 and 18.5), the creek occupies a relict channelway. Figure 18 shows the longitudinal profile of Tokul Creek. The steep section at the lower end of the watershed marks the change in elevation between the channelway and the modern elevation of

the Snoqualmie River. Tertiary volcanic rocks are exposed in the creek channel as it drops from the channelway down to the river elevation.

6.3.2.2. Raging River

The Raging River has a basin area of 33 square miles (85 square kilometers). Elevation ranges from 3517 feet on Rattlesnake Mountain to 79 feet at the confluence with the Snoqualmie River at Fall City. The Raging River drains a west-trending projection of the Cascade foothills known locally as the Issaquah Alps. Prominent foothills bounding the Raging River watershed include Rattlesnake Ridge, Taylor Mountain, Tiger Mountain, and Mitchell Hill. Most of the land area in the watershed is either in timber production or publicly owned open space. There are scattered residences along the lower 7 miles (11 kilometers) of the river. More intensive land uses are limited to the communities of Preston and Fall City, and a portion of the Snoqualmie Ridge development on the Lake Alice Plateau. Interstate 90 bisects the watershed in an east-west direction. Major tributaries to the Raging River include Canyon Creek, Deep Creek, and Icy Creek.

The glacial history of the Raging River is somewhat complicated. The entire basin was covered by ice during the Vashon glacial maximum. During ice retreat, the Preston Channel (the current location of the lower Raging River) served as one of the relatively early stage outlet channels for glacial Lake Snoqualmie (Stage 6-7 of Booth, 1990) (Figure 8). Water flowed south through this channel, then west along the alignment of the current East Fork of Issaquah Creek into the Lake Sammamish watershed. With further glacial retreat, a lower outlet became available and the Preston Channel was abandoned. Terrace remnants in the Preston area indicate that following abandonment of the Preston meltwater channel, the upper Raging River, upstream of the current site of Preston, continued to flow west along the present East Fork Issaquah Creek alignment. At some point between the current locations of Preston and Fall City, there would have been a drainage divide separating the Raging River watershed from the Snoqualmie River watershed. At some subsequent late-glacial or post-glacial time, headcutting of the north-flowing drainage through the Preston Channel progressed to the point that this drainage captured the Raging River and diverted it from the Sammamish watershed to the Snoqualmie watershed. With this increased flow, the Raging River incised to create the existing, relatively steep, confined channel between Preston and Fall City.

Tertiary volcanic and sedimentary rocks underlie the foothills bounding the Raging River basin. The entire watershed was covered by glacial ice during the Vashon glacial maximum and other previous glaciations of similar magnitude. Much of the bedrock at higher elevations is mantled with a discontinuous layer of glacial till. The Lake Alice Plateau is a typical till upland. The lower Raging River Valley incised through this till surface,

exposing a thick sequence of advance outwash overlying transitional beds. The narrow valley bottom along most of the length of the Raging River is floored with a discontinuous substrate of modern alluvium, colluvium, and landslide debris. Where the Raging River emerges from its valleys and flows onto the Snoqualmie Valley floor, the river has formed a large fan deposit. Fall City is located on the distal portion of this fan (Booth, 1990).

For much of its length, the Raging River exhibits plane-bed morphology (Photo 10). In the upper part of the watershed, the Raging River has a gradient of approximately 3 percent. From the upper crossing with Highway 18 downstream to the vicinity of Preston Channel, the river has a consistent gradient of approximately 1.5 percent. The lowest 4000 feet (1.2 kilometers) of channel, where it crosses its alluvial fan, has an average gradient of approximately 0.6 percent.

In this reach the channel is entirely confined by levees intended to protect development in and around Fall City. Under natural conditions alluvial fans are sites of rapid sediment deposition and consequent active channel migration. The levees along the lower Raging River prevent the channel from moving and confine deposition to the existing channel alignment. Figure 22 shows the rapid sediment deposition typical of this reach. Concerns regarding damage to riverine habitat have curtailed the frequent dredging that occurred here prior to the late 1960s. King County is considering management strategies to address channel aggradation in this reach of the Raging River.

6.3.2.3. Patterson Creek

Patterson Creek is the largest left bank tributary to the Snoqualmie River downstream of Fall City. It has a watershed area of 19 square miles (48 square kilometers). Patterson Creek originates in a series of wetlands on the glacial upland west of the lower Snoqualmie Valley. The stream drops from the till-mantled upland into a relict meltwater channel and follows that channel for 7 miles (11 kilometers) to the Snoqualmie River. This meltwater channel is identified as the Redmond Channel and served as the outlet from glacial Lake Snoqualmie during recessional interval 12 of Booth (1990). This relict channel feature is clearly a result of subaerial meltwater discharge during deglaciation, in contrast to the channelways east of the Snoqualmie Valley, apparently formed by subglacial flow. Patterson Creek drains the southeasterly end of this relict channel toward the Snoqualmie River, and Evans Creek drains the northwesterly end toward Bear Creek and the Sammamish River. Because of the low gradient and broad valley bottom width of the relict channel, lower Patterson Creek meanders through an extensive system of wetlands and, through this reach, has no significant capacity to erode or transport sediment (Figure 23).

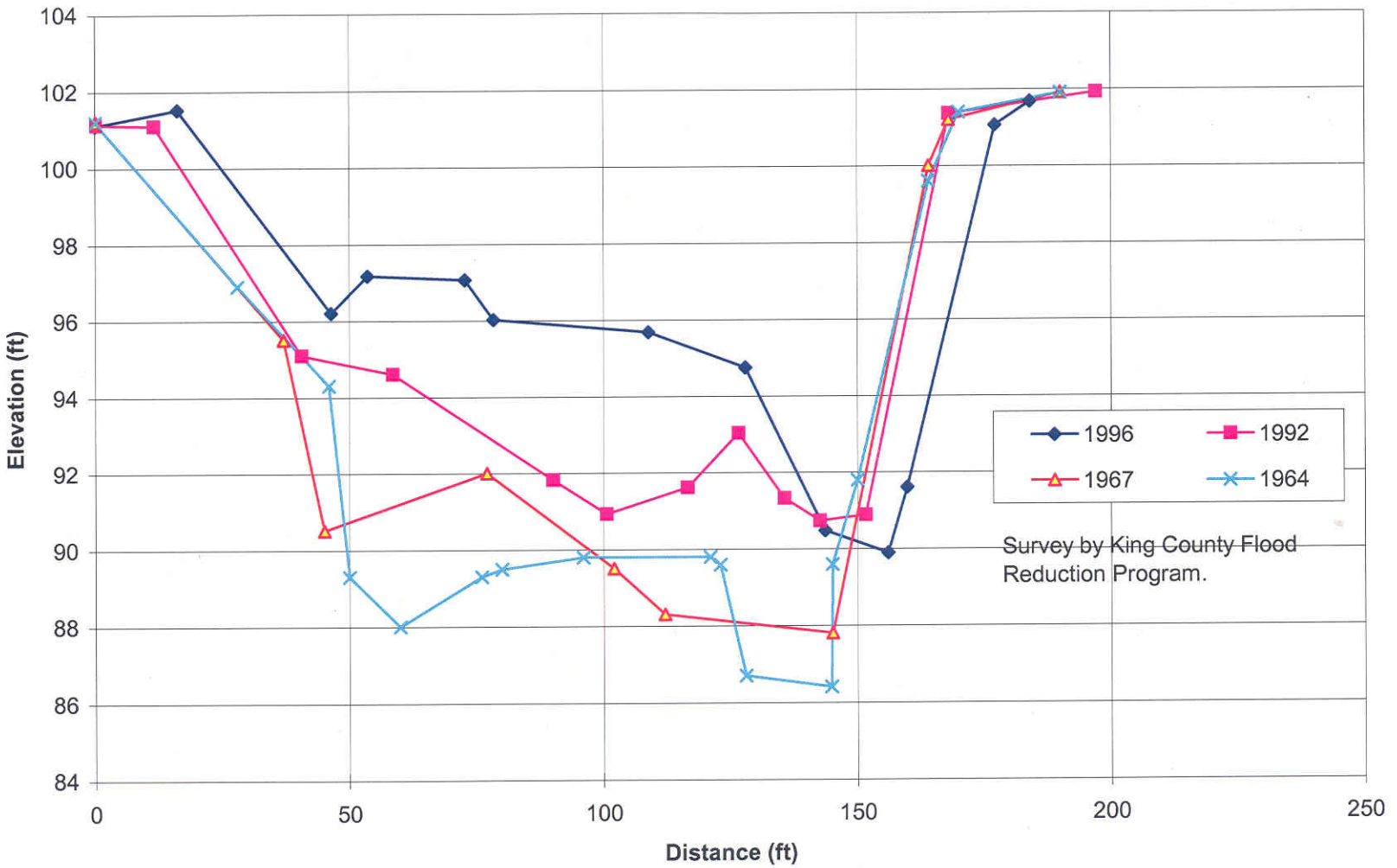

Figure 22: Historical cross-section surveys of the Raging River at a point approximately 1200 feet (350 meters) upstream of the confluence with the Snoqualmie. These sections show progressive sediment accumulation in this lowest reach of the river.

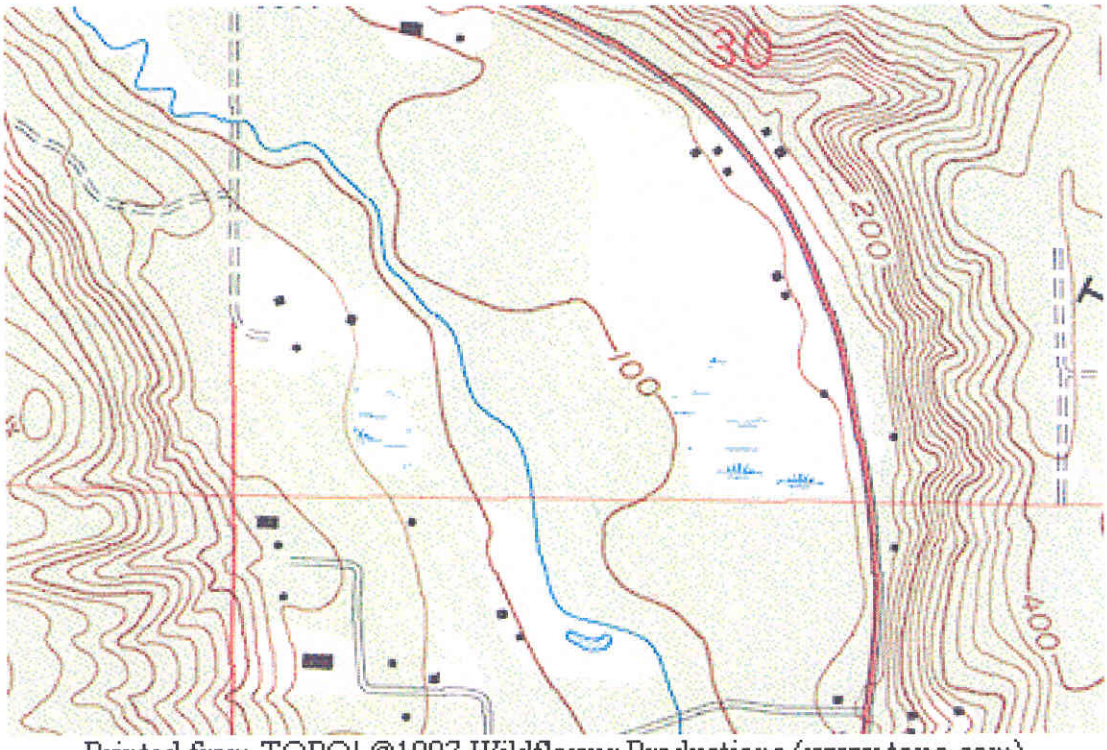

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Figure 23: The lower section of Patterson Creek is a classic underfit stream where it flows through a broad glacial meltwater channel.

6.3.2.4. Griffin Creek

Griffin Creek is a west-flowing tributary with a watershed area of 17 square miles (45 square kilometers). The Griffin Creek basin is largely underlain by glacial deposits. The lower portion of the channel is incised into the glacial surface. In the upper part of the watershed, the main channel, and many of the tributary channels, flow in a series of channelways.

6.3.2.5. Tolt River

The Tolt River has a tributary area of 97 square miles (251 square kilometers) and is the largest tributary to the Snoqualmie River downstream of Snoqualmie Falls. The watershed ranges in elevation from 5576 feet (1700 meters) on Red Mountain down to 55 feet (17 meters) at the confluence with the Snoqualmie River. The Tolt River has two major tributaries, the North and South Forks. The valleys of both forks were occupied and eroded by alpine glaciers and share the generally "U" shaped cross section typical of glaciated mountain valleys. Bedrock generally underlies the side slopes of these valleys, and the valleys are floored with alpine glacial deposits. A dam on the South Fork provides drinking water for the city of Seattle and provides some flood attenuation (Photo 20). The South Fork Reservoir collects runoff and traps sediment from about 20 percent of the Tolt River watershed.

Below approximately elevation 1100 feet (335 meters), both forks leave their relatively broad, low-gradient glacial valleys and descend through steep, narrow, partially bedrock canyons (Photo 21) to their confluence at river mile 8.8 (river kilometer 14).

From the confluence of the forks at river mile 8.8 (river kilometer 14), the mainstem flows through a steep-sided valley at a gradient of approximately 1 percent. In this reach, the Tolt varies between a single-thread and braided morphology. Historical research shows that the morphology and channel location in this reach are subject to rapid and dramatic shifts, sometimes during a single flood event (Shannon and Wilson, 1991). Because of the rapid rate of channel change in this area, King County has designated a broad belt adjacent to the channel as an area of "severe channel migration hazard." Stossel Creek is a major tributary to the Tolt River and enters at the head of this reach.

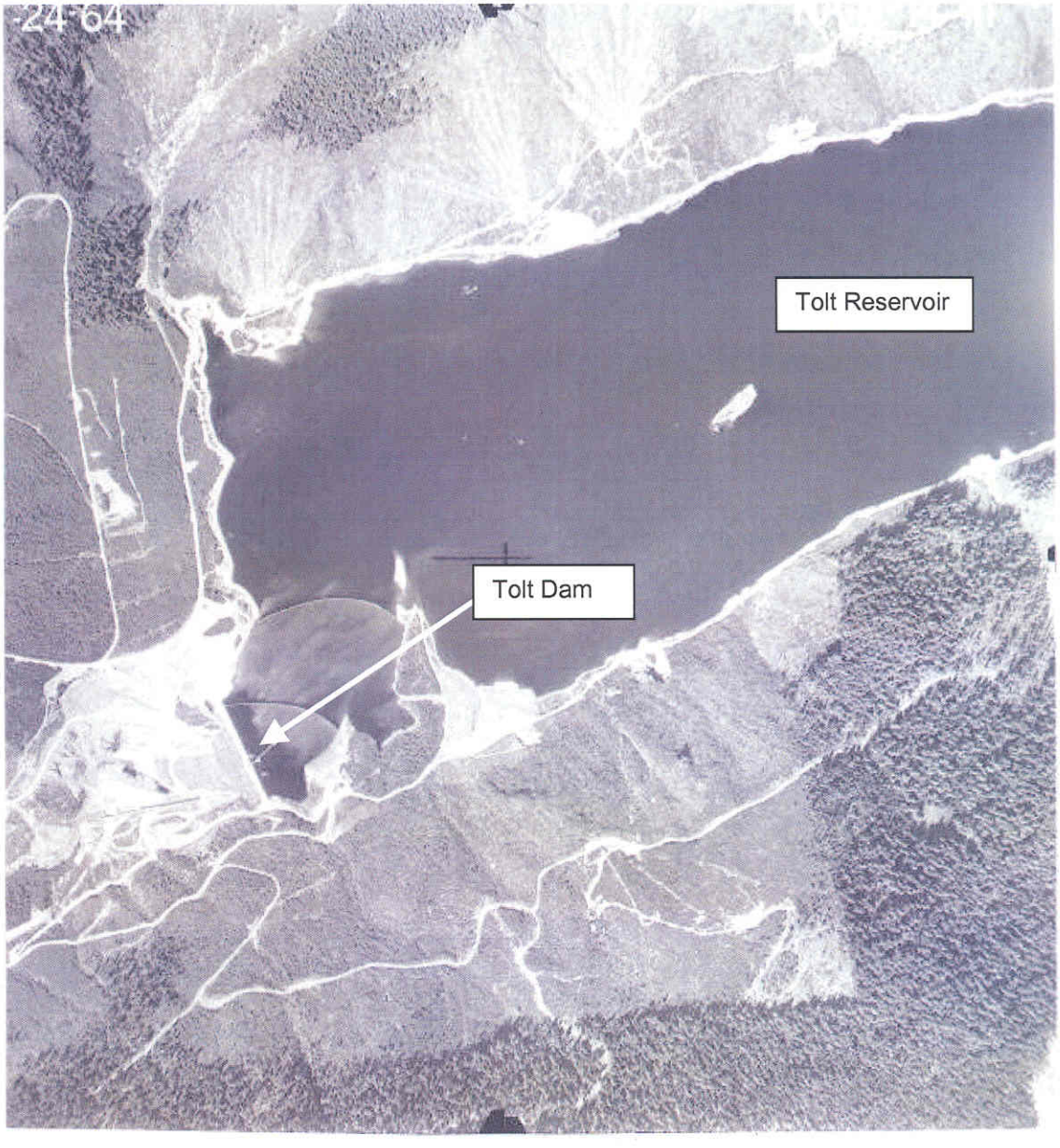

Photo 20: Seattle Public Utilities water supply dam and reservoir on the South Fork Tolt River.

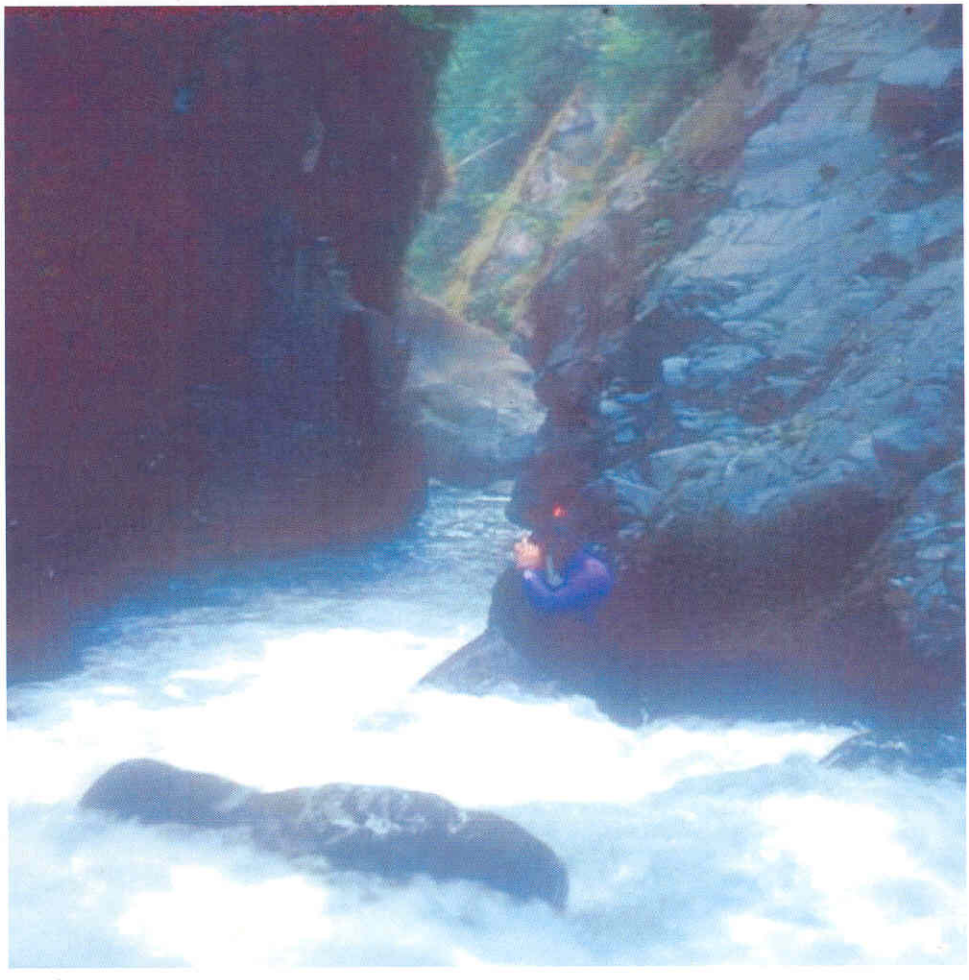

Photo 21: Bedrock canyon on the North Fork of the Tolt River. Photo Courtesy of Washington Trout.

At about river mile 2.0 (river kilometer 3.2), the Tolt emerges from its tributary valley into the mainstem Snoqualmie Valley. Deposition in this lowest section of the river has created a broad alluvial fan. The gradient of the channel crossing the fan is approximately 0.5 percent. The fan extends across the width of the Snoqualmie Valley and has forced the Snoqualmie River against the west valley wall. The modern Tolt is located on the southern edge of its alluvial fan. The city of Carnation occupies most of the center portion of the fan. Sediment aggradation, flooding, and channel migration are normal phenomena on alluvial fans. A levee system along the right bank of the Tolt extending from the mouth to river mile 1.7 (river kilometer 2.7) was constructed in the 1940s in order to protect the city of Carnation from flooding and channel migration.

6.3.2.6. Harris Creek

Harris Creek drains an area of 13.3 square miles (34.5 square kilometers) east of the Snoqualmie Valley. It originates from multiple wetlands located in channelways and depressions on the till surface. The channel descends to the Snoqualmie River floodplain through a steep ravine section. It crosses the floodplain in a low gradient channel, and then through a series of oxbow wetlands joining the Snoqualmie at river mile 22.7 (river kilometer 36.5). The Harris Creek basin ranges in elevation from 1060 feet (326 meters) down to 40 feet (12 meters) at its mouth on the Snoqualmie. The dominant land use in the Harris Creek basin is low-density, single-family housing. A small area in the eastern part of the basin remains in timber production.

6.3.2.7. Ames Creek

Ames Creek originates at Ames Lake on the west side (left bank) of the Snoqualmie River west of the city of Carnation. Ames Creek has a basin area of 7.7 square miles (20 square kilometers). Ames Lake and Ames Creek occupy a glacial recessional meltwater channel occupied during Booth's Stages 10 to 13 (Figure 8). Meltwater would have flowed through this channel from north to south during deglaciation. Subsequent channel incision has reversed the direction of flow (similar to the flow reversal described earlier in the Raging River valley), creating the present north-flowing drainage. Irregular topography in the vicinity of the lake and the presence of ice-contact deposits surrounding the lake (Booth, 1990) suggest that Ames Lake may have originated as a kettle, a depression left following melting of an isolated remnant of glacial ice.

As in other tributaries on the west side of the lower Snoqualmie Valley, the Ames Lake basin and the upland portions of the basin are pervasively developed with low to moderate densities of single-family housing. A ravine section between the lake and the Snoqualmie Valley floor is steep with more scattered development. The lowest 1.8 miles of Ames Creek flow through pasture on the Snoqualmie River floodplain. This entire length

of channel has been modified by dredging in order to improve drainage on adjacent agricultural land.

6.3.2.8. Cherry Creek

Cherry Creek has a watershed area of 25 square miles (79 square kilometers). Elevation ranges from 2760 feet (841 meters) on Drunken Charlie Mountain to 20 feet (6 meters) at the confluence with the Snoqualmie River, 3.0 miles (4.8 km) north of the city of Duvall. The headwaters of Cherry Creek drain a forested watershed underlain by glacial deposits and Tertiary bedrock. Bedrock is present at shallow depth over much of the upper watershed, even where there is a veneer of glacial deposits. This bedrock is exposed in the channel of the Cherry Creek watershed at numerous locations, creating a series of cascades and falls. The lowest of these, at river mile 6.8 (river kilometer 11), forms a natural upstream limit to anadromous fish access.

Cherry Creek originates in a series of lakes and wetlands occupying a complex topography of intersecting channelways. The channel then follows a single channelway for 5 miles (8 kilometers). Through this reach, the channel flows mostly over glacial sediments, although bedrock is commonly exposed in the channel. At river mile 2 (river kilometer 3.2), Cherry Creek emerges abruptly from this incised valley and flows into a broad lateral extension of the Snoqualmie River floodplain. At this location, channel gradient and confinement decrease rapidly, leading to localized sediment aggradation and formation of an alluvial fan. Aggradation and flooding threaten several houses built on the alluvial fan in this area.

For the lower 2 miles (3.2 kilometers), Cherry Creek flows through a broad, low-gradient reentrant into the surrounding glacial and bedrock uplands. The alluvium filling the bottom of this reentrant is a lateral extension of the Snoqualmie floodplain, and this area is inundated by even modest flood events on the Snoqualmie River. Prior to human modification, Cherry Creek followed a meandering alignment through this valley. In common with most of the rest of the Snoqualmie floodplain, this area was cleared for agriculture early in the twentieth century. Cherry Creek was relocated into a straight, excavated channel. Recent survey work by Washington Trout revealed that much of the original, meandering channel is still present adjacent to the existing excavated channel (Figure 24).

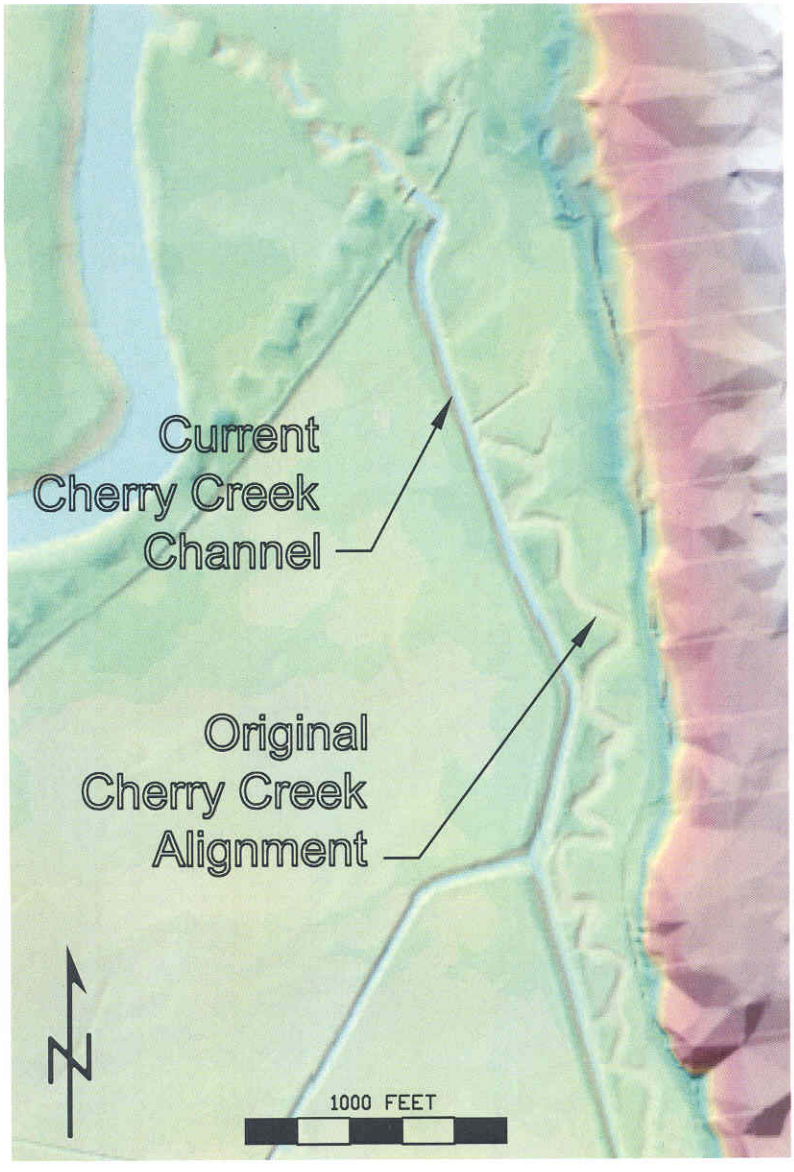

Figure 24: This shaded relief drawing shows the current, straight, excavated channel of Cherry Creek, next to the meandering, currently unoccupied original alignment. (Figure Courtesy of Washington Trout).

6.3.2.9. Small Tributaries to Lower Mainstem

There are a number of smaller tributaries to the lower Snoqualmie River, including Harris Creek, Tuck Creek, Weiss Creek, Langlois Creek, Adair Creek, Peoples Creek, and Ricci Creek, and numerous small unnamed tributaries. Many of these tributaries have common characteristics. For the most part, they originate as low-gradient streams on the rolling till uplands bordering the lower valley, often in headwater wetlands. Most of these streams flow through a steep reach that descends from the till upland to the valley bottom. This steep reach is generally located in a post-glacially incised ravine on the valley wall and is the primary source of sediment in these streams, often exhibiting channel erosion in response to development-related hydrologic changes. The steep incised ravine sections of these tributaries often intersect groundwater emerging from the valley wall, providing cool clean perennial base flow to the lower stream reaches. Typically, an alluvial fan has formed where these steep ravines open out onto the floor of the Snoqualmie Valley. Prior to non-native settlement, many of these streams flowed through valley-bottom wetlands as they crossed the floodplain to join the river. These valley-bottom reaches have generally been straightened and deepened in order to drain adjacent land for agriculture.

7.0 Human Influence on Geomorphic Processes

The Snoqualmie watershed has been subject to pervasive, albeit comparatively low-intensity, human modification. Despite this low-intensity land use, it is clear that human activities, taken as a whole, constitute the most substantial geomorphic perturbation in the Snoqualmie watershed since glaciation. The following is a description of some of the most geomorphically significant human activities in this watershed:

7.1. Logging

Logging has cumulatively affected more area in the Snoqualmie River watershed than any other land use activity (Photo 22). Logging began in the Snoqualmie watershed in the late 1800s and it has continued without interruption since that time. Many areas of the watershed have been logged twice and are now growing a third rotation of timber.

Logging can have a myriad of impacts on the fluvial network. Logging typically increases sediment delivery through a variety of mechanisms. Logging roads have been identified as the largest source of sediment associated with logging (Waters, 1995). Reid and Dunne (1984) demonstrated that fine sediment, forced through the gravel surfacing by truck traffic and washed into roadside drainage, can be the largest source of fine sediment in a watershed undergoing timber harvest. Interception of shallow groundwater by roadside ditches, creation of impervious road surfaces, and concentration of surface flow in roadway cross culverts can all contribute to increased peak flows. In the small steep channels, common to those portions of the watershed in forest production, this increased flow can cause channel erosion or initiate debris flows.

Independent of road influences, logged slopes are often more prone to landsliding than forested slopes (Sidle et al., 1985). When trees are cut, their roots decay over a period of years. Loss of tree-root reinforcement in the soil increases landsliding on steep slopes. Dramatic bank erosion and channel widening have been documented on the Tolt River as a result of historic logging of the riparian zone to the river's edge (Kennard, 2004).

In addition to increasing sediment discharge, logging in the Snoqualmie watershed (outside of the wilderness area) has largely eliminated old-growth trees from the standing stock available for LWD recruitment.

Although logging has a history and a continuing potential to cause significant adverse impacts to fluvial systems in the Snoqualmie watershed, many such impacts can be effectively mitigated by application of the controls mandated by the Washington State Forest Practices Act. Even in areas where logging has been conducted without such controls, this logged-off land probably has more potential to return to natural character and function, compared with areas used for agriculture, residential or commercial development, or any of the more intense and permanent land uses present in this watershed.

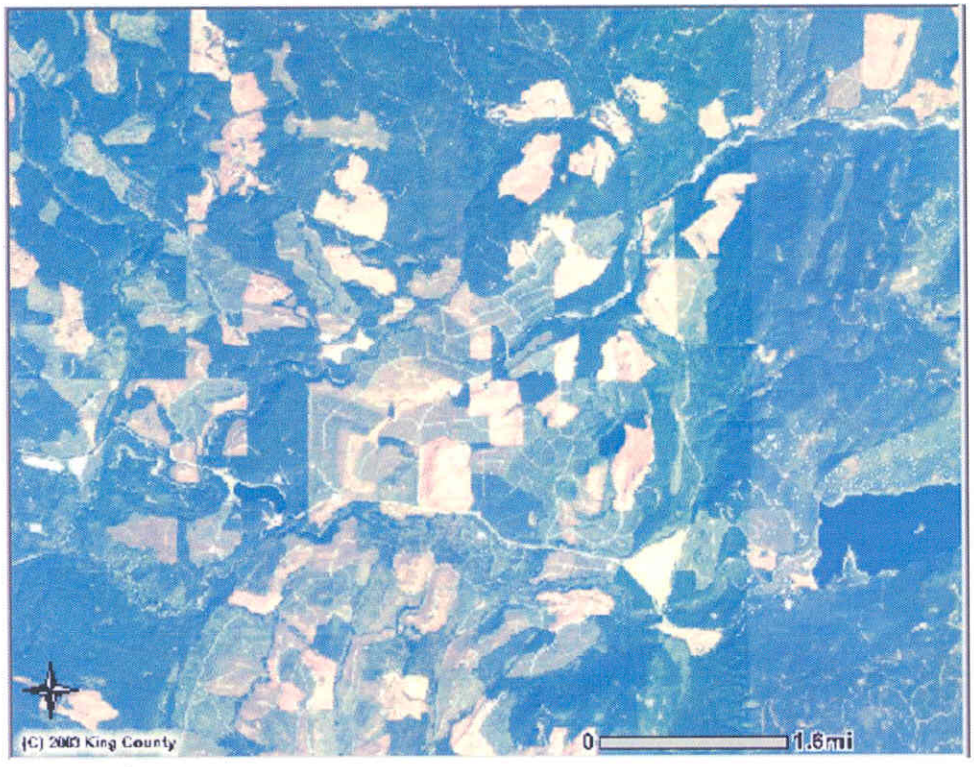

Photo 22: Logging clearcuts near the confluence of the North and South Forks, Tolt River.

7.2. Levee and Revetment Construction

There has been extensive construction of levees and revetments along the Snoqualmie River and its major tributaries (Figure 19). Constructed levees are continuous raised berms constructed along the riverbank and intended to contain floodwaters and prevent inundation of the natural floodplain. Revetments are sections of bank armoring (usually riprap) intended to prevent lateral migration of the river channel. These structures were largely built during a period of time when engineering control of river flooding, channel migration, and river alignment were widely seen as economic and life-safety enhancements, and little attention was paid to possible environmental impacts. Subsequent experience has shown that the protection provided by such projects is sometimes unreliable, the cost of maintenance can be high compared to the economic benefit, and such projects can have serious adverse environmental consequences (King County, 1993). Such projects have sometimes created an unrealistic sense of protection for adjacent properties, encouraging relatively high value land development in areas still at significant risk from riverine processes.

Many of the problems associated with levees and revetments occur because of the ways these structures alter natural geomorphic processes. Constructed levees confine floodwaters, raise flood elevations within the levees, and eliminate floodwater storage on the floodplain outside of the levees. These effects can worsen flooding and erosion in areas upstream and downstream or opposite the leveed section. Levees and revetments constrain a river to a fixed alignment, often imposing a simple channel geometry. An actively meandering river on the other hand typically develops a complex channel form with multiple sloughs and side channels. These complex forms provide a broad, complex riparian zone with multiple ecological niches for plant and animal species.

7.3. Dams

Dams with large reservoirs trap all of the suspended load, bedload, and LWD transported. The channel downstream may be sediment-starved and deficient in LWD. Lack of sediment supply can cause the channel downstream of the dam to incise the streambed texture to coarser. The only dam with a large reservoir in the Snoqualmie watershed is the South Fork Tolt River water supply dam. The elevated water surface in the reservoir behind a dam causes a corresponding elevation of the groundwater table in the area surrounding the reservoir. Given suitable topography, the resulting increase in pore water pressure can initiate landsliding. This mechanism activated a large landslide approximately 0.6 mile (1.0 km) downstream of the South Fork Tolt River dam during initial reservoir filling. This mechanism was also responsible for the 1918 “Boxley burst,” an approximately 1,000,000-cubic-yard (750,000-cubic-meter) landslide in Boxley Creek (a Snoqualmie River tributary) during filling of a water supply reservoir immediately south on the Cedar River.

7.4. Floodplain Clearing and Drainage

Floodplains along the lower Snoqualmie River offer flat topography and fertile soils. These areas were cleared for agriculture early in the non-native settlement of this area. Removal of the naturally occurring riparian forests reduces the source for LWD recruitment.

Prior to European settlement, much of the floor of the lower Snoqualmie Valley was wetland (Collins and Sheikh, 2002). Early settlers recognized the agricultural potential of the valley floor, and began clearing and constructing ditches in order to make the floodplain cultivatable. The best record of early agricultural land conversion comes from aerial photographs taken in 1936. This record shows that virtually all of the area in the lower Snoqualmie Valley, ultimately destined for agricultural production, had already been cleared and drained by that time.

Conversion and continued use of the lower Snoqualmie floodplain for agriculture has several significant ramifications for the geomorphic processes in this area. One obvious consequence of agricultural land use is the removal of most of the riparian forest that would otherwise be available to supply LWD to the mainstem.

Another consequence of agricultural use of the Snoqualmie River floodplain has been the extensive ditching required to drain the former wetlands to allow cultivation. This has dramatically altered the character of numerous, mostly small tributaries that cross these agricultural areas. These tributaries have typically been relocated through a rectilinear system of deep narrow ditches with little or no native riparian buffers (Figure 25). Many of these tributaries originate in or flow through steep ravines on the valley walls before reaching the floodplain. Under pre-developed conditions, these channels often formed alluvial fans at the break in slope between the ravine and the floodplain. The constructed ditch system does not accommodate the inevitable sediment accumulation formerly spread over the alluvial fan. As a result, the ditches require regular dredging in order to maintain their conveyance capacity. Examples of creeks now conveyed through agricultural ditches include Tuck Creek, Cherry Creek, and Peoples Creek.

7.5. Land Development

Land development as discussed here refers primarily to conversion of land from a largely forested condition to a landscape devoted to single- and multi-family residences, commercial structures, farms, and their associated infrastructure. Such conversions have a broad range of impacts to many natural systems. From the perspective of geomorphic processes, the most significant impacts result from changes in the hydrologic regime, especially dramatic increases in peak discharges in streams draining headwater areas (Booth, 1991). Erosion and channel incision as a result of development-related hydrologic changes have been well-documented in the Snoqualmie watershed (Photo 23) (Stoker, 1988). The direct impact of land development to stream channels tends to decrease with increasing contributing area. Despite dramatic impacts to a number of small tributaries, it is not clear that any such hydrologic impact can be documented for the mainstem Snoqualmie River.

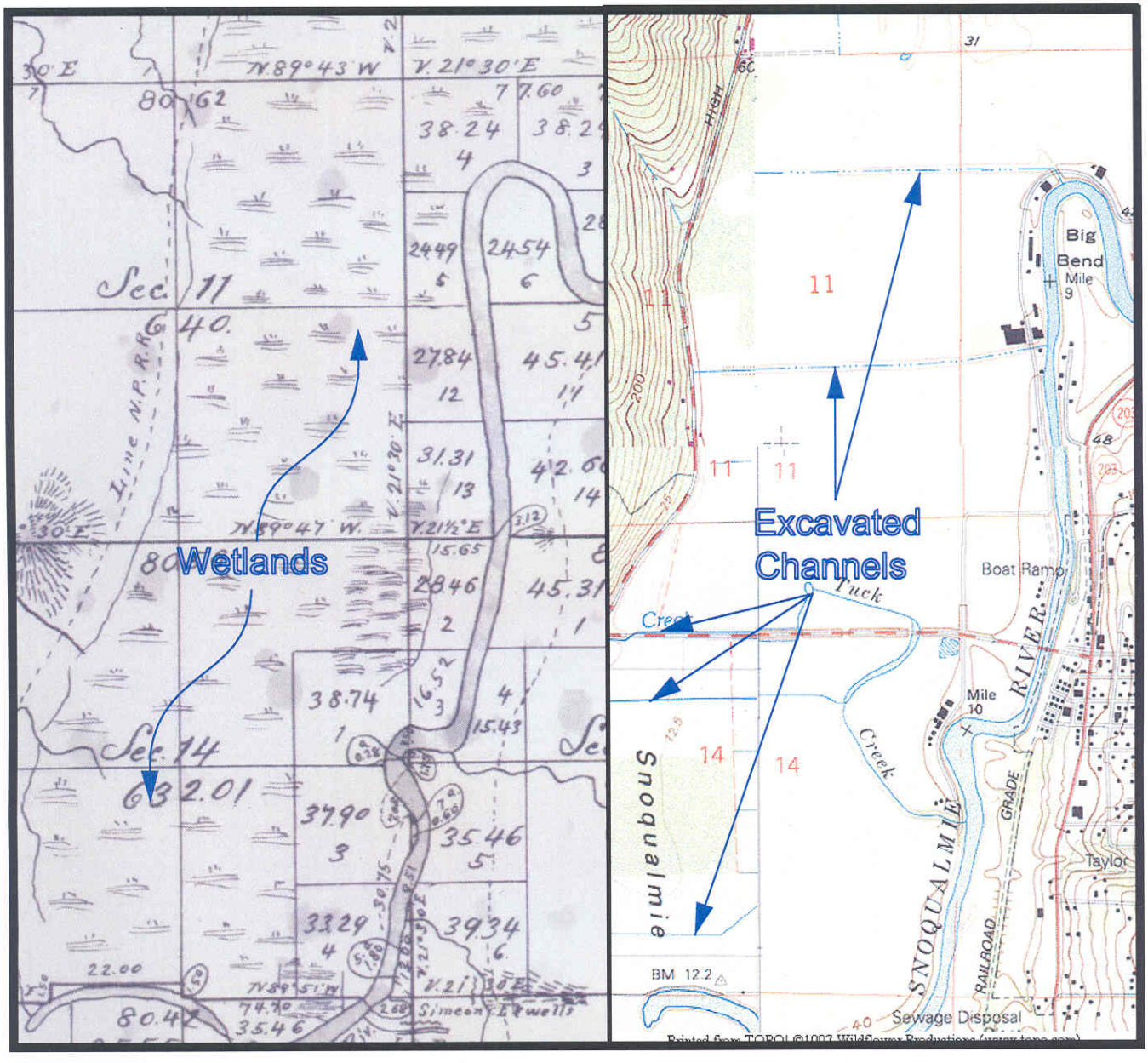

Figure 25: A Portion of the 1873 Govenment Land Office map (on the left) showing extensive wetlands on the Snoqualmie River Floodplain. Compare to recent USGS mapping of the same area (on the right) showing multiple excavated drainage channels and no wetlands

Photo 23: Severe erosion along a small, intermittent stream channel on the west wall of the Snoqualmie Valley in the vicinity of Carnation. This erosion is a result of increased peak flows resulting from upstream development. The geologic unit exposed in this canyon is Vashon advance outwash (Qva). This unit is especially subject to erosion by flowing water. Photo courtesy of Derek Booth.

8.0 Suggested Further Investigations

In the continuing effort to restore instream and riparian habitat, and to minimize risks to human life and property, it is critical to understand the physical processes that shape fluvial landscape features. During preparation of this report, several lines of investigation presented themselves.

- Some of the most heavily modified and frequently disturbed fluvial features in the Snoqualmie watershed are low-gradient channels that carry tributaries across the Snoqualmie floodplain to the mainstem channel. Such channels are common on the lower valley floodplain from Fall City all the way to the mouth. Many such channels have been straightened, shortened, disconnected from adjacent wetlands, and denuded of riparian forests. Because of their location downstream of steep ravines, and because of their low gradient, sediment accumulation in such channels is inevitable. An investigation of the biology and geomorphology of such channels would provide a valuable basis for working in cooperation with agricultural landowners to develop new management strategies for these systems.
- An extensive system of levees and revetments has been constructed along portions of the mainstem Snoqualmie River and on many of its tributaries. In large part, these facilities were intended to limit lateral movement of these channels. Several such facilities have been proposed for removal, but the removal has been delayed or abandoned because of concerns about the lateral or downstream impacts of the removal. The proposed removal of these facilities was predicated on the premise that a channel which is free to migrate across its floodplain is likely to sustain higher quality aquatic and riparian habitat as compared with a channel that is stabilized. It would be useful to investigate:
  - The likely extent and timing of increased channel mobility resulting from removal of bank protection and flood control structures, given the generally stable character of the river even before revetments were constructed.
  - The character and magnitude of habitat benefit associated with allowing a previous constrained channel the freedom to migrate.

9.0 Conclusion

The modern physical landscape in the Snoqualmie River watershed is a product of the geologic and geomorphic history of this area. The character of this landscape exerts a controlling influence on both the ecological regime and human habitation in the watershed. Landscape evolution is still very much a work in progress in this basin, however, and the processes of sediment erosion, transport, and deposition that sculpted the present topography remain active. These active processes play a critical role in creating modern habitat. For example, regular bedload movement in gravel-bed channels is critical for maintaining high-quality spawning habitat in these channels.

Many of these geomorphic processes, including large floods, landslides, channel migration, channel aggradation on alluvial fans, and LWD jam development, may appear catastrophic and even unnatural from the perspective of a human timeframe, but they are orderly, predictable, and inevitable when viewed on a geologic timescale. It is often the case that human activities that do not account for such processes entail unexpected risks and incur unexpected costs. Examples include houses built in active floodplains, communities located on actively aggrading alluvial fans, or roads built in areas of active channel migration. Recognition and characterization of and accounting for such geomorphic processes is a critical step both to implement effective habitat enhancement and conduct appropriate land-use planning in the Snoqualmie River watershed.

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11.0 Glossary

Adverse gradient: A section of stream channel that slopes uphill in the direction of stream flow. Channel reaches with adverse gradient, depending on their length, form in-channel pools, wetlands, and lakes.

Alluvial fan: A deposit of generally coarse sediment that accumulates in an area where a stream's gradient, and therefore its ability to carry sediment, decreases rapidly.

Andesite: A volcanic rock common in the Cascade Mountains. Fresh (unweathered) andesite consists of a dark gray matrix inset with scattered light and dark colored crystals.

Base flow: The amount of flow in a stream during an extended dry period, when there is no perceptible contribution from preceding storms. See Peak Flow.

Bedload: The coarser portion of a stream's sediment load that is transported by rolling or sliding along the streambed. See Suspended Load.

Cirque: A bowl-like feature at the head of an alpine valley, scoured out by glaciers that occupied the valley. Many lakes in alpine settings occupy cirques.

Clast: A single (generally coarse) sedimentary particle; for example, a single piece of gravel.

Cross-bedding: A distinctive depositional pattern, often seen in sandy gravelly sediments that indicate that the sediment was deposited in flowing water.

d_{50}: This denotes the diameter of the average grain size in a sediment sample. For example, for sediment with a d_{50} of 2 mm, half (by weight) of the grains are smaller than 2 mm in diameter and half are larger.

Delta: A delta is a sediment deposit that occurs where a stream enters a body of standing water like a lake or ocean.

Fluvial: Related to rivers and streams.

Gabbro: A dark colored plutonic rock (see below) composed of coarse dark crystals and rich in iron and magnesium.

Geomorphology: The study of the geologic processes that shape the earth's surface, and of the features that result from those processes.

Granitic: Granitic refers to a group of plutonic rocks (see below) that are rich in silica and aluminum, and have the characteristic speckled appearance of granite. Common granitic rocks in the Cascade Mountains include granodiorite and tonalite.

Impervious surface: Any type of land surface that does not allow precipitation to soak into the ground. Generally, impervious surfaces are created by development activities; for example, paved roads or rooftops. A few natural surfaces are impervious; for example, bare exposed rock.

Lacustrine: Related to freshwater lakes.

Mass wasting: Any geomorphic process in which soil or rock, not being carried by another medium (wind or water, for example) moves downhill. Landslides and rock fall are examples of mass wasting.

Peak flow: A large stream flow of short duration that results from a large storm. See base flow.

Plutonic: This refers to rock that was formed when molten rock cools and hardens deep under the earth's surface. Granite is a familiar plutonic rock.

Sinuosity: A measure of how straight or winding a river channel is. Sinuosity is found by dividing the channel distance between two points by the straight-line distance between the same points. For example, if the distance between two points along a winding channel is three kilometers, but the points are only two kilometers apart along a straight line, then that reach of channel has a sinuosity of one and a half.

Sorting: This is a measure of how much variation there is in the size of particles in a deposit. If all the particles are nearly the same size, as in clean sand, for example, the sediment is well sorted. If it contains particles of a wide range of sizes, for example, a mixture of sand, gravel, and cobbles, the sediment is poorly sorted.

Stade: During a glacial epic (commonly known as an ice age), there are typically multiple episodes of glacial advance. Such individual advances and retreats are termed stades.

Stratigraphic: Stratigraphic comes from stratigraphy, the study of layering in geologic deposits. Stratigraphy can reveal information about age, depositional environment, and post-depositional deformation of a geologic deposit.

Suspended load: The finer portion of a stream's sediment load that is transported suspended in the streamflow. See bed load.

Talus: A slope covered by angular rock fragments. Taluses are generally located below cliffs and are the accumulation of the rocks that fall off of the cliff.

Tectonic: Related to large-scale movement of the earth's crust. For example, vertical movement of the crust that creates mountain ranges or horizontal movement of crustal plates.

Texture: The texture of a granular geologic material refers to size and distribution of its constituent grains.

Underfit stream: A relatively small modern stream that flows through a large valley carved by much larger flows in the geologic past.

Valley confinement: The extent to which a stream channel is directly confined by its valley walls. For example, a stream flowing in a steep-sided gully is highly confined by the gully walls on either side. In contrast, the channel of a large stream flowing through a broad floodplain is free to move across its floodplain, seldom if ever encroaching on the valley walls. Such a stream would have low confinement.