Holocene and Recent Geomorphic Processes, Land Use, and Salmonid Habitat in two North Puget Sound River Basins

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The quantity, quality, and distribution of salmonid habitats in the Skagit and Stillaguamish River basins have changed dramatically in response to post-glacial landscape evolution and volcanism over the last 16,000 years, and the more recent history of land use (approximately 150 years). After retreat of the Cordilleran ice sheet about 16,000 years ago, streams incised rapidly into valley-filling glacial sediments, lowering valley floors and creating terraces. Mainstems and floodplain sloughs on valley floors provided the majority of habitat, but moderate-gradient tributaries on terraces provided additional habitat for some salmonids. Channels in bedrock terrain were too steep to support anadromous salmonids and remain so today. Voluminous lahars from Glacier Peak approximately 5,500 years before present created an extensive low-gradient delta on the Skagit River, which then developed abundant habitats in wetlands and distributary channels. Since non-Native American settlers arrived in the mid-1800s, removal of beaver ponds, diking, ditching, and dredging of streams on the floodplains and deltas has isolated or obliterated approximately 50% of the coho salmon winter rearing habitat in both basins. These losses are associated mainly with agricultural practices, which occupy the same landforms as the majority of historical coho salmon habitat. Forestry activities are concentrated on the steeper slopes of the glacial sediments and bedrock terrain, and contribute to habitat losses by increasing sediment supplies and reducing wood abundance. Understanding the interplay of Holocene landscape evolution, geomorphic processes, land use, and salmonid habitat provides a context for developing habitat restoration programs.

INTRODUCTION

Changes in stream habitat conditions over the past 150 years have played a significant role in reducing salmonid populations in the Pacific Northwest [*Bisson et al.*, 1992]. In the northern Puget Sound region of Washington State, these changes have resulted from direct manipulations of streams and rivers such as levee construction, and filling or ditching of channels [*Beechie et al.*, 1994], as well as from changes to geomorphic processes including landsliding and recruitment of wood from riparian forests [*Beechie*, 1998]. However, there has been little attempt to understand how these changes compare to natural habitat changes prior to recent land uses. An accounting of natural changes to the landscape and habitat conditions since retreat of the continental ice sheet around 16,000 years before present (ybp) provides a long-term context for recent habitat alterations caused by land uses during the past 150 years, and illustrates how recent disturbances differ from those prior to

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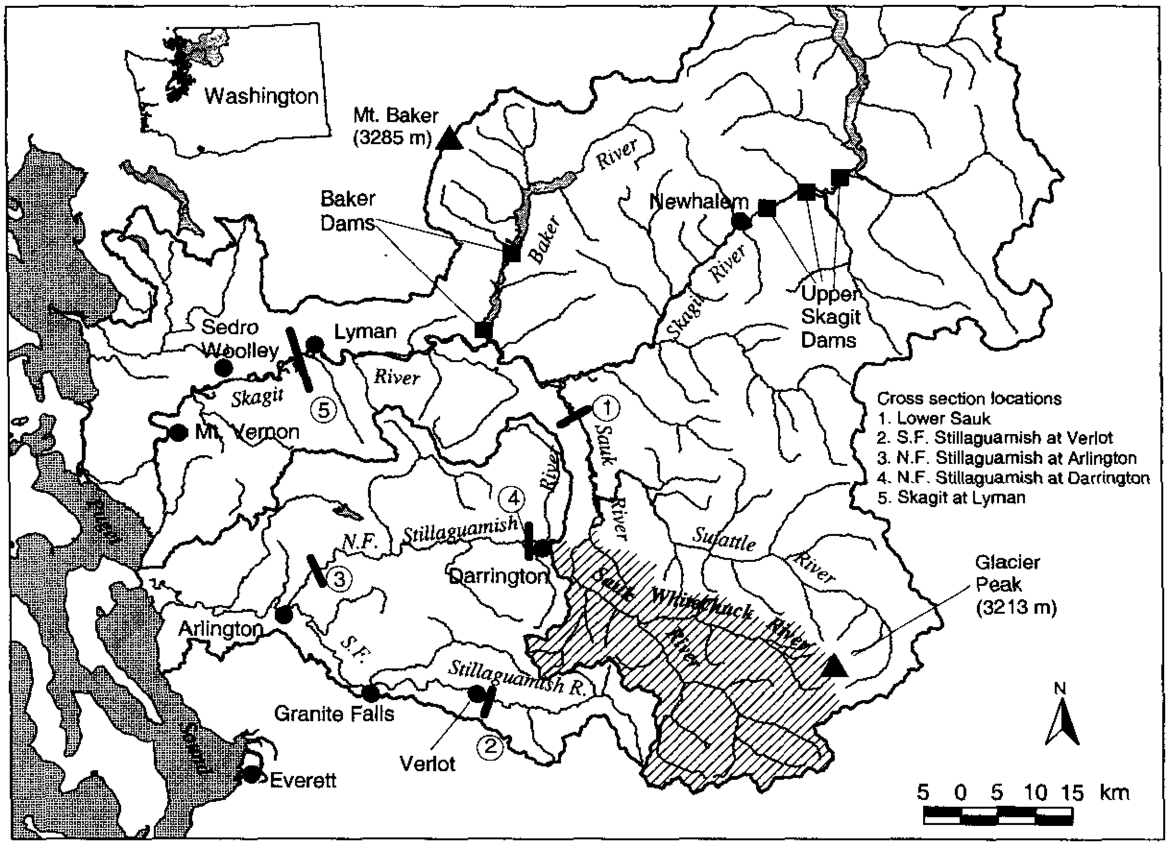

Figure 1. Study area map indicating watershed locations and boundaries, major rivers, and valley cross section locations. Hatched area indicates portion of basin that flowed into the North Fork Stillaguamish prior to 12,500 ybp, then was diverted into the Skagit drainage by lahars from Glacier Peak after approximately 12,500 ybp.

settlement by non-Native Americans. Understanding the Holocene history of geomorphic processes and fish habitat may be useful for interpreting the origins of genetic and phenotypic differences among salmon stocks [e.g., *McPhail and Lindsey*, 1986], whereas understanding how recent causes of habitat loss vary by land use and geomorphic setting is important for devising successful approaches to habitat protection or restoration [e.g., *Cairns*, 1990; *Beechie and Bolton*, 1999].

In this paper we synthesize previous studies to describe how post-glacial evolution of the landscape and recent land uses altered fish habitats in two watersheds of northern Puget Sound. We first recount the post-glacial geomorphic history of the area, describing long-term processes that altered valley floor elevation relative to sea level, which in turn altered stream channel lengths and slopes in both river basins. We then describe how short-term events such as valley-burying lahars (mudflows of volcanic origin) or forest fires may have affected habitat-forming processes and habitat conditions, and how land uses over the past 150 years have altered geomorphic processes and fish habitat in the study area. We also compare magnitudes of losses among different habitat types by estimating changes in potential coho salmon production. Finally, we describe how understanding the relationships among landforms, geomorphic processes, and fish habitat can help in developing strategies for salmonid habitat protection and restoration.

STUDY AREA

The 10,040 km^2 study area encompasses the 1,770 km^2 Stillaguamish River basin and the 8,270 km^2 Skagit River basin (Figure 1). Elevations in the study area range from sea level to 3,285 m on Mount Baker, and numerous peaks in the Skagit basin exceed 2,500 m. Elevations in the Stillaguamish basin are lower, with few peaks exceeding 2,000 m. Average annual rainfall in the study area ranges

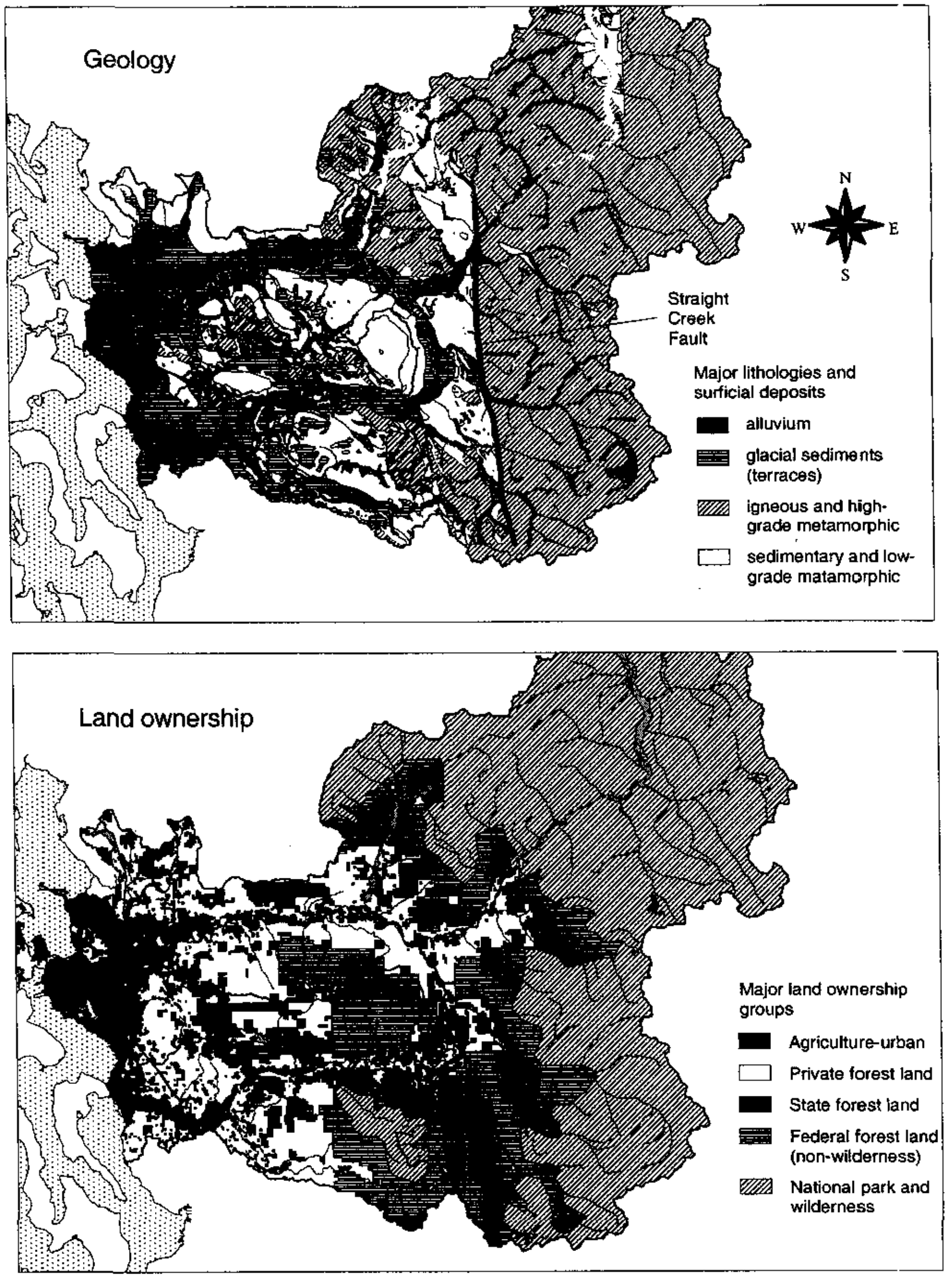

Figure 2. Simplified geology and land ownership in the study area basins. Geologic map based on 1:100,000 scale GIS themes obtained from Washington Division of Geology and Earth Resources, Olympia, Washington.

from about 80 cm in the lowlands to over 460 cm in the vicinity of Glacier Peak, and generally increases with elevation.

The core of the northern Cascade Range in the study area is composed mainly of high-grade metamorphic and igneous rocks of continental origin, which are located east of the Straight Creek Fault [*Brown et al.*, 1987] (Figure 2). The mountains and foothills west of the Straight Creek fault are composed generally of low-grade metamorphic and sedimentary rocks of marine origin, and consist of diverse rock units brought together by the northward movement of previously accreted terrains [*Brown et al.*, 1987]. Two Quaternary volcanoes, Glacier Peak and Mount Baker, are located at the eastern and northern boundaries of the study area, respectively. A lobe of the Cordilleran ice sheet repeatedly advanced into and retreated from Puget Sound during the late Pleistocene (40,000 ybp to 16,000 years ybp) [*Crandell*, 1965; *Booth*, 1987; *Porter and Swanson*, 1998], depositing a series of lacustrine clays, glacial till, and outwash sands and gravels that filled major river valleys to an elevation of at least 600 m (Figure 2) [*Heller*, 1979; *Brown et al.*, 1987].

Headwater streams are typically steep (channel slope > 0.2) and relatively small (bankfull width < 5 m), originating on mountain slopes underlain by various lithologies. Channel slopes decrease dramatically as streams traverse terraces carved into valley-filling glacial deposits (slopes typically between 0.01 and 0.08), and channel slopes are typically < 0.01 on floodplains.

Forest types in the study area vary widely depending on elevation and physical setting. Floodplain forests of the Skagit, Stillaguamish, and Sauk Rivers were historically densely populated with red alder (*Alnus rubra*), but large Sitka spruce (*Picea sitchensis*), western redcedar (*Thuja plicata*), and black cottonwood (*Populus trichocarpa*) grew within the alder forest [*Ayres*, 1899]. Upland forests to an elevation of about 600 m were dominated by Douglas-fir (*Pseudotsuga menziesii*), with the remainder in western redcedar, western hemlock, and Sitka spruce [*Gannett*, 1899; *Ayres*, 1899]. This area is currently known as the Western Hemlock Zone, based on climax forest type [*Franklin and Dyrness*, 1973]. In this zone, Douglas-fir dominated forest stands for the first 200 years after stand-replacing fire, and gradually succeeded to climax stands of western hemlock (*Tsuga heterophylla*) beyond 200 years [*Munger*, 1940]. In some wetter areas and along streams Sitka spruce or western redcedar were the most common species. Silver fir (*Abies amabilis*) and western hemlock dominate forests from about 600 m to 1,200 m (the Silver Fir Zone), and higher elevations are in the Alpine Fir (*A. lasiocarpa*) Zone [*Ayres*, 1899; *Franklin and Dyrness*, 1973].

Settlement of the study area by non-Native Americans began in the 1860s, and clearing and diking of lowlands for agriculture dominated land uses for the next few decades [*Interstate Publishing Company*, 1906]. Removal of kilometers-long raft jams by 1879 allowed rapid expansion of logging and agriculture up the river valleys, and agricultural use of upriver floodplains was extensive by 1909 [*Interstate Publishing Company*, 1906; *Mangum et al.*, 1911]. Agricultural and rural residential uses today cover 9% of the study area and are located predominantly in the lower floodplains and deltas (downstream of Lyman in the Skagit basin and downstream of Arlington in the Stillaguamish basin). Commercial forests owned by private companies, the State of Washington, or the U.S. Forest Service cover 41% of the basin and are located in the uplands. Urban development covers less than 1% of the study area. Forty-four percent of the area lies within the federally-owned North Cascades National Park, Mt. Baker and Ross Lake National Recreation Areas, Glacier Peak Wilderness, and Boulder River Wilderness. The remaining 1,040 km^2 of the Skagit basin is in the Province of British Columbia.

Anadromous salmonid species (i.e., salmonids that live the adult portion of their lives in the marine environment) in the study area include chinook salmon (*Oncorhynchus tshawytscha*), pink salmon (*O. gorbuscha*), chum salmon (*O. keta*), coho salmon (*O. kisutch*), sockeye salmon (*O. nerka*), steelhead trout (*O. mykiss*), cutthroat trout (*O. Clarkii*), and dolly varden char (*Salvelinus malmo*). There is significant overlap in the ranges of these species, and life history patterns vary considerably [*Groot and Margolis*, 1991]. Coho salmon, steelhead trout, cutthroat trout, and dolly varden char generally spawn in smaller and steeper streams (although at different times of year), and juveniles spend their first year or two in freshwater (*Williams et al.*, 1975). Chinook salmon typically spawn in the largest rivers, and most juveniles migrate to sea soon after they emerge from the gravel (*Williams et al.*, 1975). Pink and chum salmon tend to spawn in low gradient streams of widely varying sizes (but at different times and in different microhabitats), and juveniles migrate to sea immediately after emergence from the gravel (*Williams et al.*, 1975). Sockeye salmon spawn primarily in Baker Lake and upper Baker River, and juveniles rear in the lake for one year before moving to sea (*Williams et al.*, 1975). Estuaries provide an important rearing area during smoltification (the transition from freshwater to saltwater) for all species.

The ranges of coho salmon, steelhead trout, cutthroat trout, and dolly varden char in freshwater are limited mainly by natural barriers to upstream migration such as bedrock falls. Other species have shorter migrations and are limited in range by availability of preferred habitats. Upstream migration to the Baker River system has been blocked by the installation of two hydroelectric dams, but anadromous fish production is maintained through trapping and hauling operations, in addition to the maintenance of sockeye spawning beaches and smolt bypass trapping. Migration into the upper South Fork of the Stillaguamish River was naturally blocked at Granite Falls until 1954 when a fish ladder was constructed to permit anadromous fish access into the upper basin.

Adult coho salmon enter the Skagit and Stillaguamish Rivers in late summer and early fall. Spawning is concentrated in smaller tributaries, and occurs primarily between

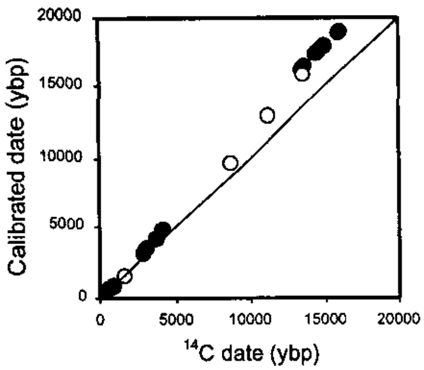

Figure 3. Calibrated dates of major events described in this paper plotted against their respective ^{14}C dates. Filled circles represent paired calibrated and ^{14}C dates reported by *Beale* [1991] and *Porter and Swanson* [1998]. Open circles indicate our calibrations of ^{14}C dates reported by *Benda et al.* [1992]. Calibrations were made using CALIB 4.0 [*Stuiver and Reimer*, 1993].

November and January. Fry emerge from the gravel in March and April and soon establish their summer rearing territories. In general, juvenile coho salmon typically remain in their natal streams, although some juveniles may be gradually displaced downstream as the summer progresses [*Chapman*, 1962; *Sandercock*, 1991]. With the first fall floods (usually in late September or October in the study area) juveniles migrate to winter rearing areas, including beaver ponds, off-channel ponds, and protected side channels [*Scarlett and Cederholm*, 1984; *Peterson and Reid*, 1984]. Coho leave their winter rearing areas in March and April and migrate to saltwater soon after.

DATA SOURCES AND METHODS

Our assessment of the distribution and function of habitats from 16,000 ybp to 150 ybp is less detailed than our assessment of habitats after 150 ybp because there are no direct means for characterizing aquatic habitats prior to 150 ybp. Therefore, we separate this paper into two sections with differing analysis methods and levels of resolution. The first section describes landscape and habitat change from 16,000 ybp to 500 ybp. For this time period we rely largely on studies of isostatic uplift, sea-level change, valley incision, and volcanic eruptions to explain changes in valley morphology and stream habitats. The second section describes pre-settlement geomorphic processes and habitat conditions (500 ybp to 150 ybp) and land use impacts to habitats over the past 150 years. We infer pre-settlement rates of habitat-forming processes such as fire or mass wasting based on their current behavior or field evidence of past occurrences. We use more detailed information on abundance of different habitat types to quantify habitat change due to land uses from 150 ybp to present. For all time periods we assume that anadromous salmonid species have habitat preferences similar to those at present. A brief summary of data sources and methods for each time period follows.

Holocene History of the Landscape and Fish Habitat (16,000 ybp to 500 ybp)

To describe landscape and habitat changes over the past 16,000 years, we compiled and analyzed data from numerous studies of ice retreat, sea-level change, isostatic uplift, and lahars. In the process of assembling these data we encountered some difficulty in reconciling ^{14}C dates and calibrated dates from the various sources. Differences between calibrated dates and ^{14}C dates are relatively small during the past 5,000 years, whereas differences between calibrated dates and ^{14}C dates near 16,000 ybp may be as much as 2,900 years (Figure 3). While most recent studies reported both calibrated dates and ^{14}C dates, a few earlier studies reported only ^{14}C dates. For studies reporting only ^{14}C dates, we calibrated ^{14}C dates using CALIB 4.0 [*Stuiver and Reimer*, 1993]. Our calibrations were based only on information included in the published sources, and the original sources did not include all of the inputs requested by CALIB 4.0. This missing information resulted in a relatively small systematic error in the calibration (evident in Figure 3). Therefore, the timeline presented here should be considered approximate.

During the Vashon Glaciation of the Puget Lowland (18,500 ybp to 16,000 ybp), the land surface was significantly lower than today due to the weight of the ice sheet [*Thorson*, 1980]. Isostatic depression was probably at least 200 m in northern Puget Sound during the glaciation [*Thorson*, 1980; *Booth*, 1987], and for the purposes of this paper we assume that depression in the study area was 200 m at ice retreat (Figure 4). Rebound of the land surface after ice retreat was initially more than 100 mm/yr, but then slowed to 20 mm/yr before 11,000 ybp [*Dethier et al.*, 1995]. We calculated uplift using a rate of 100 mm/yr from 16,000 ybp to 12,500 ybp, and 20 mm/yr after 12,500 ybp based on *Dethier et al.* [1995].

Estimates of sea level at various locations around the world approximately 18,000 ybp range from 102 to 163 m lower than today, whereas sea level in 13,000 ybp was approximately 60 m lower than today [*Matthews*, 1990]. From these data we calculated that sea level at ice retreat (16,000 ybp) was about 90 m lower than today, and that sea level rose about 12 mm/yr between 18,000 ybp and 13,000 ybp. A study of six Puget Sound salt marshes

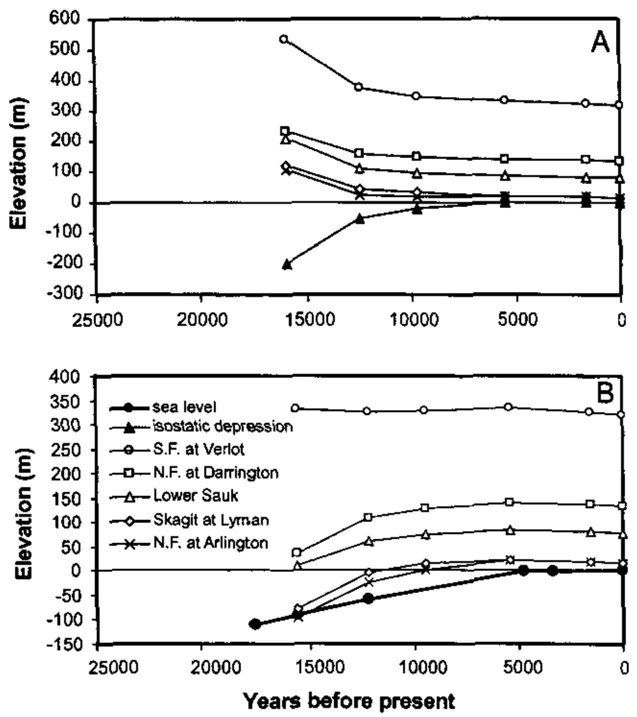

Figure 4. (A) Present-day elevations of ^{14}C-dated terraces at five cross sections (open symbols, locations shown in Figure 1), and isostatic rebound over the past 16,000 years. (B) Subtraction of isostatic depression from present-day terrace elevations yields corrected valley floor elevations relative to present-day sea level (open symbols), for comparison to documented changes in sea level over the past 16,000 years (filled circles).

showed that by 5,000 ybp sea level was approximately 3 m lower than today [*Beale*, 1991]. These data indicate that sea level rise averaged 7 mm/yr between 13,000 ybp and 5,000 ybp (rising from –60 m to –3 m), and has been less than 1 mm/yr since 5,000 ybp (rising from –3 m to 0 m).

To estimate changes in river valley elevations over the last 16,000 years, we first assumed that the highest terrace at each of five valley cross sections was the elevation of the valley floor at ice retreat (i.e., the valley floor elevation prior to erosion of the glacial sediments). (Cross section locations are shown in Figure 1.) We then measured elevations of other ^{14}C-dated valley floor surfaces on USGS topographic maps. Dated valley floor deposits were either lahar deposits from Glacier Peak [*Beget,* 1982; *Dragovich et al.*, 2000] or river gravel deposits on terrace surfaces [*Benda et al.*, 1992].

Once we had compiled the data for isostatic uplift, sea level, and river incision, we combined these data to estimate changes in valley floor elevations relative to sea level. We subtracted isostatic depression from the terrace elevations to estimate post-glacial valley elevation at each cross section. By comparing these data to changes in sea level, we estimated changes in location of river mouths in each study basin. We also described changes in drainage patterns, tributary length, and habitat quality resulting from volcanic eruptions and lahars, based on previous studies.

Recent Changes to Geomorphic Processes and Fish Habitat (500 ybp to present)

We describe geomorphic processes and natural disturbance regimes between 500 ybp and 150 ybp based primarily on previous studies of fire regimes, mass wasting, and recruitment of wood to streams in the study area. Effects of geomorphic processes on habitat characteristics are also summarized based on the scientific literature. We describe resultant pre-settlement habitat conditions using data from reference sites [*Beechie et al.*, 1994; *Pess*, unpublished data], as well as historical reconstructions of habitat conditions at approximately 150 ybp [e.g., *Collins and Montgomery*, this volume].

To describe how habitats have been altered by land uses, we rely primarily on data from *Beechie et al.* [1994] for the Skagit basin, and on *Pess and Collins* [unpublished data] for the Stillaguamish basin. Both studies employ the simple stratification of habitat types listed in Table 1. Methods for estimating historic and current habitat areas differ by habitat type, so we briefly summarize these methods here.

We examined reduction of pool areas in tributary habitats (streams < 10 m wide) by comparing pool areas in managed streams to pool areas in unlogged reference streams. Data for reference sites and for present-day conditions in the Skagit River basin were from *Beechie et al.* [1994]. Data for present-day conditions in the Stillaguamish River basin were from *Pess* [unpublished data]. For mainstem rivers we were unable to directly estimate changes in habitat conditions, but we describe likely changes based on recent studies in Puget Sound.

Historical areas of slough habitats (both side channels and distributaries) were estimated from historical maps, notes, and photos, as well as field evidence of their prior locations [*Beechie et al.*, 1994; *Collins*, unpublished data; *Pess*, unpublished data]. Present day areas were measured from aerial photographs and in the field. Lake areas were measured directly from historical and current maps [*Beechie et al.*, 1994].

Pre-settlement beaver pond areas in tributaries were estimated based on natural frequencies of beaver ponds in other parts of the U.S. and average pond area from present-day ponds in the study area. Natural beaver pond frequencies in the U.S. range from 2 ponds/km to 16 ponds/km

Table 1. Description of habitat types used to quantify loss in coho salmon rearing habitat [adapted from *Beechie et al.*, 1994].

Habitat type	Description
Mainstem	Channels with summer wetted width greater than 6 m (bankfull width generally greater than 10 m).
Tributary	Channels with summer wetted widths less than 6 m (bankfull widths generally less than 10 m).
Side-channel slough	Channels branching from a mainstem river and rejoining the river downstream. They typically have more than 90% of their surface area in pools in the summer, and maintain pool or pond-like characteristics during floods.
Distributary slough	Channels branching from the mainstem and entering estuaries. They typically have more than 90% of their surface area in pools in the summer and maintain pool-like conditions during winter base flow.
Ponds	Beaver ponds and other natural impoundments with surface area less than 5 ha.
Lakes	Natural impoundments or reservoirs with surface area greater than 5 ha.

[*Naiman et al.*, 1988]. We used the conservative lower limit of this range (2 ponds/km) for the historical pond frequency, and an average pond area of 1660 m^2 [*M.M. Pollock*, Northwest Fisheries Science Center, Seattle, Washington, unpublished data]. Present-day pond areas were measured from aerial photographs and in the field [*Beechie et al.*, 1994; *Pess*, unpublished data].

We calculated smolt production as the product of total habitat area (for each habitat type), density of juvenile coho occupying that habitat type, and survival to smolt stage [*Beechie et al.*, 1994]. Densities of rearing juvenile coho and survival rates to smolt stage (the freshwater-saltwater transition) are shown in Table 2. Juvenile coho populations are limited by availability of winter rearing habitat at present [*Beechie et al.*, 1994; *Pess*, unpublished data], so we focus our analyses of habitat losses on winter rearing habitats. ("Winter limited" means that summer habitats are more abundant and produce more fish than winter habitat areas can accommodate. Therefore, availability of winter habitat limits smolt production.) We do not consider changes to habitat quality (e.g., stream temperature or contaminants) because we are currently unable to quantify their effects on salmonid populations.

HOLOCENE HISTORY OF THE LANDSCAPE AND FISH HABITAT

Since retreat of the continental ice sheet about 16,000 ybp [*Porter and Swanson*, 1998], three long-term processes have driven landscape evolution in the two basins: isostatic uplift, erosion of glacial sediments from the valleys, and changes in sea level. Fish habitats were also temporarily altered by valley-burying lahars during the 12,500-ybp and 5,500-ybp eruptive periods of Glacier Peak (Figure 5). We separate our description of landscape evolution and fish habitats into three time periods separated by the Glacier Peak eruptions: 16,000—12,500 ybp, 12,500—5,500 ybp, and 5,500—500 ybp.

Glacial Retreat to 12,500 ybp

At ice retreat (approximately 16,000 ybp), land elevations and sea level were both much lower than today [*Thorson*, 1980; *Matthews*, 1990], and both began rising as the ice moved northward from Puget Sound [*Dethier et al.*, 1995; *Matthews*, 1990]. Accounting for isostatic depression and river incision at ice retreat we calculated that the 16,000-ybp Skagit and Stillaguamish River valley floors were 80 m and 90 m lower than today, respectively (Figure

Table 2. Densities of juvenile coho salmon (fish/m^2), density independent survival to smoltification, and resultant smolt production estimates for each of the six habitat types (smolts/m^2) [adapted from *Beechie et al.*, 1994]. Smolt production estimates for mainstem and lake habitats are in smolts/km (sm/ka) and smolts/ha (sm/ha), respectively.

Habitat Type	Density at a stage (fish/m^2)	Survival to smolt	Potential smolt production (smolts/m^2)
Side Channel and Distributary Slough			
Summer	1.3	0.25	0.319
Winter	2.5	0.31	0.775
Tributary			
Pool (summer, all pools)	1.7	0.25	0.425
Pool (winter, only backwater pools)	3.5	0.31	1.085
Riffle (Summer)	0.7	0.25	0.17
Riffle (Winter)	0.0		0.0
Mainstem			600 sm/km
Pond			
Summer	1.5	0.25	0.375
Winter	3.8	0.31	1.163
Lake			25 sm/ha

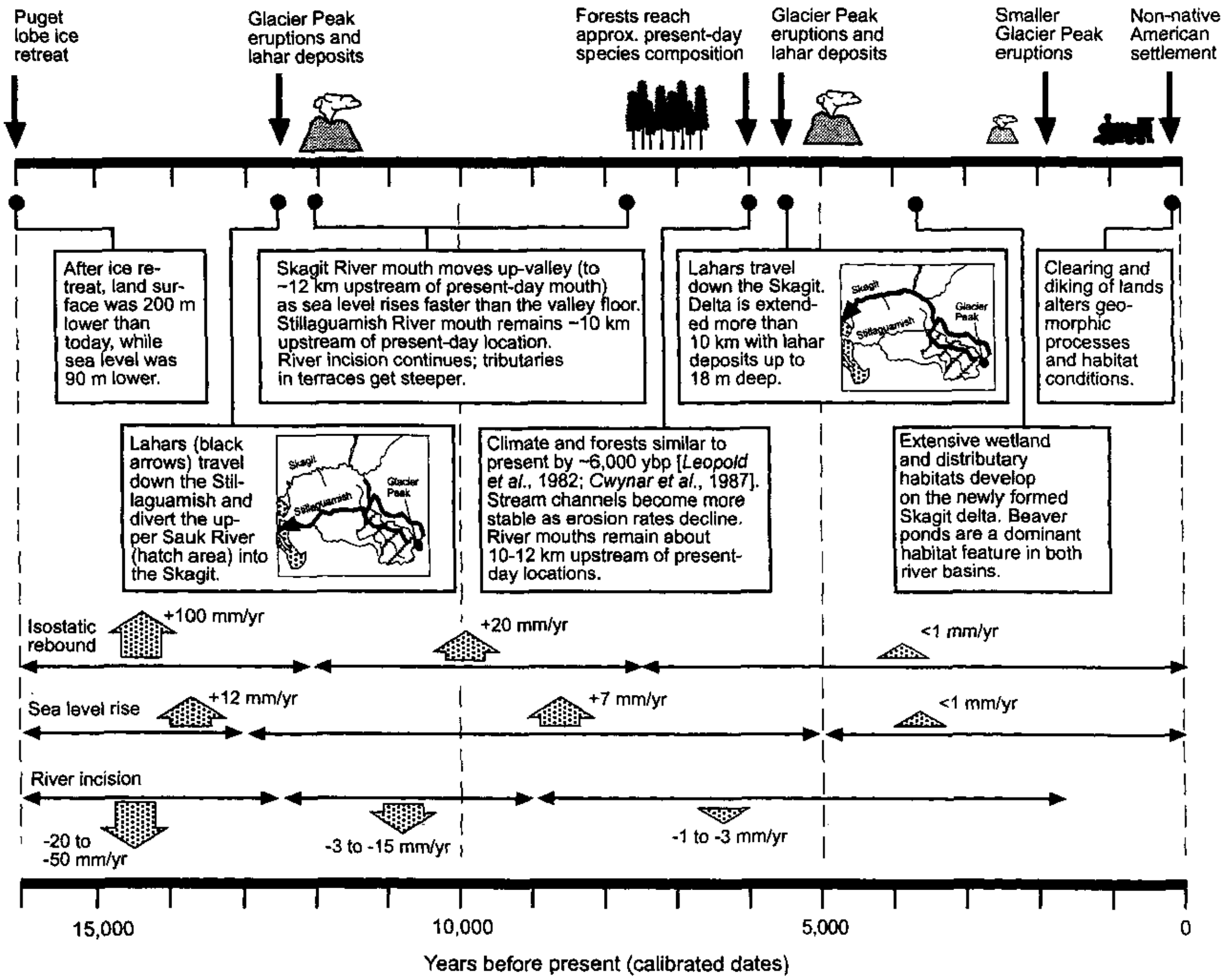

Figure 5. Timeline of major historical events (top) and rates of long–term processes (bottom). Narrative description of main effects of processes and events in center panels. See text for further explanation and sources of information.

4). Nevertheless, these valley floors were not below the 16,000-ybp sea level, as sea level was also 90 m lower than today. The 16,000-ybp valley floor of the Stillaguamish River at Arlington was at sea level, indicating that the 16,000-ybp river mouth was about 25 km upstream of the present-day river mouth. The Skagit River at Lyman was only about 10 m above sea level at ice retreat, placing the river mouth 4 km downstream of Lyman, or about 35 km upstream of its present-day location.

Between 16,000 ybp and 12,500 ybp the lower valleys rose relative to sea level, suggesting that both river mouths moved down-valley. The Stillaguamish valley floor at Arlington rose about 70 m relative to sea level during this time, whereas the Skagit valley floor at Lyman rose 75 m. Assuming that the Stillaguamish valley slope downstream of Arlington was similar to that between Arlington and Darrington, we estimated that the 12,500-ybp Stillaguamish River mouth was about 10 km upstream of its present-day location. A similar calculation for the Skagit suggests that its 12,500-ybp river mouth was approximately 5 km upstream of its present-day location.

As rivers incised into the glacial sediments between 16,000 ybp and 12,500 ybp, they created a series of terraces along the main valleys. River incision decreased the base level for tributaries originating on the valley slopes, and tributary slopes would have increased in response to the decreasing base level (Figure 6). Because anadromous salmonids generally prefer habitats in channels with slope < 0.03 [e.g., *Montgomery et al.*, 1999], the extent of usable stream length probably decreased between 16,000 ybp and 12,500 ybp as some tributaries in glacial sediments became too steep to provide suitable habitat. The distribution of present-day channel slopes in the study area (Figure 7) supports this interpretation, as nearly 75% of streams in the

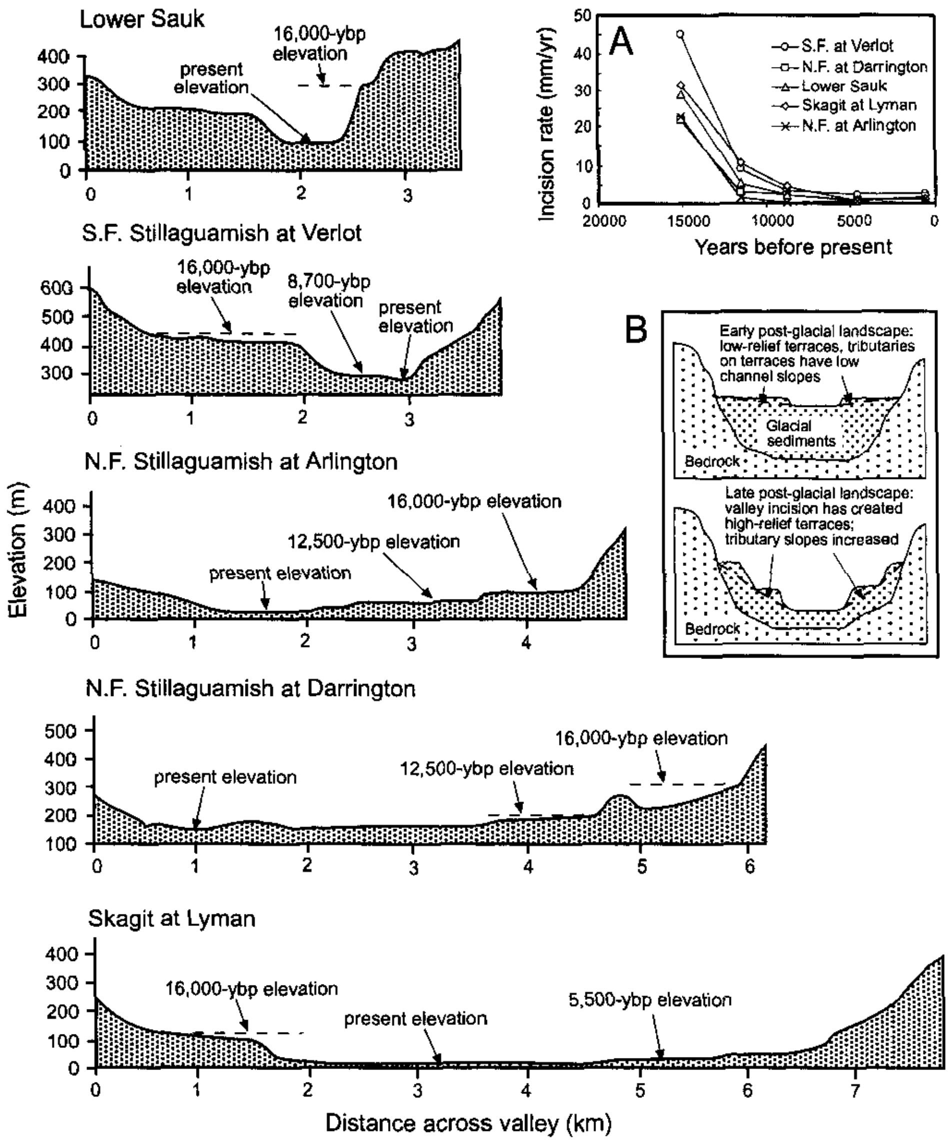

Figure 6. Valley cross sections showing ^{14}C-dated terrace surfaces (cross section locations shown in Figure 1). Inset (A) shows the decline in rate of valley floor incision at each cross section. Inset (B) illustrates how valley floor incision lowered tributary base levels, resulting in steeper tributary slopes in the terraces.

terraces are steeper than 0.03 [based on 30 m digital elevation models, *Lunetta et al.*, 1997].

The end of this first time period is marked by the 12,500-ybp eruptive episode of Glacier Peak. Lahar deposits from this episode are 2 m deep only 20 km upstream of the present-day Stillaguamish River mouth, and the lahar likely reached Puget Sound [*Beget*, 1982; *Mastin and Waitt*, 1995]. A branch of this lahar also traveled down the Sauk River valley nearly to its confluence with the Skagit River [*Dragovich et al.*, 2000]. This lahar changed the course of the Sauk River at Darrington, forcing it to flow northward to the Skagit [*Beget*, 1982]. Approximately 830 km^2 of drainage area (over 140 km of stream length accessible to anadromous salmonids) was shifted from the Stillaguamish River basin to the Skagit River basin.

The 12,500-ybp lahars likely reduced the quality of salmonid habitats in both river basins. Considering the 1980 Mount St. Helens eruption a modern analogue to the Glacier Peak eruptions (i.e., assuming that dome collapses, pyroclastic flows, and lahars of Glacier Peak produced deposits similar to those on Mount St. Helens), we infer that erosion rates increased dramatically on the slopes of the

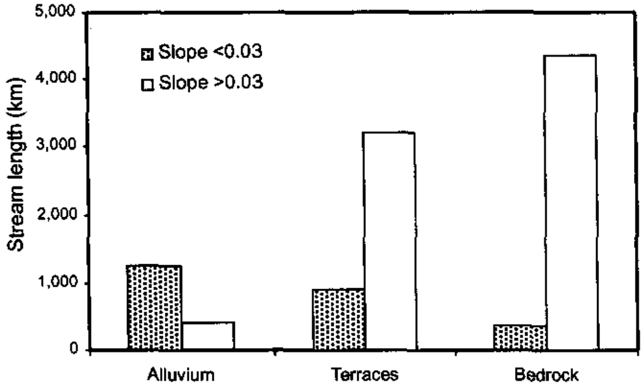

Figure 7. Distribution of channel slopes in areas mapped as alluvium, terraces (deep glacial sediments), and various bedrock lithologies in Figure 2, based on stream slopes generated from 30 m digital elevation model [*Lunetta et al.*, 1997].

volcano and lahar surfaces, leading to increased sediment loads in stream channels [*Major et al.*, 2000]. Extreme post-eruption sediment loads create a variety of habitat changes including lateral and vertical channel instability, greater exposure to high stream temperatures in summer, and reduced availability of rearing pools and cover [*Martin et al.*, 1986]. These changes then cause a significant reduction in use by salmonids [e.g., *Leider*, 1989]. Because the Glacier Peak eruptive episodes also included thickly bedded pyroclastic flow and dome collapse deposits proximal to the volcano [*Beget*, 1982], high sediment loads may have continued for decades. Sediment yields from 1980 Mount St. Helens debris avalanche remained high two decades after the eruption [*Major et al.*, 2000], and forests apparently require many decades to reestablish on the deposit [*Dale*, 1991]. Channels in distal mudflow-affected valleys may have stabilized within a few years to a decade [e.g., *Meyer and Martinson*, 1989]. Forests probably colonized such lahars soon after they stabilized, just as red alder colonized Mount St. Helens lahars within a few years [*Heilman*, 1990]. However, advanced successional stages of forest development likely spanned many decades to a few centuries [e.g., *Munger*, 1940].

12,500 ybp to 5,500 ybp

After 12,500 ybp, isostatic uplift and river incision appear to have decreased significantly, but uplift continued to outpace incision (Figure 4). As a result, valley floors rose more slowly, and valley floor elevations relative to sea level were typically stable or decreasing. Incision of the lower Skagit during the latter half of this time period approximately matched the rate of uplift, but sea level continued to rise. Thus, the mouth of the Skagit River would have moved up-valley as the lower valley was flooded by the rising Puget Sound. Assuming a valley slope similar to that of today, we estimate that by 5,500 ybp the mouth of the Skagit River had moved up-valley to approximately 12 km upstream of its present-day location. This position is consistent with the pre-lahar location estimated by *Dragovich et al.* [2000]. By contrast, the Stillaguamish River valley floor rose at about the same rate as sea level, suggesting that the mouth of the Stillaguamish River remained about 10 km upstream of its present location throughout this period.

Between 12,500 ybp and 5,500 ybp, base levels of tributaries continued to drop as the main rivers eroded into glacial sediments. Consequently, tributary slopes would have increased, suggesting that the total length of low-gradient tributary streams continued to decrease. Such changes may have favored steelhead trout and coho salmon (which utilize small streams of moderate slope), whereas species such as chum salmon were confined to habitats in low-elevation floodplains.

Around 5,500 ybp Glacier Peak entered its second eruptive period since ice retreat [*Beget*, 1982]. At least one lahar during this period reached the mouth of the Skagit River [*Dragovich et al.*, 2000]. It deposited 3 m of dacitic debris 35 km upstream of the present-day Skagit River mouth [*Beget*, 1982; *Mastin and Waitt*, 1995], indicating a 5,500-ybp valley floor elevation only a few meters above the present river elevation. Deposits up to 18 m thick near the present-day delta shoreline [*Dragovich et al.*, 2000] indicate that much of the delta downstream of Sedro Woolley was created during this eruptive episode. We estimated extension of the mainstem river during this episode at approximately 15 km based on delta aggradation equivalent to the depth of the deposit mapped by *Dragovich et al.* [2000]. This would put the post-lahar mouth of the Skagit River near its present location. Once again these lahars probably reduced the quality of salmonid rearing habitats for at least several decades in the mainstem Skagit, Sauk, and Stillaguamish Rivers.

5,500 ybp to 500 ybp

Since 5,500 ybp sea level rose about 3 meters [*Beale*, 1991], suggesting that river mouths may have moved up-valley. This also raises the possibility that 5,500-ybp deltas were larger than at present if there were no uplift or deposition on the deltas during the past 5,500 years. However, the salt marshes studied were located on shores away from major river delta deposits, and aggradation of deltas during the same time period may have effectively prevented movement of river mouths up-valley if aggradation were also at least 3 m. Assuming an average sediment supply rate of 70 $m^3/km^2/yr$ [*Paulson*, 1997] over the last 5,500 years, we estimate that the Skagit River exported more than 3×10^9 m^3 of sediment to the 450 km^2 delta (including sub-tidal areas). If all of the sediment were deposited in the delta, aggradation could have been as much as 6 m and could easily have prevented up-valley movement of the river mouth over the past 5,500 years.

Since 5,500 ybp, rates of valley floor incision decreased (Figure 6). Overall, proportions of the landscape mapped as bedrock terrain, glacial terraces, and floodplains have probably been more or less constant over the last 1,700 years. Therefore, the distribution of channel slopes has probably been relatively constant as well. Subsequent lahar deposits from Glacier Peak did not extend beyond the Suiattle and Whitechuck river valleys [*Beget*, 1982], and Mount Baker has not produced significant avalanches or lahars entering the study area since 16,000 ybp [*Gardner et al.*, 1995]. Thus, neither of the lower valleys appears to have experienced a major volcanic disturbance in the last 5,500 years.

RECENT HISTORY OF THE LANDSCAPE AND FISH HABITAT

Rates of change in valley elevation or sea level over the past 500 years have not appreciably affected the spatial extent of fish habitat. Instead, land development by non-Native Americans since 1850 has removed a large proportion of historical habitats from the landscape, and fundamentally altered some of the geomorphic processes that form and sustain remaining salmonid habitats. These changes have resulted in extensive losses of habitat on floodplains and deltas, as well as in beaver ponds and tributaries in the terraces [*Beechie et al.*, 1994; *Pess*, unpublished data]. In addition, land uses currently constrain geomorphic and biological processes that allowed habitats to recover after natural disturbances (e.g., levees block river migration and flooding, riparian forest removal prevents wood recruitment, etc.).

The four main land uses that alter rates of geomorphic processes and subsequently affect the quantity or quality of fish habitat in the study area are agriculture, forestry, rural residential development, and hydropower dams. (Urban areas occupy less than 1% of the study area, so we group urban areas under the category rural residential.) Agricultural and rural residential areas are almost exclusively within the floodplains and deltas, and overlap more than 59% of the historical range of salmon in the Skagit basin and 38% of the range in the Stillaguamish basin (Figure 8). Forest management in the study area can be grouped into two main categories: (a) intensive commercial forest management with timber harvest rotations of less than 60 years (state and private forests), and (b) multi-use management including longer rotation forestry, wilderness areas, and national parks (federal forests and parks). Intensive commercial forestry activities are concentrated on the terraces, and overlap the majority of the remaining historical range of salmon in both basins. Federal forests under multi-use management are concentrated in the bedrock terrain, and contain less than 5% of the salmon habitat in the study area.

Spatial Distribution of Habitats on the Landscape

By 500 ybp, the landscape had reached its present configuration of steep hillslopes at higher elevations, valley-filling glacial deposits eroded into terraces, and relatively narrow floodplains. This configuration controlled the distribution of channel slopes in the two basins (Figure 7), which in turn controlled some aspects of habitat formation such as the basic morphology of channel beds [*Montgomery and Buffington*, 1997], pool spacing [*Montgomery et al.*, 1995], and size of gravels available for spawning [*Beechie and Sibley*, 1997].

Channels in the bedrock terrain contained a very small percentage of total pre-settlement anadromous salmonid habitat. Examination of channel slopes in the study area revealed that most channels in the bedrock terrain have slopes > 0.2 (78% of the stream length) and only 4% have

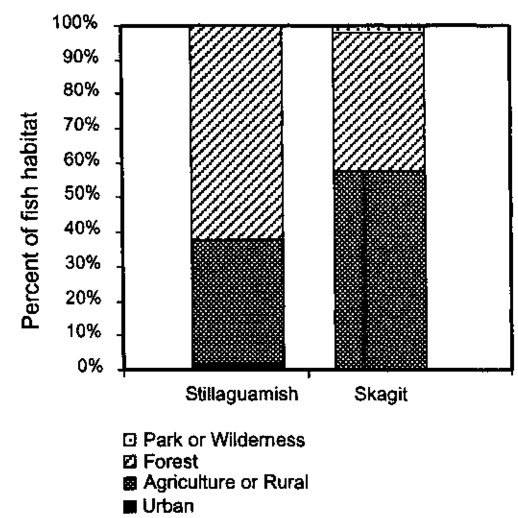

Figure 8. Proportions of anadromous salmonid habitat located in each land use category in the Skagit and Stillaguamish River basins.

slope < 0.03. Channels > 0.03 are generally too steep to support anadromous salmonids, in part because migration barriers (falls and impassable cascades) are commonly located at the lower end of streams in this terrain, and in part because these channels provide little spawning or rearing habitat [*Montgomery et al.*, 1999]. Streams steeper than 0.02 and with bankfull width less than 15 m have very little spawning gravel available, primarily because average basal shear stress is high enough that median particle size of the bed surface tends to be cobble or larger [*Beechie and Sibley*, 1997]. Thus, particle sizes in steeper channels typically exceed those useable by salmonids that occupy these small streams (i.e., gravels < 64 mm diameter used by coho salmon, steelhead trout, or cutthroat trout). In addition, pool area tends to be much lower in steeper channels [*Beechie and Sibley*, 1997].

Channels on terraces are less steep than those in bedrock areas, with 70% of channels < 0.2 and 22% of channels < 0.03. Field observations in both study basins show that small streams on terraces (bankfull widths < 15 m) are typically used by coho salmon, steelhead trout, and cutthroat trout. These channels also typically have narrow floodplains, creating preferred locations for beaver ponds in the study area. Historically, beaver ponds occupied a minimum of 8% of tributary channel length in both basins. In between beaver ponds, channels would have been predominantly forced pool-riffle channels due to large amounts of woody debris (> 0.4 pieces per meter of channel length) that provided pool-forming structure in otherwise straight reaches [*Montgomery et al.*, 1995; *Beechie and Sibley*, 1997]. Step-pool reaches (slope typically > 0.03) may have been occupied more by steelhead and cutthroat trout than by coho salmon because they contain less coho salmon spawning and rearing habitat [*Bisson et al.*, 1988; *Beechie and Sibley*, 1997].

Based on present-day topography and historical reconstructions of habitat areas, we estimate that much of the 150-ybp habitat area in both study basins was located on the deltas and floodplains. Most channels (62%) on areas mapped as alluvium in Figure 2 have slopes < 0.01, and at least 75% have a slope < 0.03. The large mainstem rivers in the study area (Skagit, Sauk, and North Fork Stillaguamish Rivers) typically migrate laterally or avulse across the alluvium, resulting in meandering or anastomosing channel patterns. The anastomosing channel pattern produces many side-channels (channels branching off the mainstem and re-entering the mainstem downstream), which account for a significant proportion of the pre-settlement channel length. For example, at least 44% of channel length in the Skagit and Sauk River floodplains were side channels prior to non-Native American settlement. Distributary channels (channels branching off the mainstem and entering Puget Sound) were numerous on the deltas, and wetland complexes covered more than half of the total delta area [*Collins and Montgomery*, this volume]. In combination, the floodplains and deltas contained more than half of the total salmon habitat area in both basins, yet they constituted less than 10% (1,010 km^2) of the study area.

Post-settlement Alteration of Geomorphic Processes and Fish Habitat

Changes in sediment supply and wood recruitment. Prior to settlement by non-Native Americans, the natural disturbance regime of fires and storms periodically altered rates of mass wasting and wood recruitment to streams in the study area, which subsequently altered channel morphology and the physical structure of tributary habitats [*Beechie*, 1998]. The recurrence interval of stand-replacing fires was about 200 years in the Western Hemlock Zone (< 600 m elevation), and about 380 years at higher elevations [*Beechie*, 1998]. Based on standard techniques for relating return intervals to stand age distributions, *Beechie* [1998] estimated that these disturbance regimes maintained an average of 12% of forest stands < 20 years old in the Western Hemlock Zone, and 7% of stands < 20 years old at higher elevations. Sediment supply rates from these immature stands (i.e., stands < 20 years old) average four times that of rates from mature forests [*Paulson*, 1997], leading to long-term average sediment supply rates 1.2 to 1.3 times the rate one would expect in the absence of fires [*Beechie*, 1998].

Based on sediment budgets for 10 sub-watersheds representing the range of lithologies and landforms in the study area (covering 672 km^2), *Paulson* [1997] found that landslide rates from roads are roughly 45 times the rate from mature forests, and landslide rates from clearcut areas are roughly 4 times that of mature forests. Total bed load supplies resulting from these altered landslide rates average 2 times the estimated natural rate in commercial forests, and 1.5 times the natural rate in multi-use federal forests [based on data in *Paulson*, 1997].

Natural fires also killed riparian forests along small streams prior to 150 ybp, which may have caused short-term pulses of wood recruitment followed by several decades of low recruitment. After a fire, forests of the Western Hemlock Zone took several decades to grow to 1 m diameter [*Munger*, 1940], which would be large enough to provide pool-forming wood to streams. Based on a model of forest growth, wood recruitment, and pool formation for northwestern Washington forests, *Beechie et al.* [2000]

calculated the percentage of riparian forests that were too small to provide pool-forming wood to streams. They estimated that under the natural fire regime, more than 60% of riparian forests consisted of trees large enough to provide pool-forming wood to tributaries less than 15 m wide (bankfull). Logging of riparian forests after 150 ybp reduced the supply of pool-forming wood to channels. Forest management regimes of the past century have reduced the proportion of riparian forests that produce pool-forming wood to less than 50% in very small channels (< 4 m wide), and to less than 25% in channels 4 to 15 m wide [*Beechie et al.*, 2000].

Habitat changes resulting from altered sediment supply and wood recruitment. Decreased wood abundance in channels reduces pool abundance and pool surface area within the study area [*Beechie and Sibley*, 1997] and throughout the Pacific Northwest [*Bilby and Ward*, 1991; *Montgomery et al.* 1995]. Large increases in sediment supply also reduce the depth, frequency, and total area of pools in the study area [*Nelson*, 1998] and throughout the western U.S. [e.g., *Lisle*, 1982; *Madej and Ozaki*, 1996]. Increased supply of bed load causes a modest reduction in the average depth of pools when sediment supply increases to more than 90 $m^3/km^2/yr$ [*Nelson*, 1998], and dramatically reduces the number and area of pools in extreme cases (i.e., sediment supply > 1,000 $m^3/km^2/yr$) [*Collins and Beechie*, unpublished data].

In both basins, almost all tributaries in agricultural lands are low-slope channels, and pool areas are much less than in the reference sites or in streams with other adjacent land uses (Table 3). Removal of wood alone is unlikely to cause such decreases in pool areas because pool areas in low-slope channels are relatively unresponsive to changes in wood abundance [*Beechie and Sibley*; 1997]. Much of this difference in pool areas is likely due to the repeated channel dredging that occurs in many agricultural streams of the study area, or to increased supply of fine sediments from pastures and croplands.

Decreased pool area in terrace tributaries was largely the result of forestry activities over the last 150 years. Increased mass wasting from forest road construction and logging has contributed to loss of pool area in tributaries, but pool losses are more directly attributable to decreased wood abundance [*Nelson*, 1998]. Reduced wood recruitment in forest lands has caused the greatest reductions in pool areas in moderate-slope streams (0.02 – 0.04) where other mechanisms of pool formation do not compensate for the loss of wood-forced pools [*Beechie and Sibley*, 1997].

Reductions of pool area in low-slope channels in rural areas are similar to those in forestry areas (Table 3), and reflect the lesser sensitivity of pool area to wood abundance in low-slope channels [*Beechie and Sibley*, 1997]. In moderate-slope channels in rural lands, percent pool areas are 36% and 46% in the Skagit and Stillaguamish basins, respectively, compared to 54% in the unlogged sites. Thus, reductions in pool area are slightly less in rural lands than in forested lands in both basins, apparently due to the limited protection of riparian forests afforded by the steep terrain adjacent to many streams. There appears to have been no change in pool areas in steeper streams due to urban or residential development.

Pool frequencies in the main stem Skagit, Sauk, and North Fork Stillaguamish Rivers have probably also decreased, based on decreased abundance of wood large enough to create log jams and pools in the similarly modified Snohomish River [*Collins and Montgomery*, this volume]. Limited data from six reference sites and 11 altered mainstem channels in the study area (bankfull widths > 24 m) also suggest that total pool area has decreased by more than 35% [*Pess*, unpublished data]. In large channels such as these, key pieces more than 1 m diameter create stable jams, which in turn create more and deeper pools [e.g., *Abbe and Montgomery*, 1996; *Collins and Montgomery*, this volume]. Clearing of this wood debris has dramatically decreased abundance of pool-forming wood in the main rivers [*Collins and Montgomery*, this volume], and logging of riparian forests has reduced recruitment of trees large enough to form pools where channels are wider than 15 m [*Lunetta et al.*, 1997].

Table 3. Average percent pool by channel slope class and land use for the two river basins in the study area. Percent pool is pool area expressed as a percentage of total wetted area in summer. N/A indicates that sample size (number of reaches) was less than ten, and an average value was not calculated. Averages for unlogged lands are from *Beechie et al.* [1994].

	Channel Slope		
	<2%	2%-4%	>4%
Unlogged lands	64	54	35
Skagit basin			
Agriculture (n=25)	47	N/A	N/A
Forestry (n=172)	61	29	27
Rural (n=95)	61	36	36
Stillaguamish basin			
Agriculture (n=20)	36	N/A	N/A
Forestry (n=76)	44	29	33
Rural (n=32)	42	46	N/A

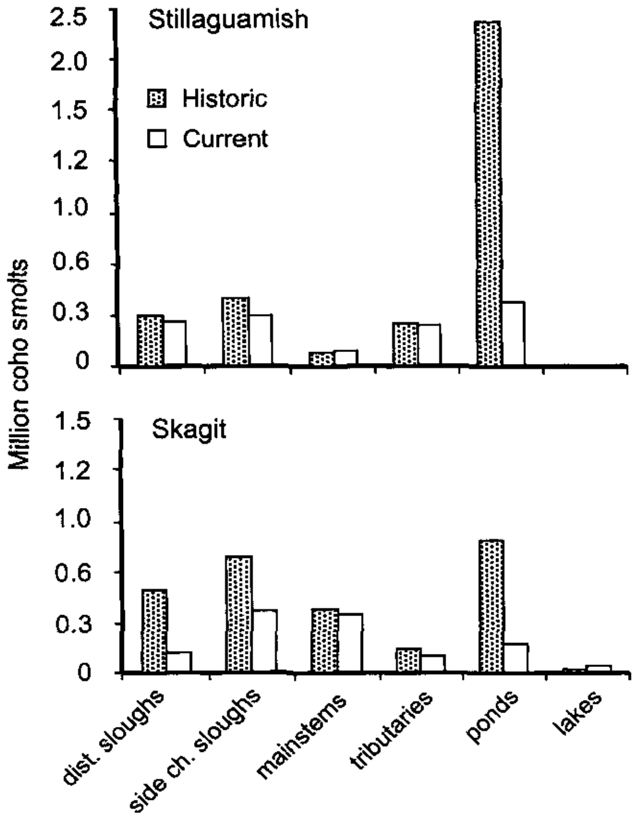

Figure 9. Historic and current winter rearing habitat capacities by habitat type for the Stillaguamish (upper panel) and Skagit (lower panel) River basins.

Estimated changes in coho salmon smolt production due to habitat alteration in tributaries (i.e., reduced pool area) are relatively small compared to losses in ponds and sloughs (Figure 9). In the Skagit basin, tributaries have lost more than 30% of their potential coho smolt production, whereas tributaries in the Stillaguamish basin have lost less than 5% of their potential coho smolt production. We cannot make similar estimates of the change for mainstem channels because there are insufficient data in the literature to quantify coho salmon use of habitats in large rivers [*Beechie et al.*, 1994].

Changes in channel migration and formation of floodplain habitats. Recent studies indicate that river migration, avulsion, and recruitment of floodplain trees to channels were fundamentally important mechanisms of habitat formation in Pacific Northwest watersheds [*Peterson and Reid*, 1984; *Featherston et al.*, 1995; *Abbe and Montgomery*, 1996]. Channel movement across floodplains forms a variety of off-channel habitat types in abandoned channels, including off-channel ponds, oxbow lakes, and side channels [*Peterson and Reid*, 1984]. Recruitment of trees from the floodplain initiates formation of log jams, which can then force channel movement and the formation of forested islands, side channels, and deep pools in the main channel [*Featherston et al.*, 1995; *Abbe and Montgomery*, 1996]. Therefore, floodplains contained a diverse array of habitat types, including small and large channels, ponds, sloughs, abundant woody debris, and pool-riffle channels. This dynamic habitat system encompassed nearly half of the low-slope channel length in the study area. Similar processes also occurred on deltas, resulting in extensive freshwater and estuarine habitats, particularly on the Skagit delta [*Collins and Montgomery*, this volume].

Historically, most coho salmon habitat was on the deltas and floodplains, and these landforms have been nearly completely occupied by agricultural uses over the past 150 years. The dominant mechanism of habitat loss on the deltas and floodplains has been the diking and draining of sloughs, wetlands, and beaver ponds [*Beechie et al.*, 1994; *Collins and Montgomery*, this volume]. In combination, these practices account for more than 90% of coho habitat losses in both river basins (Figure 10). Many channels that remain within leveed areas have been converted to ditches, and now serve as a drainage network for farmlands. These channels are inaccessible from their upstream ends during floods, so juvenile salmon can no longer access them as freshwater refugia. Some channels have partial access through tidegates at their lower (saltwater) ends, and minimal use is made of these channels as salmonids transition from freshwater to saltwater. Isolation of 40% of the distributary slough area in the Stillaguamish delta and 75% of distributary slough area in the Skagit delta has eliminated much of the winter habitat capacity from the deltas of these two basins [*Beechie et al.*, 1994; *Pess*, unpublished data]. In the Stillaguamish River basin 28% of floodplain side-channel habitats have been isolated or obliterated [*Pess*, unpublished data] and 45% have been isolated or obliterated in the Skagit River basin [*Beechie et al.*, 1994].

Blocked access to tributary habitats. Culverts and other stream crossing structures block an estimated 6% and 1% of coho rearing capacity in the Skagit and Stillaguamish basins, respectively (Figure 10). Habitats have also been inundated by the reservoirs of two dams built in the Baker River canyon. Coho winter rearing habitats inundated by the dams constituted about 5% of the total habitat loss [*Beechie et al.*, 1994]. However, increased rearing capacity in the reservoirs was about 4%, resulting in a negligible change of total winter rearing capacity caused by the dams. Three dams in the upper Skagit River do not block passage, as there is no record of anadromous fish historically

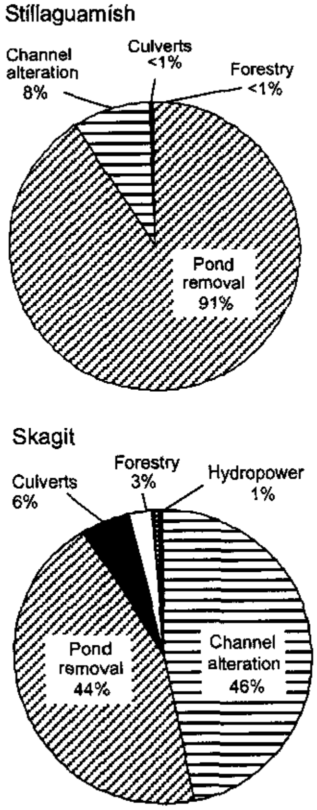

Figure 10. Distribution of losses in average smolt production (from winter rearing habitat) by type of impact in the Stillaguamish (upper panel) and Skagit (lower panel) River basins. [Beaver pond data from *M.M. Pollock*, Northwest Fisheries Science Center, Seattle, Washington, unpublished data.]

passing through the gorge above Newhalem. There are no hydropower dams in the Stillaguamish basin.

Cumulative changes to salmonid habitats

Historically, coho salmon smolt production from the Stillaguamish basin was summer limited, whereas summer and winter smolt production capacities from the Skagit basin may have been nearly equal [*Beechie et al.*, 1994; *Pess*, unpublished data]. Overall losses in coho salmon rearing areas have been greatest for winter rearing habitat, resulting in winter limited smolt production from both basins at present. In both basins estimated declines in winter rearing habitat capacity are greater than 50% (Figure 11), suggesting that pre-settlement coho smolt production was more than twice that of today.

Historic winter rearing capacity appears to have been greatest in ponds in the Stillaguamish River basin, and more evenly split among ponds and sloughs in the Skagit River basin. The greater historic areas of distributary and side-channel slough habitat in the Skagit River basin was a result of the much larger area of alluvial deposits in the Skagit basin, which allowed formation of more extensive slough channels. Dredging, diking, and ditching of channels were responsible for more than 46% of estimated winter habitat loss in the Skagit River basin, and more than 8% of estimated losses in the Stillaguamish (Figure 10). Removal of beaver ponds and trapping of beaver account for 44% and 91% of the coho salmon rearing habitat losses in the Skagit and Stillaguamish basins, respectively. Estimated losses from reduced pool areas in forestry areas account for a small proportion of habitat losses in both basins. Because riffle areas also provide rearing habitat for coho salmon (but less than pools), reductions in potential coho smolt production from loss of pools are relatively small compared to complete losses of habitat area resulting from channel alteration, culverts that block fish passage to upstream habitats, and removal of beaver ponds.

SUMMARY AND CONCLUSIONS

Historical assessments of landform development, geomorphic processes, and salmonid habitats put recent declines of salmonid habitats into a context of long-term landscape evolution. The landscape and fish habitats of the study area have been changing gradually throughout the last 16,000 years as a result of isostatic uplift, valley incision, and sea level rise. These changes slowly altered the suite of habitats available to anadromous fishes, with low-slope habitats declining in extent while moderate-slope habitats increased. These shifts probably favored species adapted to slightly steeper streams (such as steelhead and

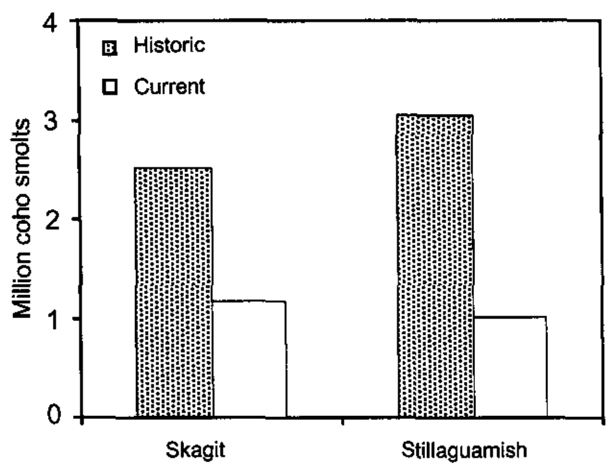

Figure 11. Historic and current total winter rearing habitat capacities for the Skagit and the Stillaguamish River basins.

cutthroat trout or coho salmon) while species such as chum salmon experienced decreasing availability of habitat. (However, we note that chum salmon are more abundant than other species today, probably due to lower harvest levels and a life history strategy that avoids significant rearing time in the freshwater environment.)

Reconstruction of geomorphic processes and fish habitats prior to non-Native American settlement illustrates that the majority of pre-settlement salmon habitat (ca. 1860) in the Skagit and Stillaguamish basins was on floodplains and deltas. Over the past 150 years, the most intensive land uses and the most severe alterations to salmonid habitats also have been concentrated on alluvial landforms. Because most of the habitat potential is in floodplains and deltas, restoring the rearing capacity of salmon habitats in the study area will now require reversal of much of the channel alteration and isolation that caused these losses. However, simple solutions (such as levee removal) are in conflict with present land uses, and habitat restoration will likely be technically and politically arduous.

These assessments document how different land uses affect different habitat-forming processes, and therefore indicate where land managers must change land management practices in order to restore habitats and the geomorphic processes that form them. For example, forestry activities are the primary land use affecting mass wasting processes because they are the only land use concentrated in the steep slopes of the bedrock terrain. In order to prevent or reverse the effects of forestry on landsliding and pool abundance in streams, timber harvest and road construction must be altered to reduce impacts on landslide-prone areas. By contrast, agricultural practices have almost no effect on mass wasting processes because they are concentrated on alluvial deposits, but they have been accompanied by widespread isolation of habitat areas by levee construction. Therefore, agricultural practices have little need to address mass wasting processes in habitat restoration, but must address the isolation and obliteration of habitats that existed on the floodplains and deltas.

A fundamental difference between habitat changes by natural disturbances and those of recent land uses is that land use changes interrupt natural process that would recover habitats. For example, a valley-burying lahar may have caused extensive habitat change, but river migration, woody debris, and re-establishment of floodplain forests all could contribute to habitat recovery. By contrast, floodplain habitats isolated by levees and simplified mainstem channels cannot recover by natural processes because rivers are presently disconnected from their floodplains and prevented from migrating. Therefore, habitat conditions cannot improve without management interventions.

Finally, the historical context for habitat-forming processes provides reasonable expectations of restored processes and habitat conditions. Without knowledge of the extent of habitats prior to intensive land uses, we have little understanding of what to expect for recovery of processes that form and sustain salmonid habitats. For these two basins, we have estimates of historical and current habitat capacity for coho salmon in different habitat types, which indicate that losses of sloughs on the Skagit delta and beaver ponds in both basins are the largest habitat losses that have occurred over the past 150 years. Therefore, restoration strategies targeting recovery of coho salmon populations must include restoration of overwintering habitats such as sloughs and ponds. Additionally, estimates of natural rates for processes such as landsliding and delivery of sediment to streams help us understand where sediment supply rates were relatively higher or lower under pre-settlement conditions, as well as where current rates of these processes deviate from natural rates. These estimates can be used to identify where habitat-forming processes are in need of restoration, and can help identify the expected outcomes of various restoration activities.

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