

Morphology and Evolution of Salmonid Habitats in a Recently Deglaciated River Basin, Washington State, USA¹

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Morphology and distribution of salmonid habitats were related to the geomorphology of a river basin at three spatial scales including reach (10^2 – 10^3 m²), subbasin (2–26 km²), and the watershed (240 km²). Stream reaches on a young fluvial terrace (1700 yr old) adjacent to the main river contain the most extensive areas of rearing and spawning habitats. In tributary subbasins, the area of spawning habitat varies according to discharge rates and channel gradients. The most extensive salmonid habitats are located along wide glacial deposits in geologically unconstrained areas of the main valley floor. During the early Holocene (~10 000–12 000 years before present (B.P.)), the recently deglaciated watershed of the South Fork Stillaguamish River was extremely erosive and vegetated by alpine forest. Fish habitats then were less suitable for salmonid rearing and spawning. A much lower erosion rate after 8000 yr B.P., and the advent of old growth conifer forests after 6000 yr B.P., indicates that stream habitats attained their present-day morphology between 8000 and 6000 yr ago. Although habitats increased in quality with increasing watershed stability and evolution of forests, they decreased in quantity after 7000 yr B.P. as landforms changed because of continuous river incision into glacial deposits.

La morphologie et la répartition des habitats de salmonidés étaient liées à la géomorphologie du bassin fluvial en fonction de trois échelles spatiales, c'est-à-dire à l'échelle du tronçon (10^2 – 10^3 m²), à celle du sous-bassin (2–26 km²) et à celle du bassin hydrographique (204 km²). Les tronçons de cours d'eau sur les terrasses fluviales récentes (datant de 1 700 ans) adjacents à l'artère fluviale principale renferment les alevinières et les frayères les plus étendues. Dans les sous-bassins d'affluents, la superficie des frayères varie selon le débit et la pente d'écoulement du canal. Les habitats de salmonidés les plus vastes se trouvent le long de larges dépôts glaciaires dans des zones exemptes d'obstacles géologiques et situées au fond de la vallée principale. Au début de l'holocène (soit environ 10 000 à 12 000 ans avant le présent (B.P.)), le bassin hydrographique de la rivière South Fork Stillaguamish, dont la déglaciation était récente, subissait une très forte érosion, et ses berges étaient végétalisées par une forêt alpestre. À cette époque, les habitats de poissons étaient moins favorables à l'alevinage et à la fraye de salmonidés. Un taux d'érosion beaucoup plus faible depuis 8 000 ans B.P. et la présence de vieilles forêts de conifères depuis 6 000 ans B.P. indiquent que les habitats lotiques ont atteint leur morphologie actuelle il y a 6 000 à 8 000 ans. La qualité des habitats s'est accrue grâce à la stabilité plus grande du bassin hydrographique et à l'évolution des forêts; toutefois, le nombre d'habitats a diminué depuis 7 000 ans B.P., au fur et à mesure que le relief changeait et que les cours d'eau s'encaissaient toujours davantage dans les dépôts glaciaires.

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Fishery biologists, geomorphologists, and hydrologists in northwestern North America have made considerable progress in describing factors that influence the morphology of salmonid habitats in streams. Most researchers have considered habitats at the scale of reaches (e.g. pools and riffles (10^1 – 10^4 m²)). Pertinent examples include the role of organic debris in structuring pool habitats (Bisson et al. 1987), variation in the quality of spawning gravels due to channel aggra-

tion with fine or coarse sediment (Collings et al. 1972; Everest et al. 1987), and the utility of hydraulic geometry measurements in predicting usable habitat areas (Hogan and Church 1989).

Fish habitat has also been studied at the scale of entire watersheds in the Pacific Northwest. Cederholm and Reid (1987) combined an analysis of the distribution of coho salmon (*Oncorhynchus kisutch*) in stream habitats with an investigation on erosion processes to determine the effects of forestry activities on salmon production in the Clearwater River basin

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(375 km²), Washington State. Their work identified streams formed on fluvial terraces as important refuge habitats for winter rearing. Cederholm and Reid (1987) also suggested that sediment production from roads and landslides reduced the survival of eggs in the redd pockets.

At a smaller basin scale, Hartman et al. (1987) examined responses of various salmonid communities to several forestry activities in the Carnation Creek watershed (10 km²), British Columbia. As part of their work, Hartman et al. (1987) identified small, low-order tributaries as having an important effect on habitat of larger streams. The Hartman et al. (1987) and Cederholm and Reid (1987) studies demonstrated the importance of considering the entire watershed when studying the morphology of salmonid habitats and the effects of land use.

This study differs from previous habitat investigations by examining how geomorphic or land-forming processes facilitate or limit the development of salmonid habitat in tributary streams over long periods (10²–10³ yr). Such an analysis allows insight into how the development of salmonid habitats is linked to the formation of landscapes. The recently deglaciated environment of northwestern Washington State provides a unique opportunity to study the evolution of stream habitats over a period of approximately 14 000 yr.

We studied the present-day morphology and distribution of salmonid habitats in the South Fork Stillaguamish River valley in northwest Washington State at a variety of spatial scales ranging between reach (10²–10³ m²), tributary basin (2–26 km²), and the watershed (240 km²). Habitats were considered in the context of the geomorphic processes responsible for their morphology. Salmonid habitats included summer rearing habitat, defined as low-velocity pools with cover provided by organic debris or undercut banks, and spawning habitat, defined as clean gravels between 13 and 75 mm in diameter.

A hypothesis was developed on the evolution of stream habitats in the study watershed since continental deglaciation (~14 000 years before present (B.P.)). This hypothesis was based on the information on present-day morphology and distribution of habitats, a radiocarbon dating analysis of the erosional history of the basin, and published literature on the development of forests in the Pacific Northwest.

Study Area

The South Fork of the Stillaguamish River basin ("South Fork") is located in the Cascade Mountains of northwest Washington, USA (Fig. 1). The river basin (240 km²) contains 18 tributary basins with areas ranging from 2 to 26 km². Elevations of the river basin range from 300 m at the downstream end of the study area to over 1800 m in the eastern portion of the basin. Annual precipitation varies from about 305 cm at Verlot (U.S. Forest Service Visitor Center) to 450 cm at the summit of Mt. Pilchuck. Snow accumulates throughout the winter months at elevations greater than 500 m. The basin is vegetated with dense stands of Douglas fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and true firs (*Abies* spp.), a forest community referred to as the Western Hemlock Zone (Franklin and Dyrness 1973). Most of the natural forests are referred to as "old growth," that is, much of the forest is composed of trees greater than 250 yr old.

The river basin is composed of a variety of lithologies including Jurassic Period (136–195 million yr) metamorphic rocks in the western portion and Tertiary Period (12–65 million yr) sedimentary and volcanic rocks in the eastern portion (Dugan 1974; Heath 1971; Wiebe 1963). The basin has been influenced by



Fig. 1. Location of the South Fork of the Stillaguamish River basin.

continental glaciation throughout much of the Quaternary Period (last 2 million yr). Most recently, a several-thousand-metre-thick cordilleran ice sheet buried most of western Canada and the northwestern edge of the United States during the late Pleistocene Epoch. Glacial damming of the South Fork by the ice sheet resulted in thick deposits of lacustrine silt and clay in the valley (Fig. 2). Retreat of the ice sheet approximately 14 000 yr ago in northwestern Washington State (Crandell 1965; Mullineaux et al. 1965) also resulted in extensive deposition of sandy, glacial outwash sediments in the valley of the South Fork. Other surficial deposits include talus (rockfall) and alluvial/debris fans at mouths of tributary valleys at the contact between bedrock and glacial sediment (Fig. 2). The surficial deposits cover 65 km² (26% of the basin area) and extend in elevation from the valley bottom to approximately 600 m.

In recent history the upper 56 km of the South Fork was inaccessible to anadromous fishes because of a natural migration barrier at Granite Falls. Access was permitted by the construction of a fish ladder in 1954. Since then, coho salmon, chinook salmon (*Oncorhynchus tshawytscha*), pink salmon (*O. gorbuscha*), and steelhead trout (*O. mykiss*) have been introduced by hatchery releases above the falls. As of the late 1970s, coho and steelhead were well established above the falls based on number of returning adults (South Fork Stillaguamish River B.U.M.P. 1978). Resident salmonid species include cutthroat trout (*Oncorhynchus clarki*) and rainbow trout (*O. mykiss*).

Habitats of anadromous salmonids, primarily coho and steelhead, occur in low-gradient (<4%) reaches of tributary streams formed in glacial sediments. High-gradient (>4%) reaches of streams on glacial sediments and channels underlain by bedrock are too steep to support anadromous salmonids. However, they provide habitat for resident species such as rainbow and cutthroat trout.

The main channel of the South Fork provides limited spawning habitat because of the high proportion of cobble and boulder substrate but provides rearing habitat in boulder pocket pools and along the edges of large pools and glides. Snorkel surveys indicate that approximately 20–30% of total summer pool and glide surface area in the main river is suitable for coho rearing (J. Doyle, Mt. Baker-Snoqualmie National Forest, Supervisor's Office, Seattle, WA, pers. comm.).

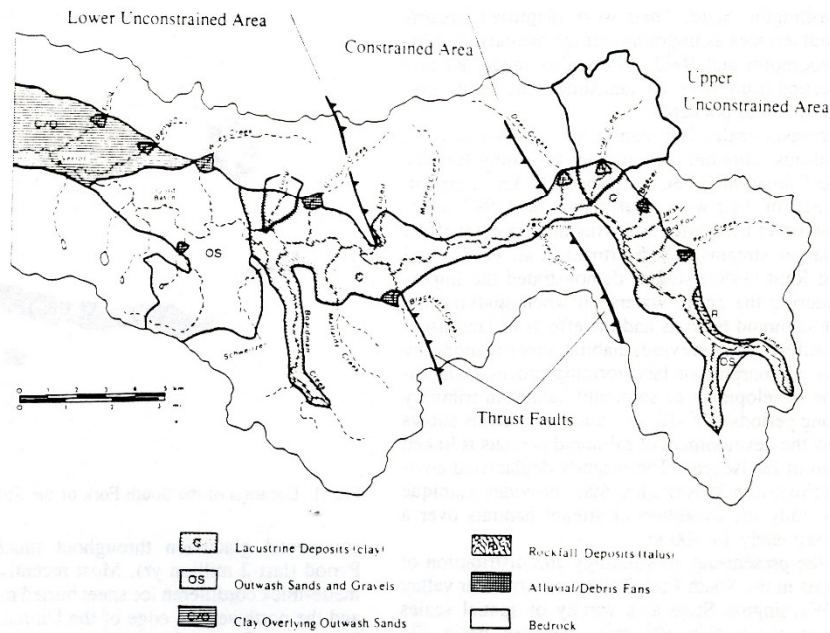


FIG. 2. Location of important geologic features (adapted from Heath 1971 and Dugan 1974) and type and distribution of surficial deposits in the South Fork of the Stillaguamish River basin. Geologically constrained and unconstrained areas of the basin are also delineated.

The South Fork has had a relatively long history of settlement and resource use dating back to the late 1800s. A railroad was built along the length of the valley to access the gold and silver mining towns of Monte Cristo and Silverton. Several small communities and shake mills followed in the wake of the railroad. Numerous stumps in the riparian areas of the main river and the tributaries attest to the large volumes of lumber needed to support these industries.

Splash-damming came into common practice in the late 1800s and early 1900s as a means to transport logs in streams in the absence of roads or railroads in the Pacific Northwest (Sedell and Luchessa 1982). Splash-damming required that all large woody debris in small tributaries be removed to allow the unhindered passage of a flood wave laden with cedar bolts and logs. The flood waves were created by building log dams in tributary channels. There is evidence that splash-damming occurred in the South Fork including the absence of old-growth, riparian conifers and the lack of large organic debris in many of the tributary stream channels.

Present-day land use, administered primarily by the U.S. Forest Service, includes timber harvest, road construction, and concentrated and dispersed recreation.

Methods

Tributary streams were the focus of this study because they account for 90% of the channel length in the basin and approximately 50% of the coho rearing habitat. The remaining habitat is found within the main river. The type and distribution of surficial deposits, including glacial sediments, were identified using a combination of field mapping and aerial photography. Particle sizes in the surface layer of stream substrates were measured (Wolman 1954) and divided into six size categories: boulders (>256 mm), cobbles (64–256 mm), gravels (22–

64 mm), pebbles (2–22 mm), and sands (<2 mm) (Wentworth 1922). Four to eight measurements were obtained in the low-gradient (<4%) portions of each of 18 tributaries. Sampling sites were located at the heads of riffle and bar areas away from large woody debris and boulders. Areas of active channels (wetted area at summer flow) containing gravel and pebble substrates were divided by the entire wetted channel area to estimate proportions of stream areas containing spawnable size substrates.

Particle sizes of the pavement of tributary stream beds were compared with stream power per unit length or SP (Richards 1982). Stream power can be used as an index of a stream's ability to transport sediment. SP (joules per second per metre) is expressed as

$$(1) \quad SP = \rho g Q S_v$$

where ρ is the fluid density, Q is the discharge determined by the U.S.G.S. method for estimating bankfull discharge for ungauged catchments (Bodhaine and Thomas 1964), S_v is the average gradient of channels in the glacial sediments measured from 1 : 24 000 scale topographic maps (map error $\sim 1^\circ$), and g is gravitational acceleration.

Surface areas of channel units were used to estimate the quantity and distribution of rearing habitats available to juvenile salmonids. Identification of channel units followed the procedure of Bisson et al. (1982) except that large channel structures (e.g. boulder, wood, bedrock, etc.) were also inventoried. Channel unit lengths and widths were visually estimated with every tenth unit measured for calibration (Hankin 1984; Hankin and Reeves 1988). Surface areas of preferred spawning substrate for coho salmon (gravels between 13 and 75 mm intermediate diameter) were visually estimated.

We computed the changing rate of erosion and sediment yield of glacial sediment (primarily sand, silt, and clay) from the

South Fork basin and its tributary watersheds over the past 14 000 yr by dividing the volume of sediment eroded between fluvial terraces of known age. This was done by dating terrace formation at two different elevations in the South Fork basin using radiocarbon dating methods (Isotope Laboratory, University of Washington, Seattle, WA). The top of the horizontal lacustrine deposit at an elevation of 550 m at the mouth of the basin at Verlot was assumed to have stopped forming at the time of deglaciation in the general area (~14 000 yr B.P.) (Crandell 1965). The volume of glacial sediment absent between the top of the lacustrine deposit and a lower, dated terrace level (8700 yr B.P.) was estimated by measuring the map area per contour interval for the elevation difference between the two terraces. This volume divided by the time interval (5700 yr) provided an average rate of sediment export. Similarly, the sediment missing between the 8700-yr-old terrace and a radiocarbon-dated, 1700-yr-old terrace adjacent to the main river was measured, and this yielded another average sediment export rate. For these calculations it was assumed that the two lowest dated terraces have gradients similar to that of the present-day river and that terraces of similar heights above the river have approximately the same age.

Results and Discussion

Reach Scale: Morphology and Distribution of Habitats on Young Fluvial Terraces

Numerous tributaries originating from the steeper bedrock portions of the valley traverse the youngest fluvial terrace prior to their confluence with the South Fork (Fig. 3). Radiocarbon dating of wood obtained from a partially buried deciduous tree (sample QL-4298) from within fluvial deposits yielded an age of 1700 yr B.P. (± 40 yr) for the young terrace.

Stream reaches on the young terrace contain preferred summer rearing habitat for coho salmon because of low gradients (<2%) and because of organic debris and boulders that create pools and provide cover. The type and amount of pool habitats for four streams on the young (lower) terrace are shown in Fig. 4.

Seven of the 18 tributaries examined on the young terrace are oriented downvalley on the river valley floor and subparallel to the main river channel. This orientation contributes to the length and low gradient of the tributary streams (Fig. 3). These tributaries include Benson, Gordon, Eldred, Deer, Schweitzer, Hemple, and Heather creeks (Fig. 2). The downvalley orientation of the seven tributaries is a consequence of the surface slope of the young terrace which include a transverse component (towards the river) and a downvalley component. Although the geometry of the terrace explains the majority of the tributaries' downvalley orientation, recent abandoned river channels, overflow channels, and flood levees also appear to contribute. Tributaries that join the South Fork in the absence of the young, 1700-yr-old terrace do not have significant downvalley orientations.

Approximately 70% of summer pool area contained in all the tributary basins is located in tributaries on the young terrace. The tributary pool habitat contained on the young terrace and the pool habitat within the active channel of the South Fork account for 85% of the preferred coho salmon rearing habitat in the watershed, an area that comprises less than 10% of the entire watershed area. Rearing habitats of the young terrace tributaries appear similar to those of the terrace tributaries described by Cederholm and Scarlett (1982) in the Clearwater Basin in Washington State.

Reach Scale: Morphology and Distribution of Habitats on Older Fluvial Terraces

In contrast with low-gradient tributary reaches on the young terrace, upstream reaches flowing through older terraces (>1700 yr old) have steeper gradients (average 4.6%). The steep gradients have developed as a consequence of the Stillaguamish River incising into the glacial sediments following deglaciation (approximately 250 m over 14 000 yr). This results in an increase in elevation difference between the river and its tributaries and a corresponding increase of channel gradients. Differences in channel gradients between younger and older terrace reaches correspond to differences in salmonid habitats as delineated by channel units.

Paired comparisons of the two reach types in Benson, Eldred, Deer, and Schweitzer creeks demonstrated that channels incised into upper, older terraces have a higher proportion of rapids and cascades (Fig. 4). The average percent pool area of 38% in upper terrace reaches compares with 57% for reaches in young terraces. The higher pool percentage in lower gradient channels on the young terrace is caused by the formation of pools in gravel beds at the outside of meanders. The relatively low occurrence of pools formed by large wood in young terrace reaches appears to be related to past logging practices within the riparian zones and removal of large wood from the channels.

Variations in the amounts of woody debris and wood-formed pools in the lower and upper terrace reaches can also be attributed to major disturbances in channels caused by natural processes and by forestry practices. During the last decade, Benson, Gordon, and Blackjack creeks have had very large floods that resulted from the rapid erosion of debris flow dams upstream (Benda and Zhang 1989). These floods altered salmonid habitat by removing large organic debris from within channels. The events in Benson and Blackjack creeks were initiated in logged portions of those tributary watersheds, pointing to the effect of forestry activities on stream habitats.

Low-gradient channels on the young terrace have 46% more channel area in spawning gravels. The abundance of small- to medium-sized gravel in streams on the young terrace is partially attributable to low channel gradient which reduce stream power or sediment transporting competence in those reaches and result in deposition of gravels and pebbles. In contrast, the tributaries flowing through the older, upper-fluvial terraces have steeper gradients and higher stream power, which causes the smaller gravel to be transported through those reaches, leaving behind coarser substrate, such as small boulders. An exception is Schweitzer Creek, which has similar amounts of spawning gravels in both the young and old terrace reaches. The Schweitzer Creek basin is contained almost wholly within sandy glacial deposits (Fig. 2), which reduces the availability of large substrates in channels.

Reach Scale: Variations in Habitat Morphology due to Paleoriver Boulders

Numerous stream reaches on both the young and old terraces contain accumulations of large boulders, 0.5–2 m in diameter, that result in morphological variations in habitats (Fig. 3). These boulders were originally deposited by the Stillaguamish River in a channel that eventually became a terrace. Wood obtained from an older terrace containing the large boulders was dated at 8690 yr B.P. ± 40 yr (QL-4296) and 8750 yr B.P. ± 40 yr (QL-4297), indicating that the Stillaguamish River deposited the boulders during the mid-Holocene Epoch. As the tributary streams eroded through the terrace of the main river,

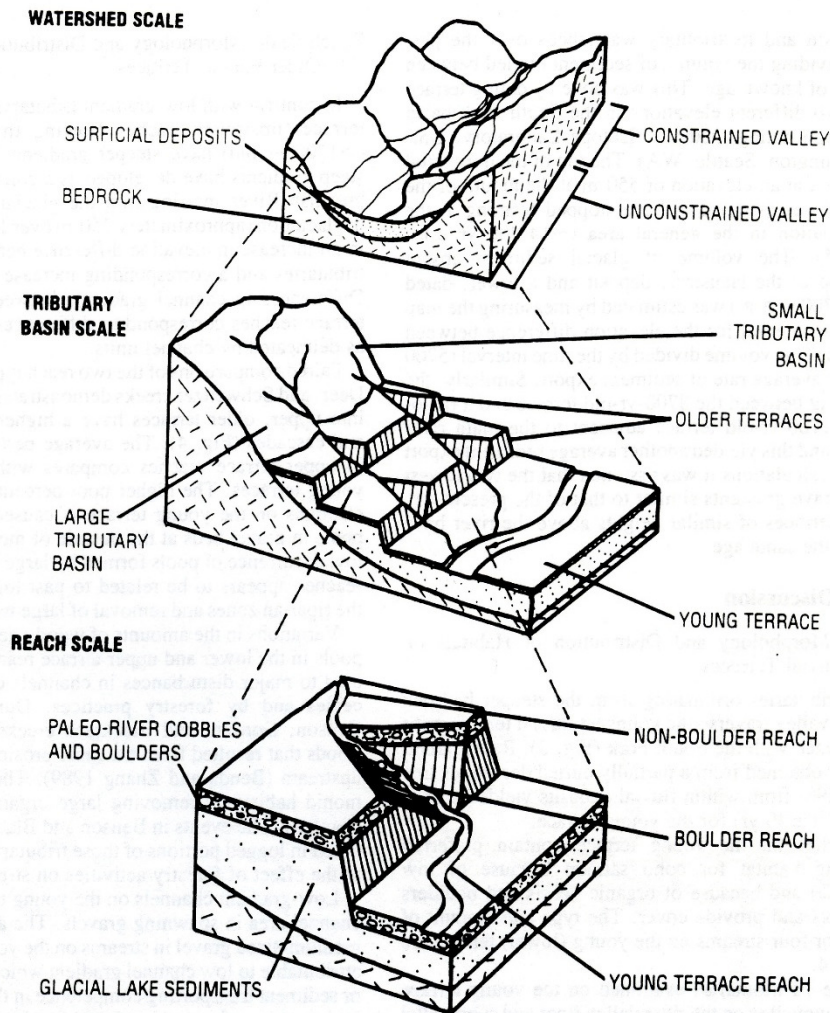


FIG. 3. Schematic diagram showing the three different spatial scales which were used to investigate the relationships between morphology and distribution of salmonid habitats and geomorphology. Important geologic and geomorphic features are indicated.

the large boulders accumulated in tributary channels because they could not be transported by the relatively small discharge of the tributaries.

Stream reaches containing paleoriver boulders are approximately 100 m in length and occur in Turlo, Benson, Wiley, and Schweitzer creeks and several smaller tributaries. Reaches containing large boulders (>0.5 m) are associated with steeper channel gradients. Gradients of seven nonboulder reaches in Schweitzer Creek ranged from 1 to 3% compared with 2.5 to 5% for six boulder reaches. The steep gradients and therefore higher stream powers of boulder-dominated stream reaches result in small areas of spawning gravels. For example, large boulders comprise 28% and gravel (16–64 mm) 21% of the streambed pavement in two boulder-dominated reaches. For nonboulder reaches the opposite trend is evident: only 3% of the streambed is covered with boulders and 50% with gravels (Fig. 5).

Along with woody debris, large boulders are important characteristics in the morphology of pool habitats. Percentage of pools in boulder reaches is 60% compared with 80% in non-

boulder reaches in Schweitzer Creek (Fig. 6). The pools contained in boulder reaches are primarily pocket pools formed in association with boulders and to a lesser extent large wood (Table 1). Pools created by wood comprised 30% of the surface area of the boulder reaches compared with 59% in the non-boulder reaches.

Tributary Basin Scale: Distributions of Spawning Habitat Areas

In the South Fork basin, variation in the amount of spawning gravels between tributary basins is not entirely explained by the presence or absence of the young terrace. The sizes of tributary basins which control stream discharges, and therefore sediment transport competence, influence the relative proportions of spawning gravels between tributaries.

Using the expression for stream power (Richards 1982, eq. 1), we evaluated relationships between discharge, channel gradient, and the proportions of spawning gravels (13–75 mm) in the lower 500-m reaches of 17 tributaries. The analysis indi-

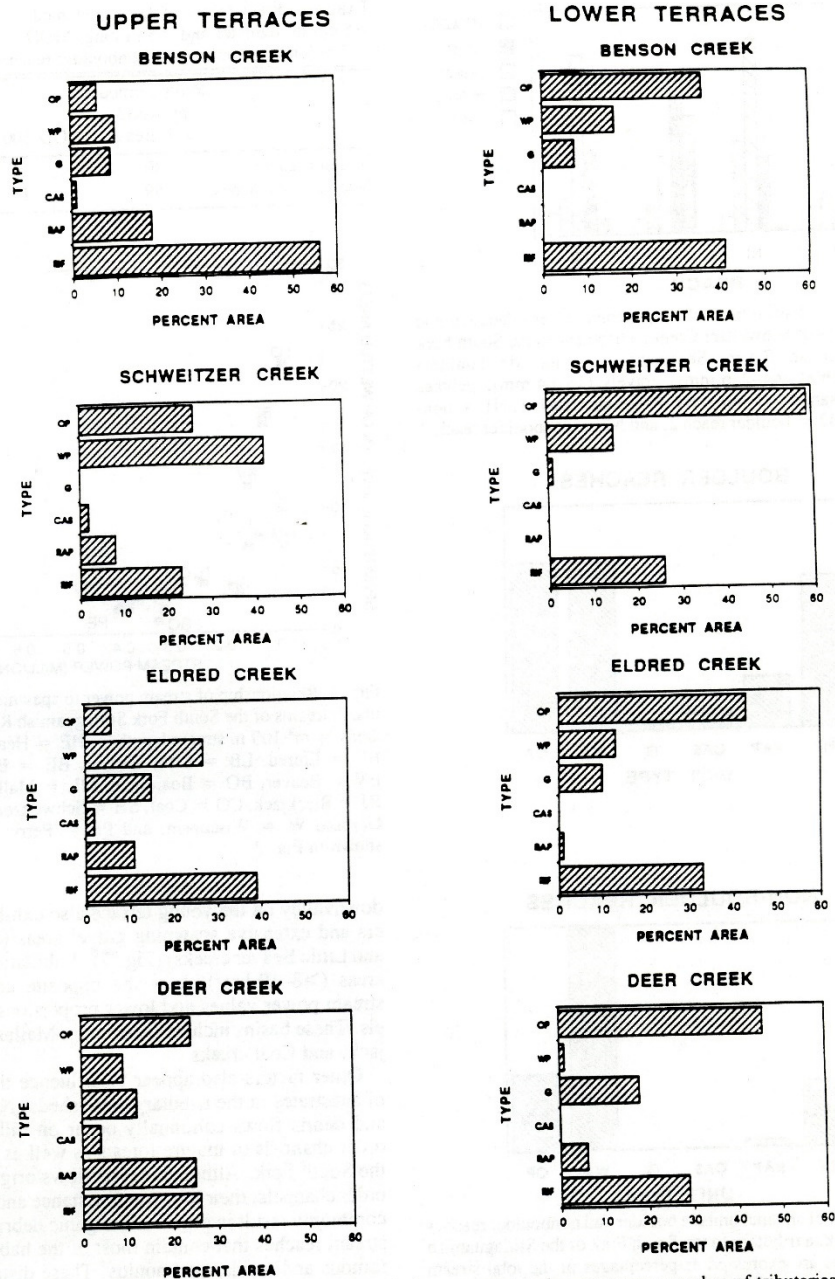


FIG. 4. Distribution of tributary channel units in lower terrace and upper terrace reaches of tributaries expressed as a percentage of total stream surface area. RIF = riffles, RAP = rapids, CAS = cascades, G = glides, WP = pools formed by large organic debris, and OP = all other pool types. Lower terraces are younger surfaces and upper terraces are older surfaces.

cated that tributaries with higher stream powers (large drainage areas and steep channel gradients) are able to transport large cobbles and boulders effectively, although probably at a lower rate than gravel. As a result, these streams have lower proportions of spawning gravels (Fig. 7). In contrast, streams with low stream powers (small basin areas and low channel gra-

dients) are dominated by gravels. In streams with low stream power, large cobbles and boulders are concentrated immediately downstream of alluvial/debris fans (Fig. 2), indicating that selective transport is responsible for the gravel dominance in the lower portions of those tributaries. The boulders contained in the fans are deposited by debris flows and large floods that

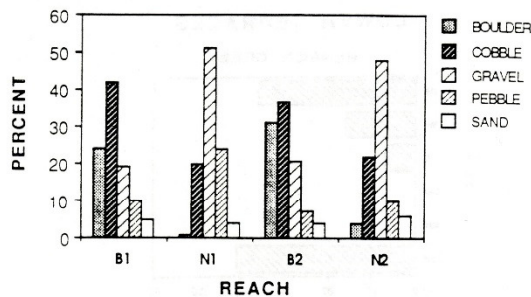


FIG. 5. Particle-size distributions of the pavement layer in boulder and nonboulder reaches of Schweitzer Creek, a tributary to the South Fork of the Stillaguamish River. Sediment sizes include boulders (>256 mm), cobbles (64–256 mm), gravels (16–64 mm), pebbles (1–22 mm), and sands (<1 mm). B1 = boulder reach 1, N1 = nonboulder reach 1, B2 = boulder reach 2, and N2 = nonboulder reach 2.

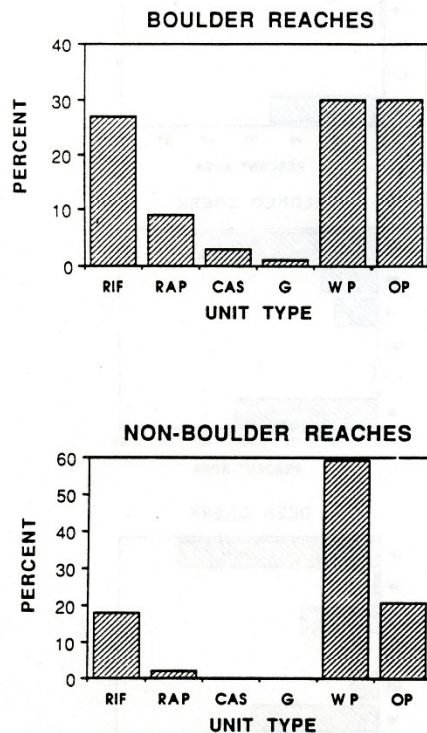


FIG. 6. Distribution of channel units in boulder and nonboulder reaches of Schweitzer Creek, a tributary to the South Fork of the Stillaguamish River. Distributions are expressed as percentages of the total stream surface area in the reach. RIF = riffles, RAP = rapids, CAS = cascades, G = glides, WP = pools formed by large organic debris, and OP = all other pool types.

originate from upper low-order valleys. The majority of tributary basins in the South Fork follow this pattern.

Tributaries basins (<5 km² in area) that have stream reaches oriented downvalley on the young fluvial terrace have the lowest stream powers and the largest spawning gravel areas (e.g. Eldred, Benson, Heather, and Hemple creeks) (Fig. 7). Smaller tributary basins (<3 km²) without stream reaches oriented

TABLE 1. Frequencies of large and medium organic debris (LOD, >5 cm in diameter and >5 m long; MOD, >20 cm in diameter and >3 m long) in boulder and nonboulder reaches of Schweitzer Creek.

	Pools formed by wood (% area)		LOD·100 m ⁻¹	MOD·100 m ⁻¹
Boulder reaches	30	6	17	
Nonboulder reaches	59	13	35	

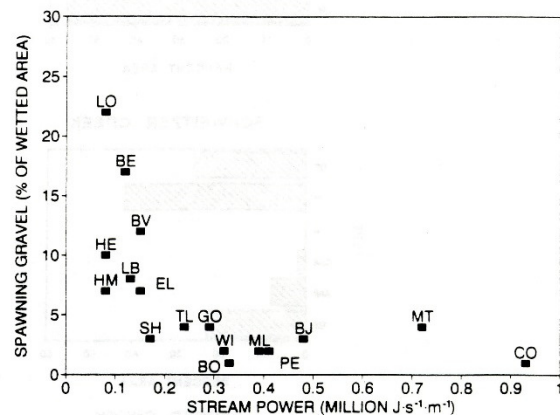


FIG. 7. Relationship of stream power to spawning gravel areas in tributary streams of the South Fork Stillaguamish River. Spawning gravel areas = m²·100 m stream length⁻¹. HE = Heather, HM = Hemple, EL = Eldred, LB = Little Beaver, BE = Benson, LO = Long, BV = Beaver, BO = Boardman, ML = Mallardy, MT = Marten, BJ = Blackjack, CO = Coal, SH = Schweitzer, TL = Turlo, GO = Gordon, W = Wisconsin, and PE = Perry. Stream locations are shown in Fig. 2.

downvalley on the young terrace also exhibit low stream powers and extensive spawning gravel areas (e.g. Long, Beaver, and Little Beaver creeks) (Fig. 7). Tributaries basins with larger areas (>8–10 km²) show the opposite conditions of higher stream power values and lower proportions of spawning gravels. These basins include Boardman, Mallardy, Marten, Blackjack, and Coal creeks.

Other factors also appear to influence the amount and size of substrates in the tributary watersheds. Numerous landslides and debris flows continually occur on hillslopes and in low-order channels of mature forests as well as in clearcut areas in the South Fork. Although debris flows originate in steep, low-order channels, their long travel distance and erosional intensity commonly result in gravel and organic debris deposits in downstream reaches that contain most of the habitats for both anadromous and resident salmonids. These disturbances can cause aggradation and therefore have consequences to salmonid habitats.

Debris flows that occurred during the past decade are most evident in Benson, Wiley, Deer, Gordon, Coal, and Blackjack creeks. The disturbances in Benson, Wiley, and Blackjack creeks originated from within logged portions of the basin, and the remaining events originated from natural forested areas. This raises the question of the effects of timber harvest on frequencies of landslides and debris flows compared with natural conditions. It is important to understand how land use activities are changing the frequency, magnitude, and spatial distribution

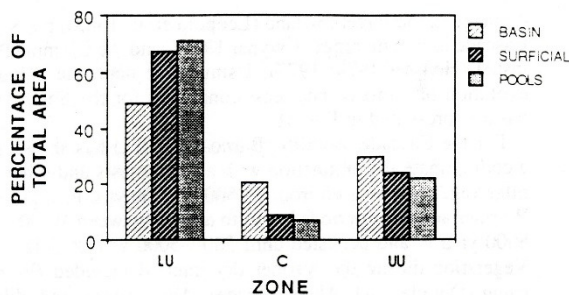


FIG. 8. Percentages of total basin area, total area in surficial deposits, and total summer pool surface area in unconstrained and constrained portions of the South Fork Stillaguamish river basin. LU = lower valley unconstrained area, C = constrained area, and UU = upper valley unconstrained area. BASIN = percent of watershed area, SURFICIAL = percent of total area of surficial deposits, and POOLS = percent of total pool area.

TABLE 2. Summary data for three areas of the South Fork of the Stillaguamish River basin. Locations of areas are shown in Fig. 2.

	Area of river basin		
	Lower unconstrained	Upper constrained	Unconstrained
Number of tributaries	13	4	7
% basin area	49	19	32
% area surficial deposits	69	9	22
% total pools	73	7	20
Mean gradient (%)	5.8	8.8	6.6
Mean % pools	39	27	37

of disturbances across landscapes and how fishes respond or adapt to these disturbances.

Watershed Scale: Distribution of Habitats along the River Valley Floor

A majority of stream channels accessible to anadromous salmonids in the South Fork basin are contained within geologically unconstrained or wide areas of the main river valley. For example, most of the stream surface areas in summer pools (73%) are in the lower unconstrained portion of the valley, an area covering nearly half of the river basin's valley floor. In contrast, the geologically constrained area includes approximately 19% of the basin area and only 7% of the total surface area of summer pool habitat in tributaries (Fig. 8; Table 2).

The wide glacial deposits of unconstrained valley areas favor the development of young terraces and low-gradient tributaries (Fig. 3). For example, six of the seven low-gradient tributaries oriented downvalley on the young terraces are located in the lower unconstrained portion of the river valley floor (Fig. 2). The width of the glacial deposits along the valley ranges from 0.8 to 3.3 km and generally increases downvalley. In the central portion of the valley (Fig. 2), a more geologically constrained area (0.8–2 km wide) lies within the erosion-resistant marbles and cherts of the Chilliwack Group, a lithological unit bounded by two parallel thrust faults.

In summary, the preceding discussions illustrate how analyses of fish habitats in large watersheds can be conducted at several different spatial scales to describe the linkages between the morphology and distribution of habitat and basin geomor-

phology. We expect that many of these geomorphic – fish habitat relationships should also apply to other recently deglaciated basins in the Pacific Northwest. For example, most of the summer pool area should be located in tributaries found on younger terraces of geologically unconstrained or wide river valley floors, and proportionally larger amounts of spawning gravels should be located in the lower portions of smaller tributary basins. These relationships are probably specific to individual physiographic and climatic regimes.

Evolution of Salmonid Habitats from 14 000 yr ago to Present

The recently deglaciated environment of the Pacific Northwest presents an opportunity to develop a hypothesis for the evolution of salmonid stream habitats since continental glaciation (~14 000 B.P.). The hypothesis was based on information on the morphology and distribution of present-day habitats discussed above, our radiocarbon dating and analysis of the erosional history of the watershed, and published data on the evolution of forests in the Pacific Northwest. Our goal was to consider how fish habitats are coupled to geomorphic development of mountain drainage basins following a major continental glacial disturbance.

The present-day South Fork fluvial environment evolved from a highly erosive and sparsely forested landscape that existed immediately following deglaciation (~14 000 yr B.P.). Today, the basin is characterized by relatively low erosion rates, stable channels, and an old-growth conifer forest community (e.g. the Western Hemlock Zone forests, Franklin and Dymess 1973).

To evaluate how the fluvial environment of the South Fork has changed over 14 000 yr since deglaciation, we estimated erosion rates and sediment yields for different time intervals. Erosion rates and sediment yields in the South Fork were estimated by determining differences in volumes of glacial sediment eroded from fluvial terraces of known age. The age of terrace formation and therefore the magnitude of erosion in the South Fork basin was based on radiocarbon dating. On the basis of this analysis, 90% of the erosion and export of glacial sediment from the South Fork occurred between approximately 14 000 and 8700 yr B.P. This was equivalent to an average sediment yield of approximately 10 000 tons·km⁻²·yr⁻¹. The high rate of sediment yield reflects the immediate lowering of base level of the Stillaguamish River following the removal of the ice dam and the absence of stabilizing vegetation. This sediment yield compares closely with those (postdeglaciation) for several river basins in British Columbia (Church and Ryder 1972).

A modern-day analogue to the fluvial environment of the South Fork during the immediate postdeglaciation period is the North Fork Toutle River in Washington State. The North Fork Toutle River channel currently resides on top of a massive debris avalanche and debris flow deposit that originated from the Mount St. Helens eruption of May 18, 1980. Sediment yield in the North Fork Toutle river during the first several years following the eruption was approximately 35 000 tons·km⁻²·yr⁻¹ and was dominated by fine particles (Janda et al. 1984). The North Fork Toutle River channel, where avulsions are common and banks are unstable, is braided and shallow and partly composed of fine substrates (Lucas 1986).

Between 8700 and 1700 yr B.P., the average sediment yield of the South Fork reduced to approximately 700 tons·km⁻²·yr⁻¹. This rate is about 15 times less than the rate during the initial postglacial period. Today, lower sediment

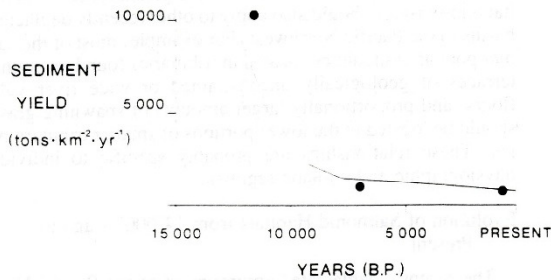


FIG. 9. Average sediment export rates of glacial sediments in the South Fork Stillaguamish River basin since the retreat of the continental ice sheet approximately 14 000 yr ago.

yields for the South Fork basin are assumed to be similar to those of other mountain drainage basins in the Pacific Northwest, that is, approximately 50–300 tons·km⁻²·yr⁻¹ (Swanson et al. 1987).

The comparison of South Fork sediment yields for the three time periods (14 000–8700 yr B.P., 8700–1700 yr B.P., and 1700 yr to present) indicates that erosion decreased dramatically during the initial 5000- to 6000-yr period (Fig. 9). Changes in erosion rates in the basin were also accompanied by changing climatic conditions and forest communities. The erosional history along with changes in climate and forest communities would have strongly influenced the development of salmonid habitats in the watershed.

Changing climatic conditions and forest communities in the South Fork during the later Pleistocene and early to mid-Holocene (14 000–6000 yr B.P.) probably resembled those defined for several locations in Washington State. Past climatic and vegetative patterns have been reconstructed using pollen and macrofossil assemblages for the Cascade foothills at Davis Lake, Washington (Barnosky 1981), the Lake Washington

drainage in the Puget lowland (Leopold et al. 1982), the North Cascade mountain range (Cwynar 1987), and the Olympic Peninsula (Heusser 1974; 1977). Using these data, the probable evolution of climate and forest conditions for the South Fork basin is presented in Fig. 10.

For the Cascade foothills, Barnosky (1981) has shown that a cool climate in conjunction with alpine forests and other conifer vegetation existed from 13 500 to 8000 yr B.P. (Fig. 10). Warmer and drier periods began to appear between 10 000 and 8000 yr B.P. and persisted until 3000–5000 yr B.P. (Fig. 10). Vegetation during the warmer dry interval included *Pseudotsuga* (Douglas fir), *Abies* (spruce), *Alnus rubra* (red alder), and several grass species. The absence of mesic taxa in the pollen assemblages of the early Holocene suggests that vegetation communities in the Cascade foothills of Washington were similar to Douglas fir woodlands and modern oak savanna in the southern Willamette Valley of Oregon (Brubaker 1991).

A shift to a more cool and moist climate began around 7000–5000 yr B.P. in western Washington and continues to persist today. This led to the colonization of more mesic taxa, such as *Tsuga heterophylla* (western hemlock) and *Thuja plicata* (western red cedar) (Fig. 10). An examination of pollen spectra indicates that old-growth Douglas fir forests similar to today's forests did not occur in the foothills of the Cascade mountain range prior to approximately 6000 B.P. (Brubaker 1991).

Therefore, the palynological studies indicate that a subalpine forest community with relatively small trees probably existed in the South Fork basin during the initial several-thousand-year period following deglaciation when erosion rates were high. Although sometime after 8000 yr ago, a cool and moist climate led to increasing amounts of Douglas fir and true fir forests, old-growth Douglas fir forests did not become fully developed until sometime after 6000 yr B.P. when erosion rates had declined significantly. Hence, organic debris of the size that occurs today would not have existed in channels prior to about 6000 yr ago in the South Fork basin.

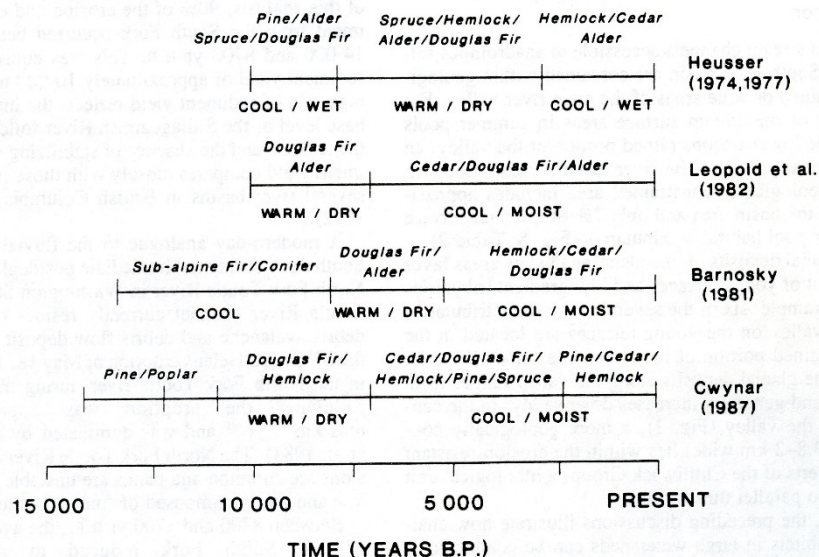


FIG. 10. Polynological studies from the Pacific Northwest showing the changing vegetation patterns and climate for the 14 000-yr period following the retreat of the continental ice sheet.

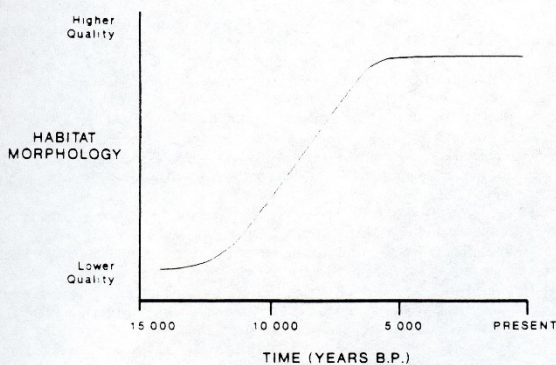


FIG. 11. Change in salmonid habitat morphology over time since deglaciation as inferred from present-day morphology and distribution of habitats, the erosional history of the basin, and published literature on the development of forests in the Pacific Northwest.

Fish habitats in low-gradient tributaries in the South Fork immediately following deglaciation were most likely abundant but of poor quality. Habitats were probably characterized by cohesive substrates, shallow and braided channels, turbid waters, and small organic debris. Such sediment-rich and unstable habitats would provide lower quality spawning and rearing habitats for fish.

Between 10 000 and 8700 yr B.P., rapidly declining erosion and sediment yields (Fig. 9), coupled with developing conifer forests during the early to mid-Holocene (Fig. 10), suggest rapidly improving stream habitats. Specifically, the quality and stability of stream gravels and the size of woody debris in channels would have been increasing. Further reduction and stabilization of erosion and sediment yields sometime after 8700 yr B.P. and the establishment of old growth conifer forests in the South Fork basin (~6000 yr B.P.) imply that stream habitats attained their present-day morphology during the mid-Holocene, between approximately 8000 and 6000 yr B.P. (Fig. 11). A seeming paradox, however, is that as habitat quality improved over time since deglaciation, there occurred concomitantly a diminution of low-gradient salmonid spawning and rearing habitat area in the watershed.

The high sediment yields following deglaciation were the result of rapid incision of the South Fork river and its tributaries into the glacial sediments (~250 m in 14 000 yr). As a consequence, the valley floor containing the youngest terrace and therefore the highest quality salmonid habitat has been diminishing in width over time since deglaciation. The width of the valley floor immediately following deglaciation and prior to river incision into glacial deposits was the width of the entire glacial deposit filling the valley which averaged 3300 m at six cross sections (Fig. 12). Hence, low-gradient tributaries containing lesser quality habitat would have existed across the entire valley floor at that time (~14 000 yr B.P.). The width of a lower terrace dated at 8700 yr B.P. (located 30 m above the present-day river) indicates that the valley floor necessary for the development of higher quality habitat diminished in width by approximately 300% in 5000 yr (Fig. 12).

Although stream habitats had probably attained today's morphology between approximately 8000 and 6000 yr ago, the width of the valley floor, and therefore lengths of low-gradient reaches, has since been in decline because of river incision into glacial deposits. Therefore, salmonid habitats in the South Fork basin would have attained their greatest areal extent during the

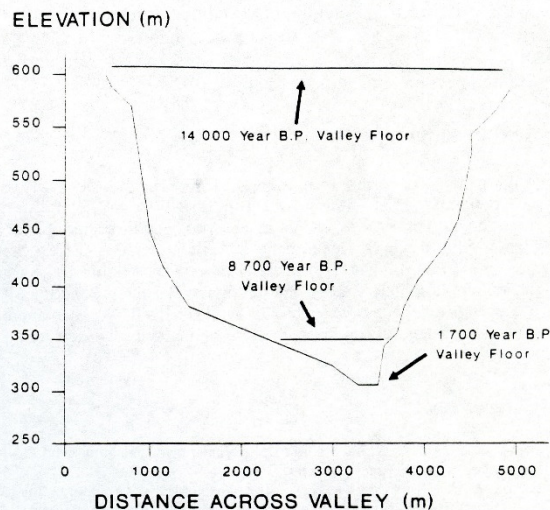


FIG. 12. Changing valley floor widths averaged at six cross sections in the watershed showing the diminution over time of the area containing the low-gradient terrace and salmonid rearing habitat.

mid-Holocene, approximately 7000 yr ago, and they have been in slow, steady decline ever since.

The incision of the South Fork into the glacial sediments caused a replacement of low-gradient streams with higher gradient streams more suitable for steelhead trout and resident trout species. Therefore, we infer that the South Fork basin during the Holocene may have been characterized by a shifting of habitat fortunes from anadromous to resident salmonid species. Our perspective of the postglacial evolution of the landscape in the South Fork Stillaguamish River valley suggests that anadromous stocks may have attained eighteenth or nineteenth century population levels about 8000–6000 yr B.P. Although a waterfall downstream near the mouth of the South Fork basin denied access to salmonids in recent times, it is not known when the falls became exposed following deglaciation.

Conclusion

Relationships between the morphology and distribution of salmonid habitats and geomorphology were evident at several spatial scales ranging from reach, tributary basin, and the watershed. Many of these relationships should apply to other watersheds in the region that have similar histories of continental glaciation.

Our hypothesis on the evolution of salmonid habitats in the study watershed provides an example of how development of habitats is coupled to formation of landscapes following a major glacial disturbance. Habitats increased in quality in concert with increasing watershed stability and evolution of forests but decreased in quantity as landforms changed over 14 000 yr.

This information can also be used for managing fishes and forests in the river basin. For example, forests on the young terrace could be managed for old-growth characteristics and the recruitment of large organic debris to channels because preferred coho salmon habitats are concentrated in such areas. Harvest activities could be consolidated on hillslopes in the geologically constrained areas of the watersheds that have tributaries not suitable for salmonids. Similarly, more attention

could be directed to potential environmental impacts from forestry activities in areas where salmonid habitats are the most abundant and of high quality, such as in the lower unconstrained portions of the watershed.

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