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DISTRIBUTION OF FISH AND STREAM HABITATS AND INFLUENCES OF WATERSHED CONDITIONS, BECKLER RIVER, WASHINGTON

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ABSTRACT

A basin-wide synthesis provides an analysis of anadromous fish distributions, stream habitat conditions and influences of watershed physiography and human land-uses in the Beckler River basin, Washington. This analysis was conducted within the constraints of existing information provided by the Mt. Baker-Snoqualmie National Forest. Almost all the anadromous and resident fish populations and habitats appear impacted by upslope land failures, sediment inputs and unstable streambank and channel conditions. The degradation of stream habitats by excessive substrate deposition, channel erosion, and removal of large woody debris (LWD) for flood control purposes is evident in the greatly reduced habitat diversity and potential capacity to support fish. The combined effects of burial of large rocks due the excessive input and accumulation of finer substrates, and removal of large trees from channels, have greatly reduced the complexity of channels and in some cases eliminated pool habitats. These conditions appear confounded by timber harvest patterns over the past forty years that have caused the timing of snowmelt and peakflows to shift to earlier in the year. These changes can cause reduced streamflows in the summer when fish entrapment and high temperatures could lead to fish mortalities. The identification of unstable terrestrial areas that impact riparian and stream ecosystems is facilitated by land-failure relationships between land-use and physiographic conditions. Subsequent geographic analysis (GIS) assesses the spatial distributions of roads, unstable soils, immature forest stands, rain-on-snow areas, and critical terrain slopes. Overlapping distributions of immature forests (age <35 years), unstable soils, and critical terrain slopes (>19°) suggest highly unstable terrain locations in riparian areas near streams. These unstable areas are used to identify modifications to prescribed riparian widths for fish-bearing streams. These findings indicate several improvements are needed for effective ecosystem management. A summary of the recommendations include the following: (a) a basin-wide strategy that addresses resource issues that encompass the entire river basin and emphasize the protection and restoration of habitats; (b) the formation of integrated management teams that focus their efforts and experiences on improving coordinated long-term inventories and monitoring programs; (c) and the acquisition of new information for assessing ecosystem processes and developing, initiating and evaluating fisheries and watershed projects.

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KEY WORDS

Beckler River, Rapid River, salmon, fish habitats, large woody debris, stream substrates, riparian, restoration, basinwide, watersheds, geographic analysis, and GIS.

INTRODUCTION

In 1993, President Clinton's Forest Summit in Portland, Oregon, focused on the influences of forest harvest and other management practices on the health of Pacific Northwest ecosystems. The resultant recommendations of an interagency team of scientists calls for improvements by implementing an aquatic conservation strategy (USDA Forest Service 1993a). Major components of the strategy include riparian reserves that protect streams, key watersheds that provide refugia for at-risk salmon species, and watershed analyses that provide the basis for monitoring and restoration programs. The first step in addressing the needs of salmon populations and their life history requirements involves determining how fish populations and their habitat conditions in large river basins (>50 km^2) are influenced by terrestrial conditions.

This paper presents an analysis of anadromous fish distributions, stream habitat conditions and influences of watershed physiography and human land uses in the Beckler River basin, Washington. The objective is to provide a basin-wide synthesis of fish resource and watershed conditions and recommendations for improving ecosystem management. The recommendations include (a) width adjustments to improve riparian reserves for protecting riparian and stream ecosystems, and (b) additional information needed for developing, initiating and evaluating watershed restoration projects.

The basin-wide synthesis was conducted within the constraints of existing information provided by the Mt. Baker-Snoqualmie National Forest. This information covers all land ownerships which allows for management planning to proceed at different landscape levels. However, most of this data was collected for specific management purposes, such as timber harvest, with few provisions for landscape level analyses. Common analytical difficulties included stream and watershed data being derived from small scale surveys, transects or other methods. Also, the extrapolation of the fine scale data to a larger basin-wide scale usually required an assumption of spatial homogeneity or knowledge of resource heterogeneity.

This analysis addresses some of these analytical problems by considering fish and stream habitat conditions at scales more comparable to those of upslope conditions. Distributions of fish and important habitat morphometric characteristics of large woody debris (LWD) and bottom substrates are expressed per hectare (ha). This spatial unit alleviates some of the problems associated with the variability of habitat specific information. The instream scales information, and those for unstable streambanks, permit the assessment of what portions of the river basin are unstable. This information also allows for the consideration of riverine landscape positions in relation to the spatial distribution of upslope conditions (km^2). The spatial heterogeneity and unstable areas of upslope attributes are assessed using GIS software.

BECKLER RIVER BASIN

The Beckler River basin is located on the west side of the Cascade Mountains within the Mt. Baker-Snoqualmie National Forest. The mainstem of the Beckler River originates at Jacks Pass (elevation 789 m) and flows 20.9 km southeast before joining the South Fork of the Skykomish

River (elevation 283 m) near the town of Skykomish, Washington. The Rapid River, the largest tributary to the Beckler River, flows west from the crest of the Cascade Mountains. Some of the higher elevations include Eagle Peak (1711 m) and Burley Mt. (1649 m) to the west of the Beckler River and Mt. Fernow (1887 m) and Evergreen Mt. (1703 m) to the east. An example of the high relief is a vertical rise of 1400 m from the lower Beckler River channel to Eagle Peak, <2 km away.

The Beckler River basin has an area of 260 km^2 that includes three major geographic regions, the drainages of the upper and lower Beckler River and the Rapid River. These drainages have their confluence 12.3 km above the mouth of the Beckler River (Fig. 1). The largest drainage area and drainage density occurs in the Rapid River, 106 km^2 and 4.24 km km^{-2}, respectively. The lower and upper Beckler regions have smaller areas (88 and 66 km^2) and drainage densities (3.84 and 3.60 km km^{-2}), respectively.

The basin is divided into 16 subwatersheds with Forest Service management codes A to P (Fig. 1, Table 1). The largest subwatershed areas occur adjacent to the main river channel in the lower Beckler drainage (subwatershed C, 26.6 km^2) and along the lower Rapid River (subwatershed K, 31.4 km^2). The lower Rapid River includes a reach that extends upstream 6.6 km from the Beckler River confluence. The largest drainage densities (km km^{-2}) occur in the headwaters of the Rapid River drainage (subwatersheds L, M, N, O and P) indicating longer lag times for water runoff because of greater lengths of channels in stream networks. The total length of all stream channels (1024.9 km) in the Beckler River basin includes 112.6 km of potential fish-bearing and 912.3 km non-fish bearing streams as defined by the Forest Service (USDA Forest Service 1993a).

The primary geological formations of the Beckler River basin are comprised of metamorphic Tertiary rocks of the Easton group, the Tonga and Eagle Greenschist formations (Yeats 1958). The mainstem of the Beckler River from its mouth to Jack's Pass (20.9 km) is underlain by the Tonga formation, a low grade metamorphic rock consisting of conglomerates. In the lower Beckler valley (0 - 12.4 km), the Tonga formation is covered by Quaternary deposits from the Pliocene. To the east of the Beckler River (~1 to 3 km) lies the Evergreen Fault. This fault line runs almost parallel (north to south) for the entire length of the Beckler River valley. The fault line crosses Evergreen Mt. and the lower reaches of the Rapid River (~2 km from its Beckler River confluence) then extends south through the headwaters of Johnson and Harlen creeks. High grade metamorphic rock formations lie to the east of the Evergreen Fault. To the west of the Evergreen Fault, where low grade metamorphic rocks predominate, unstable soils overlay much of the Tonga formation (USDA Forest Service 1972). Highly unstable conditions appear near 4th of July Creek because of a fault in the Beckler River valley that extends west for almost the entire length of 4th of July Creek (Yeats 1958).

Tertiary metamorphism occurred in the Beckler region during the Columbia Basin Basalt time. The principal uplift and consequent erosion forming of the mountain ranges occurred in the Pliocene time. The mountainous Cascades were already considerably dissected by streams at the beginning of the Quaternary volcanism. Pleistocene glaciation modified the already dissected range to create the landscape we see today (Willis 1903).

The climate of the Beckler River basin is primarily influenced by elevation, terrain, and the prevailing winds. Distance and direction from the ocean, and the position of pressure systems over the North Pacific Ocean also influence the climate. Precipitation patterns of frontal systems moving through the Skykomish and Beckler River drainages are related to a convergent zone in Puget Sound induced by orgographic affects of the Olympic Peninsula.

Annual total precipitation at the mouth of the Beckler River (US Weather Bureau station 7708, elevation 283 m) and at Steven's Pass (15 miles east of the Beckler River at US Weather Bureau station 8089, elevation 1340 m) averages from 266 cm to 208 cm, respectively. Almost 77% of the total precipitation falls between October and March. While most of the total precipitation occurs at the lower elevations as rain, snowfall and depth accumulations increase rapidly with increased elevations. The Beckler River basin can receive an annual snowfall ranging from 160 cm at the mouth of the Beckler River to about 1,265 cm at the 1340-m elevation. Winter daytime temperatures approach freezing at the higher elevations and range from 4 to 10°C at the mouth of the Beckler River. Summer temperatures can range from 10 to 20°C at the higher and lower elevations, respectively.

The Rapid River drainage, which drains from an easterly direction, usually exhibits a dryer climate than the lower and upper Beckler River valleys. The driest conditions exist during summer when pressure patterns produce easterly winds that bring high temperatures, low humidity and an increased danger of fires. The Rapid River drainage experienced major fires in 1930, 1941, 1967 and 1973. The effects of the Evergreen Mt. fires are still evident at the confluence of the Beckler and Rapid rivers.

The annual discharge rate for the Beckler River averages 17 $m^3 sec^{-1}$. The average discharge for the base flow and peak flow are 9 $m^3 sec^{-1}$ and 187 $m^3 sec^{-1}$, respectively. Rain-on-snow events can cause rapid melting of snow and flooding at lower elevations. Snowfall accumulations at higher elevations between November and January can be followed by heavy rainfall. Major flood events in 1959, 1975, 1976, 1980, 1985 and 1990 occurred as heavy rainfalls (30 to 75 cm per month) saturated the ground and snowpacks (snow depths of 18 to 58 cm). The elevations of the transitory rain-on-snow zones usually occur between 305 m to 1067 m (Coffin 1991). The increase in temperatures and rainfalls in March can also produce peak flows events in the Beckler River. Peak flows range from 67 $m^3 sec^{-1}$ to 484 $m^3 sec^{-1}$. The highest recorded peak flow of 484 $m^3 sec^{-1}$ (December 15, 1959) shows an estimated reoccurrence period of 29 years. This compares with an estimated peak flow of 119 $m^3 sec^{-1}$ for a 10 year reoccurrence period. Discharge records for the Beckler River (USGS gauging station 12131000) include daily flows from 1929–33 and 1947–49, and peak flows from 1929–1970 (Williams et al. 1985).

European man's activities in the area began in the late 1800s with beaver trapping followed by mining (copper, gold and silver), logging operations and the establishment of the town of Index in 1885 near the North Fork of the Skykomish River. In 1893, the Great Northern Railroad Company completed the first transcontinental railroad to the Pacific Northwest, passing through the towns of Index and Skykomish. This led to new copper mines being established, ore shipments to smelters in Everett and a general increase in commerce. As the rail system proliferated, a lucrative timber industry grew to take advantage of the region's dense forests. As these developments progressed, fish populations and habitat conditions declined (Ruth Burgstahler, no date, Index: A Historical Perspective, 53 p.; G. Katzenberger, Mt. Baker-Snoqualmie National Forest, pers. comm.).

Between 1910 to 1945, 25 miles of railroad were constructed within the Beckler River basin leading to the harvest of nearly 10% of the 260 km^2 basin. Almost all the harvested areas were along the valley floor and foothills of the lower Beckler River. After World War II, when surplus heavy equipment became readily available, truck logging began and lead to an acceleration in timber harvest. Between 1954 to 1993, about 40 km^2 was harvested from the valleys and upslopes. Most of the harvested and roaded areas are in the lower and upper Beckler River drainages. The influences of recent logging and the Evergreen fires is evident in the high frequency of immature forest stands along the mainstem Beckler and Rapid rivers. Concern over environmental issues, litigation and the presence of sensitive species, such as the northern spotted owl and depressed anadromous fish stocks, currently precludes significant harvests.

Recreational damage to riparian areas and streams are a concern within the Beckler River basin. Recreational activities began with the arrival of railroads, increased throughout the 1930s, then accelerated after World War II with the popularity of car camping. Presently, about 30,000 visitors per year use the Beckler River basin for a variety of activities such as fishing, panning gold, hiking, motor biking and watching wildlife. The proximity of these activities, and dispersed campsites within riparian areas along streams, have damaged these ecosystems. For example, soil erosion as well as compaction by land uses prevent plant development, lower vegetative diversity and cause the narrowing of functional riparian forest corridors. These impacts, combined with confinement by roads and dispersed traffic uses, alter water storage, nutrient cycling, and wood inputs to streams.

The Beckler River, a major tributary to the South Fork Skykomish River, supports populations of coho (*Oncorhynchus kisutch*) and pink (*O. gorbuscha*) salmon, smaller runs of summer chinook (*O. tshawytscha*), chum (*O. keta*) salmon. There are also anadromous summer steelhead (*O. mykiss*), cutthroat trout (*O. clarki*) and Dolly Varden (*Salvelinus malma*) (Williams et al. 1975, USDA Forest Service 1992, USDA Forest Service 1994a, Washington Dept. Fisheries et al. 1993). The presence of these fish in the Beckler River is a result of a "trap and haul" facility located at Sunset Falls, a natural barrier to fish passage, at river kilometer 82.9 on the South Fork Skykomish River. The Washington State Department of Fisheries (WDF) has operated the facility since 1958. Spawning surveys by WDF between 1974 and 1985 (August to December) were conducted for 28 tributary and river reaches within the Beckler River basin (WDF Salmonsrv Internet System). Only two of the reaches showed fish observations, the main channel of the Beckler River from 0 to 17 km upstream at the mouth of Boulder Creek, and the main channel of the Rapid River from 0 to 5 km upstream to where cascades become barriers to fish migration. The number of fish present ranged from 109 to 137 coho km^{-1}, 0 to 10 pink km^{-1}, and 2 to 4 chinook km^{-1}. These adult fish densities range from 2 to 4% of the escapement levels observed at Sunset Falls (1978 to 1985), USDA Forest Service (1992).

The decreasing number of quality pool habitats in recent years may be a major limiting factor for salmonid use of the mainstem Beckler River. The low number and quality of pools appears due to the lack of pool forming structures in channels such as large woody debris (LWD) as well as the burial of pools by substrates. Debris removal programs between 1978 and 1981 were conducted in the lower and upper Beckler River for the purposes of flood control and protection of roads, bridges and private property. All LWD (debris jams, logs, branches, root wads) >7 cm in diameter were removed from channels and banks and burned (USDA Forest Service 1994a).

Historically, the Beckler and Skykomish River basins were the lands of several Native Americans tribes, including the Skykomish, Snoqualmie, Duwamish, Snohomish and Stillaguamish, collectively known as the Southern Coast Salish Indians. The Skykomish or "upstream people" could have lived in the Beckler River area. The Treaty of Point Elliott in 1855 forced most Native Americans onto the Tulalip Reservation near Marysville, Washington. This treaty and the Native rights to traditional fisheries were reinforced by the Boldt decision in 1974. During the 1980s, concern about declining coho and chinook fish stocks led to cooperative efforts by the Tulalip Tribes, WDF and the Forest Service in initiating stream channel, bank stabilization and habitat improvement projects in the Beckler River basin (USDA Forest Service 1994a). The monitoring of fish populations has been too infrequent to determine the success of these projects.

METHODS

The fish density, stream habitat and channel stability data, physiographic and management information used in this study was furnished by the Skykomish Ranger District of the Mt. Baker-Snoqualmie National Forest. This information was collected and organized geographically by the Forest Service according to the 16 subwatersheds (Fig. 1 and Table 1).

Fish density and stream habitat data were obtained using the stream inventory procedures of the Forest Service (USDA Forest Service 1993b, Hankin and Reeves 1988). The information includes snorkel surveys of juvenile and adult fish, measurement of habitat units (riffles, glides, pools and side channels), large woody debris (LWD) and channel bottom substrates (USDA Forest Service 1993b). The available fish data is limited to the main channels of the Beckler and Rapid rivers which were the habitat areas used by salmon. The total number of habitat units sampled during the snorkel surveys included 14 units in the lower Beckler River, 10 units in the Upper Beckler and 25 units in the Rapid River. These studies were conducted during August and September of 1990 and 1991.

LWD measurements for the habitat units included the following three size categories (>31 cm diameter and >8m length; >61 cm diameter and >15 m length; >91 cm diameter and >15m lengths). LWD is expressed as the frequency of occurrence of pieces per 100 m of channel (LWD 100 m^{-1}) and pieces per unit area (ha). The LWD >61 cm diameter category is used to examine the relationship of LWD 100 m^{-1} of channel to the presence of large sized forest stands (trees >61 cm diameter) in riparian areas. The lengths of large sized riparian stands (LSR) adjacent to channels were calculated as:

$$LSR = \text{forest stand length x (reach length/total stream length)} \quad (1)$$

where the stand length represents large timber adjacent to channels.

The substrates of the habitat units were inventoried by size categories and expressed as dominant and subdominant sizes occurring within habitat areas. The substrates include five size categories sand (<2 mm), gravel (2–64 mm), cobble (64–254 mm), small boulders (254–1016 mm), large boulders (>1016 mm) and bedrock (USDA Forest Service 1993b). Additional stream surveys of streambank and channel stability conditions were based on inventories using the procedure of Pfankuch (1975). All the above stream data was obtained during low flow conditions (July-August) in the Beckler River basin.

The physiographic data sets include maps of rain-on-snow zones and soils. The rain-on-snow zone was based on a range of elevations (305 to 1067 m) which has the greatest frequency of rain-on-snow events in the central Cascade Mountains of Washington (Coffin 1991). The soil maps and descriptions were from the Soil Resource Inventory (USDA Forest Service 1972). Soils were mapped according to potentials for sediment yield to streams. Soil potentials were based on soil texture, structure of subsurface materials, slope, drainage patterns and landform.

Forest stand data includes stand age <35 years and two stand sizes <12.7 cm and >51 cm diameter breast high (dbh). The stand age <35 years and stand size <12.7 cm are used to examine forested areas of the landscape that may not have attained "hydrologic recovery" following tree removal by timber harvest and fires. These stand age and size categories for the Beckler River basin suggest the lack of development of rooting strengths that are necessary to prevent soil erosion and minimal canopy covers for the removal of excess belowground waters through evapotranspiration (Stuart Woolley, Mt. Baker-Snoqualmie National Forest, pers. comm.; Sidle et al. 1985; Coffin 1991). Land failure sites, frequencies and sediment inputs to streams between 1970 and 1990 were from observations mainly in harvested and roaded areas (G. Katzenberger, Mt. Baker-Snoqualmie National Forest, pers. comm.). No background information is available about the natural frequency of land failures.

A GIS is used to assess interactions of spatial heterogeneity of attribute patterns at the landscape level. GIS layers include physiographic data (unstable soils, terrain slopes, rain-on-snow areas), forest stand (age and size), management information (land failures and road density), and terrain slopes. The GIS and data layers are used in a three phased analysis. Phase 1 uses a GIS to assess the spatial distribution of various landscape attributes within the different subwatersheds of the Beckler River basin. GIS data analysis at the landscape level begins by dividing attributes, such as forest stand and soil areas, into irregular polygons whose borders are delineated by curvilinear boundaries rather than edges of square cells. The aggregate properties of other types of data are also considered, such as the number and location of land failures and road densities.

Phase 2 uses simple regression analyses to examine relationships between the spatial distribution of various landscape attributes and the number of land failures within subwatersheds. The attributes are expressed relative to the subwatershed areas. The regression analyses provide the initial identification of attributes (e.g., unstable soils) that could be the major factors influencing land failures. Multivariate analyses are not used but will be employed when exact locations of land failures and unstable landscape conditions are better defined.

Phase 3 examines (a) the spatial interaction of different combinations of landscape attributes, and (b) their occurrence within riparian reserve widths. The objective is to use the distribution of specific physiographic attributes to determine the locations of unstable landscape conditions. Unstable conditions within riparian areas are then used to apply modifications to widths for previously prescribed riparian management zones. The prescribed widths are riparian reserves defined by the Forest Service for fish-bearing streams (USDA Forest Service 1994b). The modified widths are applied to fish-bearing streams in the Beckler River basin identified as perennial streams where Class I are of sufficient discharge and habitat area to support anadromous fish and smaller streams (Class II) support resident trout species (Gregory and Ashkenas 1990). Class III and IV streams are beyond the scope of the present study. Class III perennial streams and Class IV intermittent or ephemeral streams are streams not meeting the criteria for Class I and II streams (Gregory and Ashkenas 1990). The analysis of upslope conditions and riparian widths is facilitated by using slope information provided by a digital elevation model (DEM) distributed by the US Geological Survey, EROS Data Center. Appendix I provides the GIS commands used to examine modified widths for riparian management zones.

RESULTS AND DISCUSSION

Fish Distribution

Juvenile anadromous and resident fish populations are dispersed among riffle, pool, glide and side channel habitats in the Beckler drainage. The primarily habitats for anadromous fish occur in the main channels of the lower Beckler (12.3 km), upper Beckler (6.6 km) and lower Rapid (6.6 km) rivers. The relative abundance of different fishes indicates low densities and diversities for fish communities. Snorkel surveys of the three river channel segments indicate total counts of 1000, 375 and 1800 juvenile fish, respectively. The lowest fish numbers were in the upper Beckler River and the highest in the lower Rapid River: Juvenile coho exhibited the highest percentages, 60% in the lower Beckler River, 47% in the upper Beckler River, and 71% in the lower Rapid River (Fig. 2). The most diverse juvenile fish community of coho, chinook, cutthroat, rainbows, and sculpins exists in the upper Beckler River. The total number of juvenile fish relative to total habitat areas in the three river channel segments indicate that the lower Rapid River has a greater capacity to support fish (163 fish ha^{-1}) than the upper Beckler (61 fish ha^{-1}) and lower Beckler (48 fish ha^{-1}) rivers.

Lower Beckler River

The total number of juvenile fish for all habitats included 600 coho, 75 chinook, and 325 cutthroat and rainbow trout (Fig. 3A). Coho were most frequent (60%) in glides and side channels. Cutthroat and rainbow trout were the only juvenile fish observed in pools. Adult fishes were relatively abundant (270 fish) and diverse, being represented by cutthroat, rainbow trout, pink salmon, whitefish, and sculpin (Fig. 4A). The most abundant adult fish were pink salmon (160 fish), with 94% being in pools. Adult whitefish were second in abundance (80 fish) with >90% also being in pools.

Upper Beckler River

The total number of juvenile fish observed in all habitats of the upper Beckler River were 175 coho, 25 chinook, 100 cutthroat and rainbow trout, and 75 sculpins. Coho salmon, the most abundant juvenile fish (Fig. 3B), occurred most frequently in side channels and pools. Chinook and cutthroat, and rainbow trout were most frequent in riffles. Adult fish were less abundant (30 fish) and were represented by cutthroat, rainbow trout and sculpin (Fig. 4B). Riffles had the most adult fish: 10 rainbows and 10 sculpins.

Lower Rapid River

The total number of juvenile fish for all habitats were 1275 coho and 525 cutthroat and rainbow trout (Fig. 3C). Coho salmon were the most abundant fish and were evenly dispersed among all habitats. Cutthroat and rainbow trout occurred in all habitats, with 67% being in riffles and glides. Adult fish were represented by 85 cutthroat and rainbow trout and 17 coho (Fig. 4C). Cutthroat and rainbow trout were most abundant in pools (41%) and riffles (19%).

Fish Habitat Distribution

Low channel gradients in habitats of the main river segments of the Beckler River drainage permit access by anadromous fish (Fig. 5). Channel gradients range from 2% to 4% in the lower Beckler, upper Beckler, and lower Rapid rivers. Higher channel gradients limit anadromous fish movements to upstream river reaches. The main channel of the upper Rapid River has gradients of ≥10% which effectively limits access only to resident fish (Fig. 6). The total channel length containing anadromous fish habitats includes 12.3 km in the lower Beckler, 6.6 km in both the upper Beckler and lower Rapid rivers and 1.1 km in the tributaries. The total channel length available to anadromous fish (26.6 km) is 24% of the total 112.6 km for Class I and II fish-bearing streams in the Beckler River basin.

Of the total anadromous habitat area of 38.07 ha in the Beckler and Rapid River systems, the smallest habitat proportions occur where the channel gradients increase and the river valleys become constrained. Minimal anadromous habitat occurs in the subwatersheds of the Beckler River. Subwatersheds with potential anadromous habitat include Bolt, Eagle, Johnson, and Harlen creeks of the lower Beckler and Bullbucker and 4th of July creeks in the upper Beckler drainage. The total habitat length accessible to anadromous fish in these tributaries approaches 1 km. These habitats are in low gradient reaches within tributary confluences and alluvial fans on the floodplains of the main river channels.

Lower Beckler River

The total habitat area for anadromous and resident fish in the main channel of the lower Beckler River is 20.91 ha. The lower Beckler River's floodplain widths (100 to 180 m) allow for channel adjustments during peak flows. Fifty percent of the habitat area (10.53 ha) lies within 9 km of channel from the Beckler river mouth to Harlen Creek. The remaining habitat area (10.38 ha) is between Harlen Creek and the main river's confluence with the Rapid River (river km 12.3).

The percent habitat types relative to the total area in the Lower Beckler River includes 48% riffles, 49% glides and 3% pools (Fig. 5). The pool area (0.62 ha) is 16 times less than the areas of riffles (10.04 ha) and glides (10.25 ha). No surface area information was collected for side channels. However, side channels as percent of the total channel length (12.3 km) approaches 13%. This percentage exceeds the length of pool habitat (3%), suggesting side channels could be more frequent than pools.

Upper Beckler River

In the upper Beckler River, the total habitat area of 6.12 ha is one third the total habitat area in the lower Beckler River. The valley widths are narrow (30 m to 90 m) allowing minimal channel meandering and space for habitat formation. The habitat proportions relative to the total area include 68% riffles, 30% glides and 2% pools (Fig. 5). The pool area of 0.13 ha is approximately 3% of the riffle area (4.14 ha). No surface area data are available for side channels, but as percent of the entire channel length (6.6 km), side channels total 15% while pools approach 3%.

Lower Rapid River

The habitat area accessible by anadromous fish in the lower Rapid River totals 11.04 ha. This habitat area occupies the 6.6 km of channel above the Rapid River's confluence with the Beckler River. The habitat areas includes riffles (56%), glides (26%), pools (11%) and side channels (7%) (Fig. 5). The pool area of 1.15 ha exceeds the total pool area (0.75 ha) in the Beckler River channels. The larger pool areas correspond with higher frequencies of large woody debris (LWD).

Upper Rapid River

The total habitat area in the main channel of the upper Rapid River (6.6 to 13.9 km) is 11.13 ha. The proportions of habitat relative to the total area includes riffles 75%, glides 11%, pools 9% and side channels 5% (Fig. 5). The pool area of 0.96 ha appears related to the presence of LWD, the occurrence of large sized boulders and increased channel gradients (≥10%). Most of the Rapid River lies within a narrow, v-shaped valley (<90 m wide) constrained by steep hillslopes, which appears to favor LWD recruitment to channels and in forming pool habitats.

Large Woody Debris Characteristics

Changes in LWD Characteristics with Channel Size

The frequency of LWD 100 m^{-1} of channel is comparable for the main channels of the Beckler and Rapid rivers. The average amounts (± 1 standard deviation) are 5.1 ± 8.9 LWD 100 m^{-1} (lower Beckler), 7.9 ± 5.0 LWD 100 m^{-1} (upper Beckler), and 8.8 ± 3.6 LWD 100 m^{-1} in the lower Rapid River. The average is higher for the upper Rapid River (16.0 ± 14.1 LWD 100 m^{-1}) where most of the watershed is roadless and free of timber harvest and past fires.

The minimal amounts of LWD in the lower river channels of the river basin can be attributed to the chronology of past management practices and natural disturbance events. The history includes timber harvest of old growth conifers on the valley floodplains (1930s-1950s), LWD removal from channels for flood control purposes during the 1970s and 1980s, losses of LWD during six major floods between 1959 and 1990, and forests fires. A series of large fires from the 1930s through the 1970s removed most of the timber from the south-facing slopes of the lower Rapid River. The occurrence of LWD in the river channels of the Beckler drainage are low in comparison to the range of LWD values (~17 to 24 LWD 100 m^{-1}) for channels of harvested and unharvested regions in northwestern Washington (Ralph et al. 1994).

The frequency of occurrence of LWD in the Beckler River drainage channels and tributary streams are very low in comparison to other undisturbed regions (Table 2). The average amounts of LWD for three channel width intervals (<7 m, 7 to 10 m , >10 m) in the Beckler drainage indicates a range of 7.2 to 14.4 LWD 100 m^{-1} with the higher amounts of LWD in the smaller channels. Comparison of LWD for the same channel width intervals for undisturbed streams indicate higher values ranging from 14 to 50 LWD 100 m^{-1} in southwestern Washington streams (Bilby and Ward 1989) and 25 to 38 LWD 100 m^{-1} in southeast Alaska streams (Robison and Beschta 1990). The increased amounts of LWD in Alaskan streams appear to be due to the high input and retention of large diameter trees. These differences also relate to the frequent occurrence of debris jams and the effect of wood orientation in the low gradient coastal streams.

As shown in Table 2, the amounts of LWD in the Beckler River channels increase as channel widths decline. The highest amounts of LWD occur in the upstream reaches of the Rapid and Beckler rivers (Fig. 7). Of the 63 sampling sites (Fig. 7), only 5 sites ranged from 26 to 59 LWD 100 m^{-1}. This relationship is similar to that for streams in unharvested forests (Bilby and Ward 1989).

The volumes of LWD (m^3) for the Beckler River drainage are also low in comparison with unharvested areas, ranging from 0.2 to 1.7 m^3. The range of volumes for streams of the undisturbed areas range from 0.2 to 5.2 m^3 in southwestern Washington and 1.4 to 2.2 m^3 in Alaska (Table 2). Positive relationships can occur between LWD volumes and channel widths in these streams. Bilby and Ward (1989) demonstrated that LWD volumes increase with increasing channel widths. Similar trends are evident in the streams of southeast Alaska (Robison and Beschta 1990). For the Beckler River basin, the LWD volumes show no increases with increasing channel widths.

Changes in LWD Characteristics with Habitat Type

For the main river channels in the Beckler River drainage, the habitats containing the highest amounts of LWD (>15 LWD 100 m^{-1}) are pools and side channels of the upper Rapid River and pools of the upper Beckler River (Fig. 8). Much of the LWD in these channels appears to be small coniferous and deciduous trees recruited from young forest stands of nearby riparian areas. LWD recruitment occurs as channels shift and stream banks erode during periods of high discharge. No LWD data was collected for the side channels in the lower and upper Beckler River.

The occurrence of large-sized LWD (>0.6 m diameter and >15m length) within several river channel reaches and subwatershed streams (Johnson, Harlen and Evergreen creeks) appears related to the input of large conifers (>0.6 m diameter). The frequency of occurrence of LWD 100 m^{-1} (>0.6 m diameter) in the channels increases as the lengths of stands of riparian large trees increased (0.1 to 1.7 km lengths of stands) along the channels (Fig. 9). The r^2 value indicates that 49% of the variance of LWD in the channels is associated with large riparian trees. The averages for the large-sized LWD are 3.5 ± 2.9 LWD 100 m^{-1} for the lower Beckler River, 6.8 ± 4.1 LWD 100 m^{-1} for the upper Beckler, and 9.4 ± 6.1 LWD 100 m^{-1} for the tributaries. The averages for the Rapid River are higher in both the lower channel, (9.7 ± 4.2 LWD 100 m^{-1}) and upper channel (28.1 ± 18.0 LWD 100 m^{-1}).

LWD, Habitat Roughness and the Distribution of Fish

LWD and large boulder substrates can enhance the quality of fish habitats (Griffith and Smith 1993, Shuler et al. 1994). The presence of LWD and large substrates increases the surface area and roughness which contributes to habitat complexity and the potential carrying capacity for fish and other organisms. These large structures help create a variety of habitats such as refuge and rearing areas for juvenile fish, and holding pools for spawning salmon and resident fish.

The potential occurrence of LWD in habitats frequented by juvenile salmon was examined for coho in habitats of the lower Rapid River. The densities of juvenile coho salmon were assessed in relation to LWD ha^{-1} in pool, glide, riffle and side channel habitats (19 total habitats). The average fish densities ha^{-1} of habitat increased as LWD ha^{-1} increased in glide, riffle, and side channel habitats (Fig. 10). The standard errors for the fish densities ranged from 22% to 38%, with the largest occurring in riffles and glides. The errors for the average LWD ha^{-1} range from 53% to 63%.

The increased densities of both fish and LWD in glide, riffle, and side channel habitats in the lower Rapid River implies that woody debris enhances the complexity and perhaps the capacity of habitats to support juvenile coho salmon. The amount of LWD in these habitats ranged from 54 to 174 LWD ha^{-1} (Fig. 10). The highest average densities of fish occurred in the side channels (1,068 ± 231 coho ha^{-1}) and the lowest densities in the glides (397 ± 133 coho ha^{-1}). The opposite conditions were observed for the pool habitats (Figure 10). High densities of fish (1,057 ± 320 coho ha^{-1}) and less LWD (23 pieces ± 14 ha^{-1}) suggest several factors are important in forming pools.

Juvenile cutthroat and rainbow trout occurred in the same habitats of the lower Rapid River as juvenile coho salmon. For the Rapid River, the total densities of cutthroat and rainbow trout include 350 ± 144 fish ha^{-1} in riffles, 264 ± 86 fish ha^{-1} in pools, and 198 ± 55 fish ha^{-1} in glides. The high fish density of the riffles corresponded with higher numbers of LWD (100 ± 92 ha^{-1}). Lower amounts of LWD occurred in the pools and glides, 23 and 53 LWD ha^{-1}, respectively. No rainbow and cutthroat trout were observed in the side channels. Rainbows occurred more frequently than cutthroat in the Rapid River.

Less frequent observations for habitats (13 habitats) in the lower and upper Beckler River showed fish densities ranging from 76 to 572 coho ha^{-1}, with the lowest densities in riffles and highest in glides and side channels. Riffles and glides were the only habitats containing woody debris, 22 ± 11 LWD ha^{-1} and 93 ± 91 LWD ha^{-1}, respectively. No fish and LWD were observed in the pools, the most infrequent habitats.

For the Beckler River, pools contained the highest cutthroat and rainbow densities (679 ± 474 fish ha^{-1}), followed by glides (266 ± 98 fish ha^{-1}) and riffles (232 ± 114 fish ha^{-1}). The high fish densities in pools occurred in the absence of LWD. However, fish of the riffles and glides were accompanied by LWD ranging from 22 to 93 LWD ha^{-1}, respectively. No cutthroat, rainbow trout and LWD were observed in the side channels. Cutthroats occurred more frequently than rainbow in the Beckler River.

The abundance of fish in habitats containing LWD, as well as the lack of pool habitats in the river channels, point to the role of several structural and fluvial factors in forming complex habitats required by fish. For example, the occurrence of pools with little or no LWD in wide channels suggests the importance of flow convergence and scour processes in forming pools. Such conditions prevail where channel gradients are low (2%) and the width-to-depth ratios are >10 (Leopold et al. 19634, Keller and Mellhorn 1978, Montgomery and Buffington 1993). These fluvial processes appear to occur in the Rapid River. However, they appear ineffective in forming pools in the river channels of the lower Beckler River. The excessive amounts of bed load materials in the low gradient channels (<2%) most likely reduces the formation of scour and pocket pools. For the smaller tributary streams (<7 m width), pool formation appears controlled by structural elements and peak flow events. Pool formation in small streams, with low width-to-depth ratios (<10) and steep gradients, commonly depends on the presence large bed materials, LWD and peak flow events (Chin 1989, Grant et al. 1990, Montgomery and Buffington 1993).

Distribution of Bottom Substrate in Habitats

The bottom substrates occurring in the Beckler and Rapid rivers are compared by dominant size categories occurring within habitat areas (Figs. 11–13). The purpose of these comparisons is to determine the relative distributions of different sized sediments and habitat areas. A major concern is the distribution of sand and finer sediments (<2 mm). The occurrence of sand substrates is assumed to indicate areas storing sediments that are received from the subwatersheds. The comparisons for the Rapid River includes the lower and upper river valleys. For the Beckler River valley, the region with the most intensive and spatial land-use history, the comparisons include upstream and downstream channel reaches within both the lower and upper river valleys. Side channel areas and substrate data are considered for the Rapid River, but no side channel data exists for the channels of the lower and upper Beckler River.

Lower Beckler River

For the downstream reach of the lower Beckler River (9 km), the habitat areas include 4.69 ha of riffles, 5.40 ha of glides and 0.44 ha of pools. The most frequent areas of substrates in riffles are cobble (3.52 ha) and sand (0.98 ha). Glides are dominated by cobble (2.75 ha) and gravel (1.78 ha), while pools are dominated by sand (0.22 ha) and gravel (0.16 ha) (Fig. 11).

The upstream reach extends 3.4 km along the river channel from Harlen Creek to the Rapid River. The habitat areas include 5.35 ha of riffles, 4.85 ha of glides and 0.18 ha of pools. The dominant substrate areas within riffles are cobble (3.32 ha) and small boulders (2.03 ha). Glides are dominated by gravel (3.54 ha) and cobble (1.02 ha), and pools entirely by gravel (Fig. 11).

Although cobble substrates predominate in both reaches, the occurrence of areas of small boulders upstream and sand downstream suggests patterns of sediment routing in the river. The appearance of areas dominated by small boulders in the upstream reach, but not downstream, suggests that fine materials are transported downstream to lower gradient areas (<2%) where they effectively bury the larger substrate sizes.

The sources of sand and fine sediments (<2 mm) includes materials transported to the river channel by subwatershed streams. The total sediment inputs from land failures in subwatersheds between 1970 and 1990 ranged from 3,530 m^3 to 3,668 m^3, respectively. Other sediment sources include unstable bank conditions adjacent to tributary streams and the main river channels (Table 3).

Upper Beckler River

The upper Beckler River channel is divided into two reaches, the downstream reach that extends 4.7 km from the confluence of the Beckler and Rapid rivers to Boulder Creek, and the upstream reach from Boulder Creek to Evergreen Creek (1.9 km). The total habitat area (4.78 ha) downstream includes 3.26 ha of riffles, 1.45 ha of glides and 0.07 ha of pools. The most dominant substrate areas in riffles are cobble (2.15 ha) and small boulders (0.98 ha). Glides are dominated by gravel (0.74 ha) and cobble (0.58 ha), while pools are dominated by cobble (0.05 ha) and gravel (0.02 ha) (Fig. 12).

For the upstream reach, the habitat areas include 0.88 ha of riffles, 0.40 ha of glides and 0.06 ha of pools. The lower habitat areas are related to the short length of the river reach (1.9 km) and the narrow valley widths. The dominant size-classes of substrates in riffles are cobble (0.44 ha) and gravel (0.39 ha). Glides are dominated by sand (0.20 ha) and gravel (0.20 ha) while pools are dominated by sand (0.04 ha) and gravel (0.01 ha) (Fig. 12). The predominance of sand in glides and pools suggests excessive inputs of fine sediments (<2 mm) from the subwatershed streams. The tributaries upstream from Boulder Creek received a total input of sediment between 1970 and 1990 of 12,569 m^3. This sediment input is over 1.8 times greater than sediment received (6,916 m^3) from downstream subwatersheds during this period. Many of the subwatersheds in the upper Beckler River valley contain low drainage densities and unstable bank and channel conditions (Tables 1 and 3). Low drainage densities imply short retention times of water and sediments.

Lower Rapid River

The total habitat area for the lower Rapid River channel of 11.04 ha covers 6.6 km of channel. The habitat areas include 6.20 ha of riffles, 2.87 ha of glides, 1.15 ha of pools and 0.82 ha of side channels. The dominant substrate areas in riffles and glides are cobble, 5.58 ha and 2.18 ha, respectively. Pools are dominated by both cobbles (0.56 ha and sand (0.40 ha) while the side channels are dominated by sand (0.34 ha) and gravel (0.31 ha) (Fig. 13).

Upper Rapid River

In contrast to the lower river channel, the higher gradient channels of the upper Rapid River exhibit an increase in areas of small boulders in riffles, pools and side channel habitats (Fig. 13). The habitat areas include 8.40 ha of riffles, 1.23 ha of glides, 0.96 ha of pools, and 0.54 ha of side channels. Dominant substrates of riffles include cobble (5.63 ha) and small boulder (2.27 ha), while glides are dominated by cobble (0.68 ha) and gravel (0.52). Pools are dominated by cobbles (0.41 ha) and small boulders (0.28 ha) and side channels by cobbles (0.28 ha) and small boulders (0.14 ha). The total area of sand deposits for all habitats is minimal (0.05 ha).

The larger area of sand deposits (0.74 ha) in the lower Rapid River habitats is dispersed among the pool and side channel habitats (Fig. 12). These sand deposits are in low gradient areas and imply increased supplies of fine sediments. The potential for sediment inputs to the lower Rapid River channel is evident in the 46,687 m^3 of sediment received from subwatersheds between 1970 and 1990. This input greatly exceeds the sediment input (1,901 m^3) from subwatersheds of the upper Rapid River. The high sediment inputs received from downstream subwatersheds reflect land uses and extensive fire history in the uplands of the lower Rapid River valley.

Unstable Streambank and Channel Conditions

For the Beckler River drainage, the majority of the unstable streambank and channel conditions occur in areas influenced by land-use practices and unstable physiographic features. The factors contributing to these conditions for the main river channels and subwatershed streams of the Beckler River drainage are shown in Table 3. These factors are expressed as percent of the channel length surveyed.

Beckler River and Subwatershed Streams

Along the lower Beckler River's main channel, bank conditions are unstable for 38–100% of its length and channels are unstable along 54–84%. The major factors contributing to unstable banks include mass wasting, debris jams, and erosion. Mass wasting and debris jams occur within the central reach of the river valley while bank erosion appears to extends along the entire of the channel length. The factors contributing to unstable channels include consolidation of bottom materials, unstable bottom substrates, and scouring. Scouring tends to be the most extensive factor occurring along 84% of the channel.

For the lower Beckler drainage, the most prevalent unstable bank and channel conditions occur in three subwatersheds, Bolt, Eagle and Harlen creeks (Table 3). Bolt Cr. displays the most unstable streambank and channel conditions along its length (37% to 64%). Unstable streambank conditions in Eagle (5% to 75%) and Harlen creeks (47% to 95%) are more dominant than unstable channel conditions. The most frequent factors contributing to unstable streambanks occur in Bolt and Harlen Creeks. The contributors include unstable landforms, mass wasting, debris jams, the lack of protective vegetation, large obstructions, bank erosion and deposition. Factors contributing to unstable channels include consolidation of bottom materials, unstable bottom substrates, and scouring.

In the upper Beckler drainage, numerous unstable conditions occur along both the river and subwatershed tributary channels (Table 3). The river exhibits unstable streambank conditions along 28–32% of the channel length in areas where debris jams and erosion predominate. The factors causing unstable channel conditions (consolidation of bottom materials, unstable bottom substrates, and scouring) occur along 38–72% of the channel. Unstable streambank conditions for the subwatersheds are more extensive, ranging from 7–100% of the channel lengths. The most frequent contributors to unstable banks includes unstable landform slopes, debris jams, erosion, and deposition. The major factors contributing to unstable channel conditions include substrate compaction, unstable bottom substrates, and scouring (12–73% of the channel).

Rapid River

For the lower Rapid River, unstable streambank conditions relate to mass wasting, debris jams and bank erosion along 31 % of the channel (Table 3). All three contributing factors occur in a constrained valley segment just upstream from the confluence. Most of the channel appears stable. For the upper Rapid River, the streambanks and channels show a greater array of factors contributing to unstable conditions. However, these factors only occur along 10% to 26% of the channel. Most of these contributing factors are associated with a upstream channel reach that flows through a narrow valley. Streambanks appear to be protected by vegetation along both the lower and upper river channels.

Land Failures: Influences of Forest Harvest and Physiography

The spatial distribution of the land failures in the Beckler and Rapid River drainages, relative to areas of immature forest stands and the distribution of roads, is shown in Figure 14. The same pattern occurs for land feature sites contributing sediment to streams. The total number of land failures observed in the entire Beckler River basin during the two decades was 103 (Figure 14). The number of failures in the lower and upper Beckler and Rapid drainages were 45, 48 and 10, respectively. The proportions of the failures reaching stream channels were 73% in the lower Beckler, 65% in the upper Beckler, and 90% in the Rapid River.

For the Rapid River drainage, the volume of land failures contributing sediment to streams between 1970 and 1990 is almost twofold greater than in the Beckler River drainages. Comparison of volumes show 48,588 m^3 for the Rapid River, 19,485 m^3 for the upper Beckler, and 7,198 m^3 for the lower Beckler. The sediment inputs in the Rapid drainage are of a lower frequency, but higher magnitude. Of the 10 failure sites (Fig. 14), two sites in the lower Rapid valley show volumes of 7,647 m^3 and 38,233 m^3. Most of these failures occur in areas containing roads, immature forest stands, steep landforms, and influences of the Evergreen Fault. For the Beckler river valley, the frequency of failures yielding sediments to streams is higher, but the volumes are less, ranging from 20 m^3 to 1,912 m^3. Most of the land failures in the Beckler drainages occur near roads in immature forests and on steep terrain.

The apparent influences of landscape conditions on the number and distribution of the land failures are suggested by relationships between several forest harvest and physiographic attributes and the number of failures. Regression analysis show land failures increase in subwatersheds containing greater areas of rain-on-snow zones, unstable soils, immature forests (stand age <35 years), small sized forest stands (diameters <12.7 cm) and high road densities (km km^{-2}) (Fig. 15). The r^2 values indicate that 70% of the variance of land failures is associated with road densities. The variances of land failures related to the other attributes are lower: 62% associated with forest stands of small diameter; 47% with immature forest stands; 60% with unstable soils; and 60% with rain-on-snow zone. All these relationships suggest more frequent land failures in managed subwatersheds. Additional analysis of these relationships will be required because the land failure occurrences lack background information about the natural frequency of failures. The locations and landscape characteristics of the different subwatersheds in the Beckler River Basin are described in Figure 1 and Table 1.

The land failure relationships with roads, forest stands, unstable soils and the rain-on-snow zones also indicate that the greatest number of land failures are co-occurring in physiographic areas of the river basin. Geographic maps showing theses attributes, and Class I and II streams (fish-bearing), indicate how these areas overlap (Figs. 14 and 17). The patterns of land failures point to the extreme sensitivity of many subwatersheds to disturbances from harvest activities and natural events such as floods induced by rain-on-snow. The simultaneous occurrence of these attributes on steep slopes near stream channels also suggests the occurrence of highly unstable conditions near riparian and stream ecosystems.

Modified Riparian Reserve Widths

Overlapping areas for immature forest stands, unstable soils, and terrain slopes steeper than 19°, facilitate the location of highly unstable areas in the Beckler River basin (Fig. 17). The distribution of immature forest stands in the Beckler drainage are more frequent within riparian areas than other stand characteristics. The co-occurrence of moderate to very unstable soils and immature forests is most evident on the eastside of the Beckler valley and along the lower Rapid River. The immature forests are considered as potentially unstable areas because of minimal vegetative regeneration of roots and canopy cover. These early stages of forest development are insufficient in providing adequate hydrologic recovery (e.g., sufficient rooting strength and evapotranspiration) to stabilize soils following disturbances such as timber harvest and fires (S. Woolley, Mt. Baker-Snoqualmie National Forest, pers. comm.; Sidle et al. 1985). The unstable soils represent soil areas on terrain slopes with the greatest potentials for yielding sediments to streams. The locations of the soils and critical slopes (>19°) are based on the Soil Resource Inventory (USDA Forest Service 1972) and terrain model derived from a digital elevation model (DEM).

The overlapping distributions of immature forest stands, unstable soils, and critical terrain slopes are used to modify riparian reserve widths (Fig. 17). The current riparian reserves are within fixed widths of 90 m on each side of fish-bearing streams (USDA Forest Service 1994b). These 90-m prescriptions for fish-bearing streams in the Beckler River drainage appear inadequate because they do not take into account the river basin's landscape physiography, forest developmental stages, and disturbance regimes.

The proposed modifications to riparian widths are at locations where overlapping unstable stand, soil and slope attributes co-occur within the 90 m riparian reserve width (Fig. 18). The adjusted widths represent four possible overlapping combinations:

- 150 m (90 m+ 60 m): slopes (266 unstable soils, forest stand age <35 years
- 135 m (90+ 45 m): slopes >19° and unstable soils
- 120 m (90+ 30 m): slopes >19° and forest stand age <35 years
- 105 m (90+ 15 m): unstable soils and forest stand age <35 years

These modified widths are considered to be conservative relative to the distributions of narrow valley widths (<100 m) in the Beckler River drainage. A majority of the unstable riparian locations occur in these narrow valleys. These valleys predominate along upstream reaches of the main river channels and subwatershed streams where land failures and channel changes are frequent during flood events. The overlays (Fig. 18) with increased riparian widths indicate where these valleys correspond with unstable areas. These areas are also Class I and II stream channels. Further assessments will be required to examine this process of selecting different riparian widths. The analysis of valley-width distributions, landforms, and slopes will provide better definitions of riparian reserve widths for all sizes of stream (Classes I to IV).

The proposed modifications for riparian reserve widths (Fig. 18) demonstrates how landscape paradigms based on biological and terrain information can be used to identify sensitive portions of riparian and stream ecosystems. Sensitive or unstable areas of ecosystems commonly appear when they are exposed to disturbances (e.g., natural and land-use related) of high frequency and magnitude. When disturbances occur in riparian corridors of mountainous landscapes, the sensitive areas can exhibit several rapid response phases followed by long recovery periods (Wissmar and Swanson 1990). An improved capability to define variable riparian widths, by applying landscape paradigms to identify unstable areas, will enable managers to develop more integrated protection and restoration programs for riparian and stream ecosystems.

CONCLUSIONS

The analysis of the Beckler River basin indicates that fish populations, stream habitats, riparian and upland areas are impacted by land uses and unstable physiographic conditions. Almost all the anadromous and resident fish populations and habitats of the lower and upper Beckler and Rapid rivers appear impacted by upslope land failures, unstable streambank and channel conditions, sediment inputs and accumulation. The locations of unstable terrestrial areas that impact riparian and stream ecosystems are indicated by land failure relationships with land-use and physiographic conditions and by GIS analysis of the spatial distributions of roads, unstable soils, immature forest stands, rain-on-snow areas, and critical terrain slopes. Overlapping distributions of immature forests (age <35 years), unstable soils, and critical terrain slopes (>19°) suggest highly unstable terrain locations in riparian areas near streams.

The degradation of stream habitats by excessive substrate deposition, channel erosion, and removal of LWD for flood control purposes is evident in the greatly reduced habitat diversity and potential capacities to support fish. The low habitat diversity is evident in the low pool frequencies and decreases in roughness provided by large rocks and trees. The combined effects of burial of large rocks due the excessive input and accumulation of finer substrates, and removal of large trees from channels, have greatly reduced the complexity of channels and in some cases eliminated pool habitats. These conditions appear confounded by timber harvest patterns over the past forty years that have caused the timing of snowmelt and peakflows to shift to earlier in the year. These changes can cause reduced streamflows in the summer when fish entrapment and high temperatures could lead to fish mortalities. Hydrologic studies in western Oregon and Washington show greater snowfall accumulations in clearcuts will melt earlier with increased rainfall and exposure to solar radiation (Harr 1983, Coffin 1991). Earlier snowmelt and peak flows reduce water storage in surface and subsurface soils which leads to lower discharge rates and reduced habitat holding capacities for fish during summer and base flow periods.

These adverse impacts are especially significant because the ranges for salmon migration and habitat use are naturally limited to the main river channels of the Beckler and Rapid rivers. Constraints to fish migration are naturally imposed by channel obstructions and steep gradients. The channel length occupied by all life history stages of anadromous fish approaches only 3% of the total stream channel length (1025 km) in the Beckler River basin. The limited amounts of available habitat and the degraded status and dysfunction of terrestrial and aquatic ecosystems indicates there is an urgent need to protect and restore the capacity of available habitats to produce and rear fish.

Landscape Management Strategies

The future improvement of fisheries, stream, and riparian ecosystems in the Beckler River basin will require additional data to effectively design and implement a landscape strategy. The strategy needs to address issues that encompass the entire river basin. For example, integrated plans are needed to account for basin-wide interactions of physiographic and biological processes that cause unstable conditions in terrestrial and adjoining aquatic ecosystems.

The results of this study indicate that the first priority in developing a strategy is the acquisition of data that bridge gaps in understanding how different attributes of the landscape operate at the subwatershed scale (km^2) versus smaller scales (ha, m^2). Much of this information is required to define interfaces between unstable conditions between different ecosystems. Specific information on the functional relation between unstable soils and immature forest stands is needed for both upslope and riparian ecosystems. The interfaces need to be defined in terms of scale, location, and changing conditions due to floods and other disturbances. Consideration of this priority will provide an improved capability to target basin-wide issues of upslope impacts on riparian and stream systems.

The second priority calls for the strategy to be implemented by an integrated management team that includes different disciplines. The team responsibilities include operating coordinated data inventories and management systems for implementing and monitoring protection and restoration programs. The objective is to protect and improve the quality and quantity of fish habitats and riparian areas in a manner that sustains and increases fish survival and population levels of different life history stages.

The keystones for the integration of the Beckler River Basin strategy include (a) upslope, riparian, and stream protection and restoration measures that account for the spatial distribution of unstable landscape conditions, (b) networks of riparian zones on Class I through IV streams with variable widths for buffering streams from highly unstable conditions, and c) networks of stream channels and habitats that link fish migration corridors between different habitats.

The riparian networks need to include provisions for improving and protecting riparian areas near unstable upslopes. The stream network needs to connect habitats required for a) various fish life history stages (spawning and rearing), (b) refugia from disturbances, and c) source areas that provide populations for colonizing disturbed and restored habitats (Sedell et al. 1990, USDA Forest Service 1994b). To increase the potential of restoring wild fish populations, the ecosystem strategy needs to include viable fish populations and habitats of adjoining river basins that are potential sources of colonizers (Doppelt et al. 1993).

Information Gaps

The current development of effective protection and restoration plans for the Beckler River basin is limited by the lack of adequate data required to evaluate ecosystem functions. The required protection and restoration plans are difficult to develop and execute because most of the existing data were obtained for management purposes other than the analysis of ecosystem functions. This Beckler River analysis of fish habitat conditions and influences of upslope factors demonstrates many of these problems. For example, the Beckler River basin-wide analysis only serves to identify large-scale areas of the broader landscape (km^2) that exhibit stable and unstable conditions. Additional data and analysis are required to define how specific attributes interact and function at smaller scales (ha) to create critical conditions. A more detailed retrospective analysis with aerial photos and GIS software of changes in watershed characteristics during the past 50 years would be of great value (Smith 1993, Wissmar et al. 1994, McIntosh et al. 1994). The acquisition of this information will permit the design of a Beckler River strategy that provides protection and restoration programs that are coordinated by integrated inventories, data management and monitoring procedures (MacDonald et al. 1991, Frissell and Nawa 1992, Wissmar 1993). The data acquisition and design of the strategy need to occur prior to the implementation of protection and restoration projects.

Data needed to facilitate the design of a strategy for improving fish and habitat conditions in the Beckler River basin includes spatial and seasonal distributions of fish populations and the availability of different habitats. The following seasonal assessments are needed for anadromous and resident fish: (a) juvenile population characteristics and distributions in different habitats, and (b) spawning population densities, behavior, and distribution. Inventories for juvenile and spawning populations should include provisions for repeated surveys within critical seasons of concern. Important supporting information includes hydrologic descriptions of base flow and dewatering periods that could isolate and strand fish. Temperature measurements are also important for assessing the temperature adaptability of fish during droughts and unseasonably warm periods. Reduced streamflows and fish entrapment combined with high temperatures can lead directly to salmon mortality (Hicks et al. 1991).

The acquisition of fish habitat information needs to be integrated with the collection of the above fisheries information. This integration can be accomplished by conducting basin-wide habitat inventories in conjunction with fish population surveys. The distribution of habitats need to be defined seasonally in terms of providing for fish requirements of rearing, spawning, refugia, migration and colonization. Habitat formation and changing conditions also need better definition. Important questions concern (a) the contribution of LWD and large-sized boulders to the physical roughness and diversity of habitats, (b) the distribution of different substrate sizes, and (c) the storage time of fine sediments in spawning and other habitats. The importance of roughness characteristics and the formation of pool habitats needs to include descriptions of the distribution and amounts of large boulders and large woody debris in stream ecosystems (Leopold et al. 1964, Keller and Mellhorn 1978, Chin 1989, Grant et al. 1990, Montgomery and Buffington 1993). The questions of the distribution of different substrate sizes (Wolman 1954) and sediment storage needs to be augmented by hydrologic analyses of the frequency and magnitude of peak flows and base flow periods (Dunne and Leopold 1978). A key measure that needs to accompany all these data is the actual measurement of channel gradients. The above information will facilitate improved assessments of influences of land uses on altering stream habitat conditions and flow regimes (Hicks et al. 1991).

Additional riparian information is needed for identifying stable and unstable upslope and riparian areas. The required data include the distribution of developmental stages and rooting strengths of riparian vegetation and the co-occurrence of specific soil types, terrain slopes, and valley landforms (Sidle et al. 1985, Smith 1993, Gregory and Ashkenas 1990, Benda et al. 1992). These data are needed to provide a more complete examination of (a) the spatial interaction of different combinations of landscape attributes and their occurrence within riparian reserve widths, and (b) criteria for modifying riparian widths. The identification of unstable conditions within riparian areas provides information that facilitates the definition of the spatial configurations of riparian widths for all sizes of stream (Classes I to IV). This effort will require GIS analyses of the distributions of valley widths, landforms and terrain slopes.

For the Beckler River basin, additional upslope analyses are needed for identifying stable and unstable areas and potential impacts on riparian and stream ecosystems. The exact locations of the land failures and attributes, whose overlapping distribution indicate unstable conditions, need to be better defined to understand the significance of the correlations found in this study. Our initial screening analyses of land failure relationships indicates that the failures appear correlated with specific attributes. GIS approaches can be extended to improve these assessments. Further data analysis will also benefit from nonparametric statistical analysis.

The land failure inventories for the Beckler River basin need to be extended to include all managed and unmanaged areas to determine their potential contributions of sediments to smaller Class III and IV streams (Gregory and Ashkenas 1990). These inventories need to be repeated to assess influences of disturbance events (e.g., fires and floods). GIS software that uses data layers from retrospective analyses of aerial photograph coverage can be used to assess the frequency and spatial distribution of land failures. This information will enhance and extend the use of other hillslope stability and sediment budget inventories. Useful approaches for different analyses of landscape patterns are described by Baker (1989).

The land failure inventory procedures need to be integrated with other inventories and existing information. Field estimates of failure volumes and potential contributions to streams can be coordinated with surveys of streambank-channel stability and substrate conditions of stream habitats. The land failure inventories can be further integrated into expanded inventories of road systems that include unstable secondary, old and abandoned roads. This integration can be accomplished by including estimates of sediments lost from road fills, road surfaces and culvert replacements. All these attributes can be recorded in relation to existing geologic maps showing the distributions of unstable features (e.g., bedrock formations, faults and surficial deposits) as well as unstable soils on steep slopes, rain-on-snow zones and other physiographic attributes. Other useful reference areas include the locations of immature forest stands that are unstable because of poor root development and minimal canopy closure.

Restoration projects have been initiated by the Forest Service in the Beckler River basin. However, more complete basin-wide protection and restoration strategies are needed for effective long-term ecosystem management (Doppelt et al. 1993). Protection of habitats in relatively intact subwatersheds includes networks connecting stream and riparian systems. This will require a basin-wide plan that considers the life history requirements of fish and wildlife using critical habitats. A key component of this strategy is improving upslope conditions (e.g., vegetative) in relatively intact and adjacent pristine watersheds (e.g., roadless and wilderness areas). This component helps prevent erosion in steep uplands as well as providing areas that function as sources for fish populations that can colonize disturbed and restored ecosystems. The protection strategy should also focus on identifying and conserving biotic refuge areas.

Restoration of critical habitats and corridors can be accomplished by securing and connecting critical habitats as well as providing connections to more degraded habitats. The basin-wide plan should also consider the life history requirements of fish and wildlife using critical habitats. These restoration objectives can be accomplished by expanding riparian and floodplain areas that buffer areas that function as critical fish habitat and migration corridors. A key component of this strategy is improving riparian vegetative, soil, and road conditions.

The Beckler River restoration strategy needs to require that all protection and restoration plans be based on subwatershed reconnaissance, screening analyses that use available data, and if needed, more detailed watershed analysis that require new data. The purpose of field reconnaissance and screening analyses is to document the spatial distribution of functional and dysfunctional components of the ecosystems. Large scale basin-wide assessments and ongoing monitoring programs can be used to examine causes and consequences of watershed damage to determine the most appropriate protection and restoration measures. Monitoring programs need to focus on the evaluation of the long-term effectiveness of protection and restoration actions (Wissmar 1993).

River basin-wide assessments and perspectives should be used to set restoration objectives that are coordinated across the basin. For example, an important objective in the Beckler River basin is reducing the impacts of sediment erosion and deposition throughout the subwatersheds, and the mainstem river channels. However, if the strategy does not include headwater portions of the subwatersheds, the restoration objectives may be difficult to attain. The headwaters typically contain high gradient slopes and natural sediment source areas. If harvest practices and other developments on mixed ownership lands continue to be uncoordinated in the headwaters, they can negate restoration and protection efforts throughout the river basin.

In summary, basin-wide restoration strategies need to recognize that the natural variability of the different subwatersheds and habitats requires coordinated basin-wide restoration plans, long-term objectives and monitoring programs. The restoration objectives need to include specific time-lines for expectations of returning treated areas towards "natural conditions." The purpose of the monitoring programs are to evaluate long-term objectives of protection plans and restoration treatments (Wissmar 1993). The objectives and monitoring programs should include provisions for determining whether fish and wildlife communities are suited to types of changes in specific habitats that the restoration treatments are intended to induce. Monitoring actions can be used to document the successes and failures of different restoration treatments (Frissel and Nawa 1992).

REFERENCES

Baker, W.L. 1989. A review of models of landscape change. Landscape Ecol. 2: 111-133.

Benda, L., T.J. Beechie, R.C. Wissmar, and A. Johnson. 1992. Morphology and evolution of salmonid habitats in a recently deglaciated river basin, Washington State, USA. Can. J. Fish. Aquat. Sci. 49: 1246-1256.

Bilby, E.R. and J.W. Ward. 1989. Changes in characteristics and function of woody debris with increasing size of streams in Western Washington. Trans. Amer. Fish. Soc. 118: 368-378.

Chin, A. 1989. Step pools in stream channels. Prog. Phys. Geogr. 13: 391-407.

Coffin, B.A. 1991. The effects of forest cover on rate of water delivery to the soil during rain-on-snow. MS thesis, Univ. Washington, Seattle, WA. 140 p.

Doppelt, R., M. Scurlock, C. Frissell, and J. Karr. 1993. Entering the Watershed. Island Press, Washington D.C. 462 p.

Dunne, T. and L.B. Leopold. 1978. Water in Environmental Planning. W.B. Freeman and Co., New York. 796 p.

Frissell, C.A. and R.K. Nawa. 1992. Incidence and causes of physical failures of artificial structures in streams of western Oregon and Washington. N. Am. J. Fish. Mgmt. 12: 182-197.

Grant, G.E. Swanson, F.J. and M.G. Wolman. 1990. Pattern and origin of stepped-bed morphology in high-gradient streams, Western Cascades, Oregon. Geol. Soc. Am. Bull. 102: 340-352.

Gregory, S. and L. Ashkenas 1990. Riparian Management Guide, Willamette National Forest. Portland, OR, Pacific Northwest Region. US Government Printing Office: 1990-591-401/35008. 120 p.

Griffith, J.S. and R.W. Smith. 1993. Use of winter concealment cover by juvenile cutthroat and brown trout in the South Fork of the Snake River, Idaho. N. Am. J. Fish. Mgmt. 13: 823-830.

Hankin, D.G. and G.H. Reeves. 1988. Estimating total fish abundance and total habitat area in small streams based on visual estimation methods. Can. J. Fish. Aquat. Sci. 45: 834-844.

Harr, R.D. 1983. Potential for augmenting water yield through forest practices in Western Washington and western Oregon. Wat. Res. Bull. 19: 383-393.

Hicks, B.J., R.L. Beschta, and R.D. Harr. 1991. Long-term changes in streamflow following logging in western Oregon and associated fisheries implications. Wat. Res. Bull. 27: 217-226.

Keller, E.A. and W.N. Mellhorn. 1978. Rhythmatic spacing and origin of pools and riffles. Geol. Soc. Am. Bull. 89: 723-730.

Leopold, L.B., M.G. Wolman, and J.P. Miller. 1964. Fluvial Processes in Geomorphology. W.H. Freeman and Co. 522 p.

MacDonald, L. A. Smart, and R.C. Wissmar. 1991. Monitoring Guidelines to Evaluate Effects of Forestry Activities on Streams in the Pacific Northwest and Alaska. US Environ. Protect. Ag. EPA/910/9-91-001. Edwards Brothers, Ann Arbor, MI. 166 p.

McIntosh, B.A., J.R. Sedell, J.E. Smith, R.C. Wissmar, S.E. Clarke, G.H. Reeves, and L.A. Brown. 1994. Historical changes in fish habitat for select river basins of eastern Oregon and Washington. Northw. Sci. Spec. Iss. 68: 268-285.

Montgomery, D.R. and J.M. Buffington. 1993. Channel classification, prediction of channel response, and assessment of channel condition. Washington State Timber/Fish /Wildlife Agreement, Report TFW-SH10-93-002. 84 p.

Pfankuch, D.J. 1975. Stream reach inventory and channel stability evaluation. A watershed management procedure. USDA Forest Service. Region 1, Missoula, MT. 25 p.

Ralph, S.C., G.C. Poole, L.L. Conquest, and R.J. Naiman. 1994. Stream channel morphology and woody debris in logged and unlogged basins of western Washington. Can. J. Fish. Aquat. Sci. 51: 37-51.

Robison, E.G. and R.L. Beschta. 1990. Characteristics of coarse woody debris for several coastal streams of Southeast Alaska, USA. Can. J. Fish. Aquat. Sci. 47: 1684-1693.

Sedell, J.R., G.H. Reeves, F.R. Hauer, J.A. Stanford, and C.P. Hawkins. 1990. Role of refugia in recovery from disturbances: modern fragmented and disconnected river systems. Environ. Mgmt. 14: 711-724.

Shuler, S.W., R.B. Nehring, and K.D. Fausch. 1994. Diel habitat selection by brown trout in the Rio Grande River, Colorado, after placement of boulder structures. N. Am. J. Fish. Mgmt. 14: 99-111.

Sidle, R.C., A.J. Pearce, and C.L. O'Loughlin. 1985. Hillslope Stability and Land Use. Wat. Res. Monog. Series 11, Am. Geophys. Union. 140 p.

Smith, J.E. 1993. Retrospective analysis of changes in stream and riparian characteristics between 1935 and 1990 in two eastern Cascade streams. MS thesis, School of Fisheries, Univ. Washington, Seattle, WA. 143 p.

Washington Department of Fisheries, Washington Department of Wildlife, and Western Washington Treaty Indian Tribes. 1993. 1992 Washington State salmon and steelhead inventory. Washington Department of Fisheries. Olympia, WA. 212 p.

Williams, R.W., R.M. Laramie, and J.J. Ames. 1975. A catalog of Washington streams. Vol. 1. Puget Sound Region. Washington Department of Fisheries. Olympia, WA.

Williams, J.R., H.E. Pearson, and J.D. Wilson. 1985. Streamflow statistics and drainage-basin characteristics for the Puget Sound region, Washington. USGS Open File Rep. 84-144-B. 420 p.

Willis, B. 1903. Contributions to the geology of Washington: Physiography and deformation of the Wenatchee-Chelan district, Cascade Range. US Geol. Surv. Prof. Paper. 19: 41-101.

Wissmar, R.C. and F. J. Swanson. 1990. Landscape disturbance and lotic ecotones. Pages 65-89 *in* R.J. Naiman and H. Decamps (eds.), Ecology and Management of Aquatic-Terrestrial Ecotones. Parthenon Press, London.

Wissmar, R.C. 1993. The need for long-term stream monitoring programs in forest ecosystems of the Pacific Northwest. Environ. Monit. Assess. 26: 219-234.

Wissmar, R.C. , J.E. Smith, B.A . McIntosh, H.W. Li, G.H. Reeves, and J.R. Sedell. 1994. A history of resource use and disturbance in riverine basins of eastern Oregon and Washington. Northw. Sci. Spec. Iss. 68: 233-267.

Wolman, M.G. 1954. A method of sampling coarse river-bed material. Trans. Am. Geophys. Union. 35: 951-956.

USDA Forest Service 1972. Soil Resource Inventory Snoqualmie National Forest. *In* R.V. Snyder and J.M. Wade (compilers), USFS Pacific Northwest Region. Mt. Baker-Snoqualmie National Forest, Supervisors Office, Mountlake Terrace, WA. 228 p.

USDA Forest Service 1992. Fisheries analysis on the Beckler River, Washington. Mt. Baker-Snoqualmie National Forest, Supervisors Office. Mountlake Terrace, WA. 16 p.

USDA Forest Service. 1993a. Forest ecosystem management: an ecological, economic and social assessment. *In* Aquat. Ecosystem Assessment , Chap. 5 (V-1 to V-95), Report of the Forest Ecosystem Management Team. US Government Printing Office: 1903-793-071.

USDA Forest Service. 1993b. Stream Inventory Handbook, Level I and II, Version 7. Region 6, Portland , OR. 98 p.

USDA Forest Service. 1994a. Preliminary watershed restoration assessment, Beckler watershed. Mt. Baker-Snoqualmie National Forest, Supervisors Office. Mountlake Terrace, WA. 7 p.

USDA Forest Service. 1994b. Record of decision for amendments to Forest Service and Bureau of Land Management planning documents within the range of the northern spotted owl. Standards and guidelines for management of habitat for late-successional and old-growth forest related species within the range of the northern spotted owl. US Government Printing Office: 1994-589-111/00001, Region 10.

Yeats, R.S. 1958. Geology of the Skykomish area in the Cascade Mountains of Washington. PhD dissertation, Dept. Geology, Univ. Washington, Seattle, WA. 243 p.

FIGURES

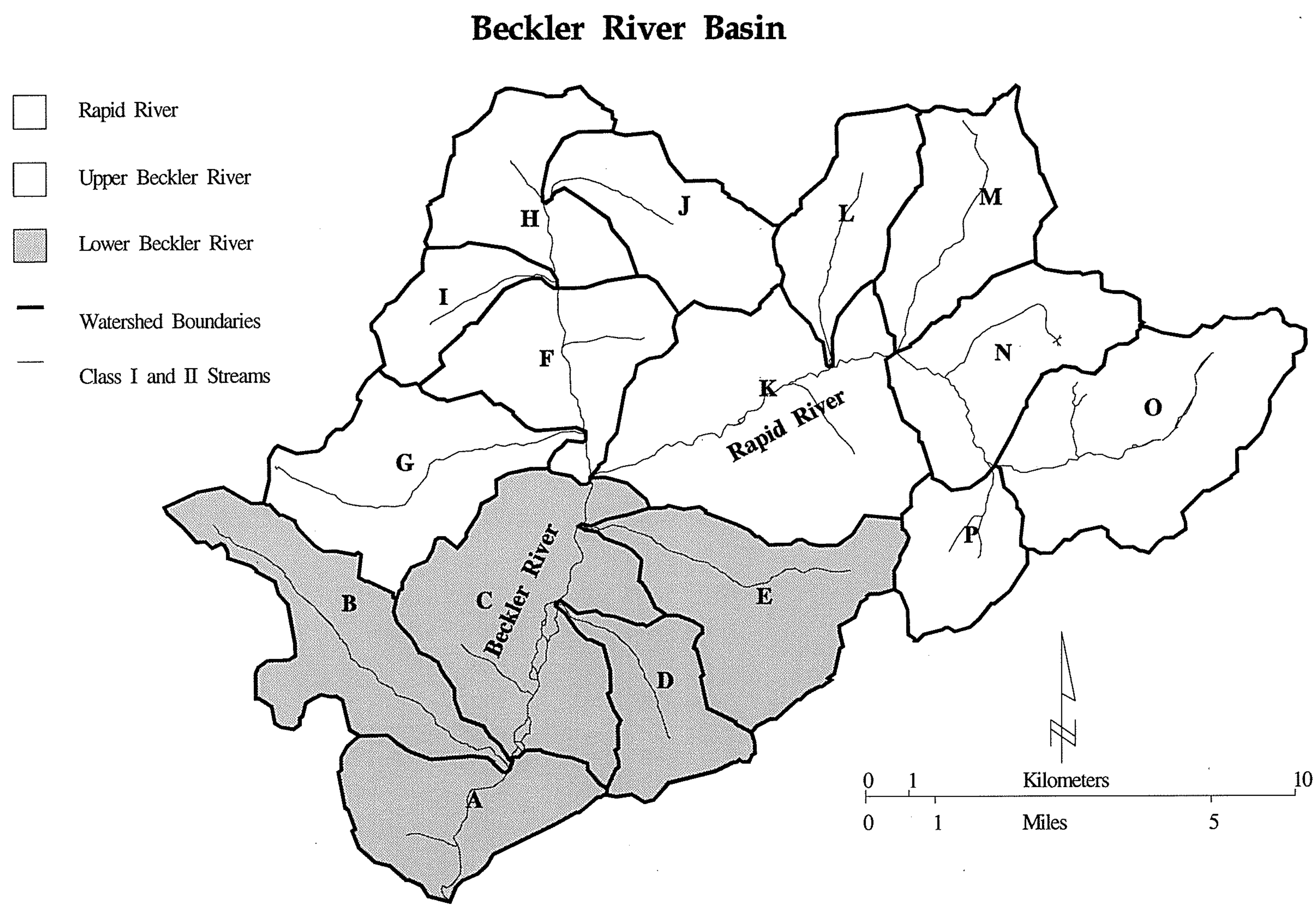

Figure 1. Map of the Beckler River drainage, a tributary to the South Fork of the Skykomish River in the Cascade Mountains of Washington. The Beckler River drainage (260 km^{-2}) includes three sub-drainages, the lower and upper Beckler and Rapid rivers. The letters indicate watershed management codes of the Skykomish Ranger District. Class I streams include perennial streams with sufficient discharge and habitat to support anadromous fish and Class II streams support resident trout (Gregory and Ashkenas 1990).

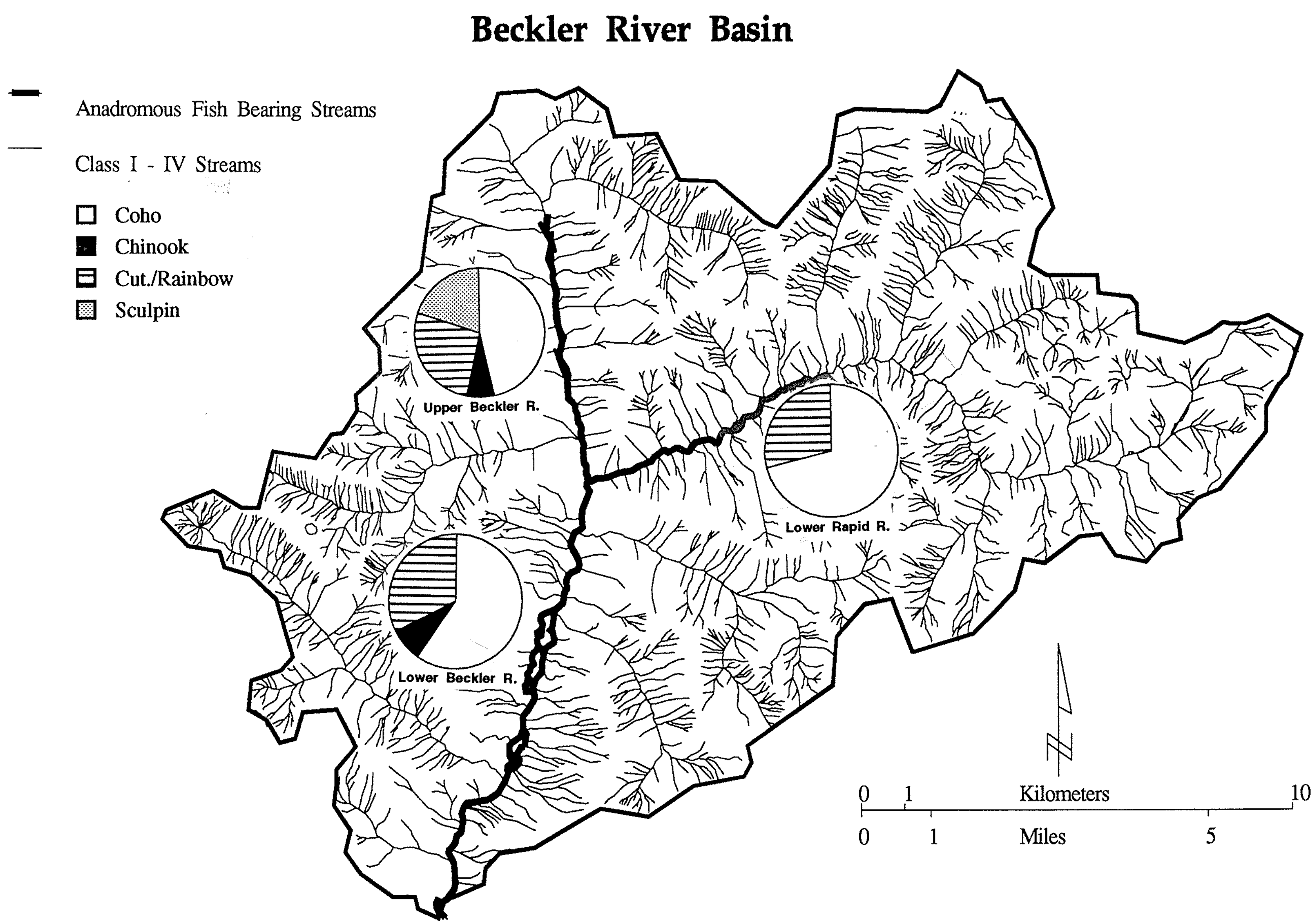

Figure 2. Relative abundance of juvenile fish in the main river channels of the lower and upper Beckler and Rapid rivers. The proportions are relative to the total densities of juvenile fish in the three main river channels (1000, 375, and 1800 fish, respectively).

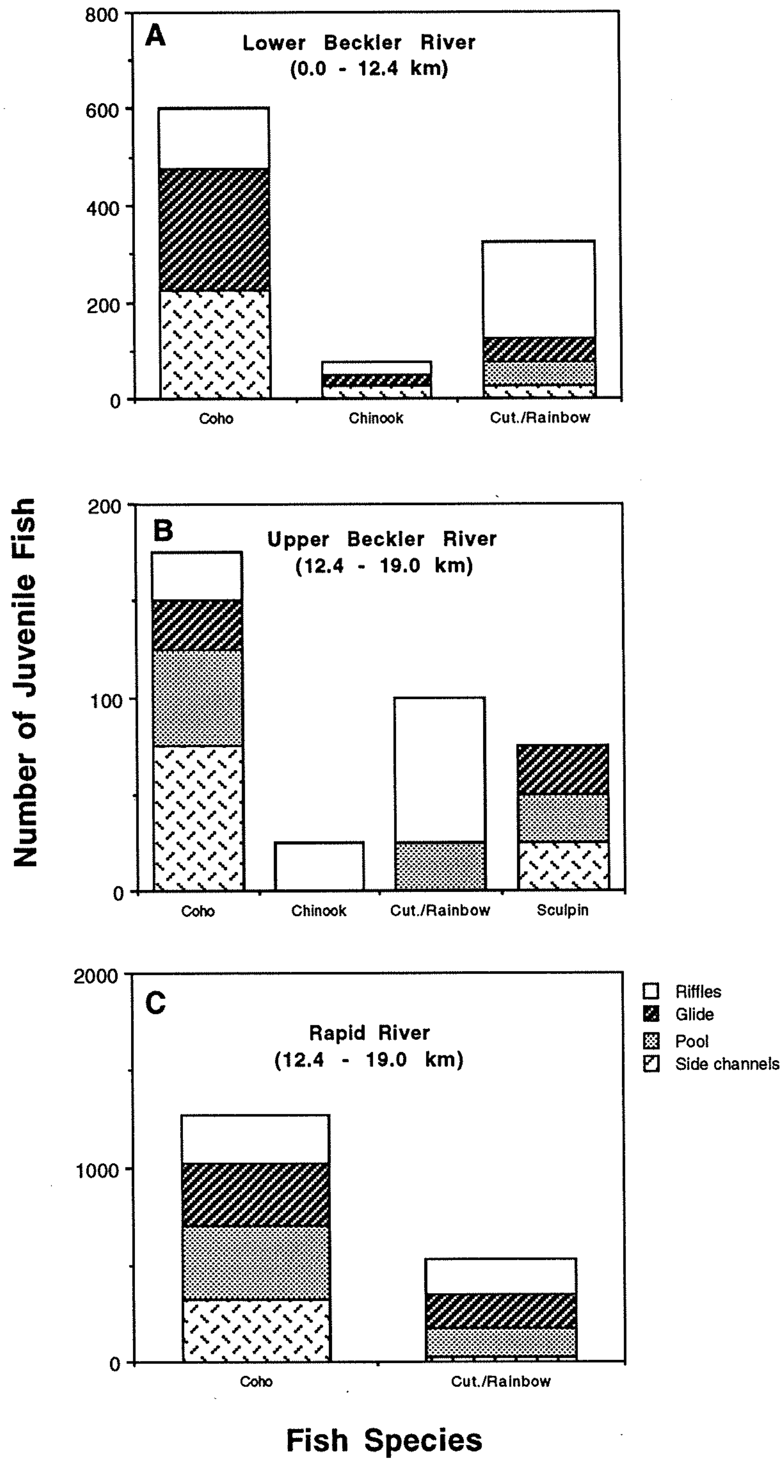

Figure 3. Number of juvenile fish in riffle, glide, pool and side channels habitats of the main river channels of the lower and upper Beckler and Rapid rivers. Population estimates based on August and September snorkel surveys.

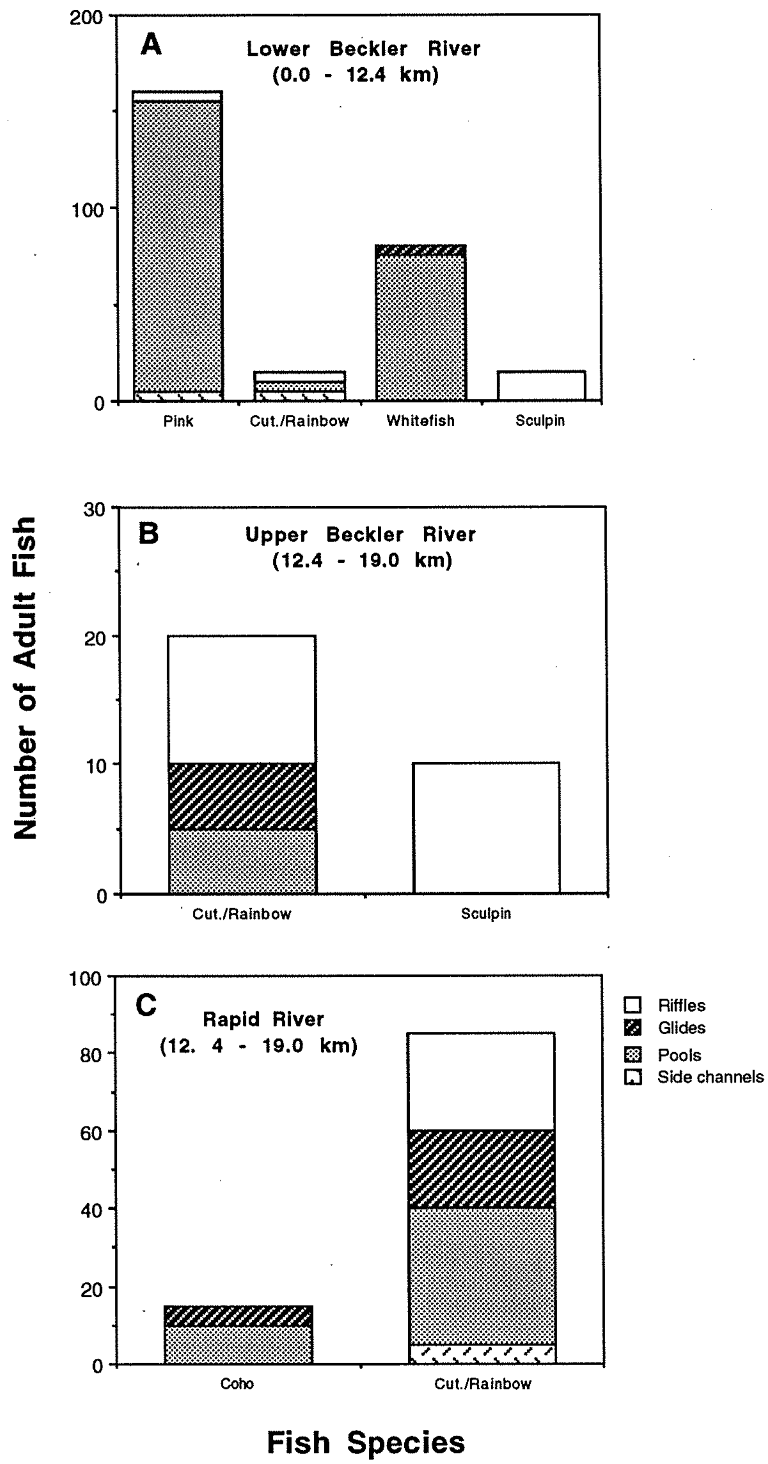

Figure 4. Number of adult fish in riffle, glide, pool and side channel habitats of the main river channels of the lower and upper Beckler and Rapid rivers. Population estimates based on August and September snorkel surveys.

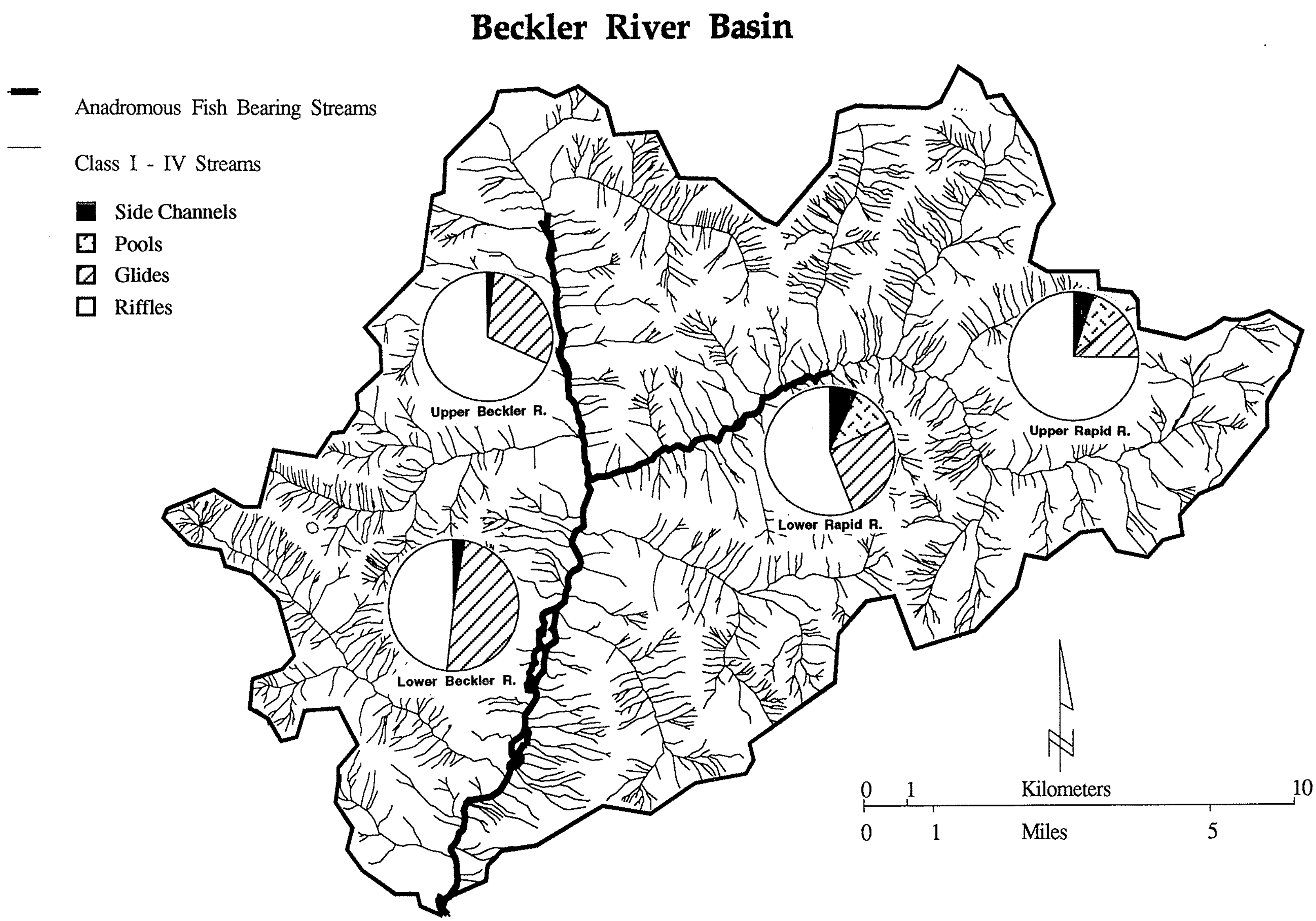

Figure 5. Relative abundance of riffle, glide, pool and side channel habitats in the main river channels of the lower and upper Beckler and Rapid rivers.

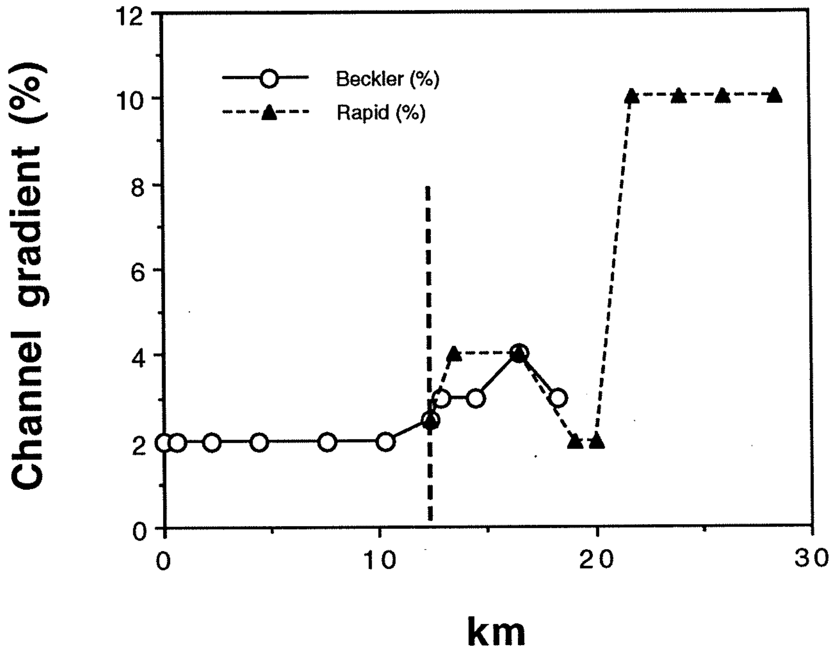

Figure 6. Channel gradients of reaches in the main river channels of the lower and upper Beckler and Rapid rivers.

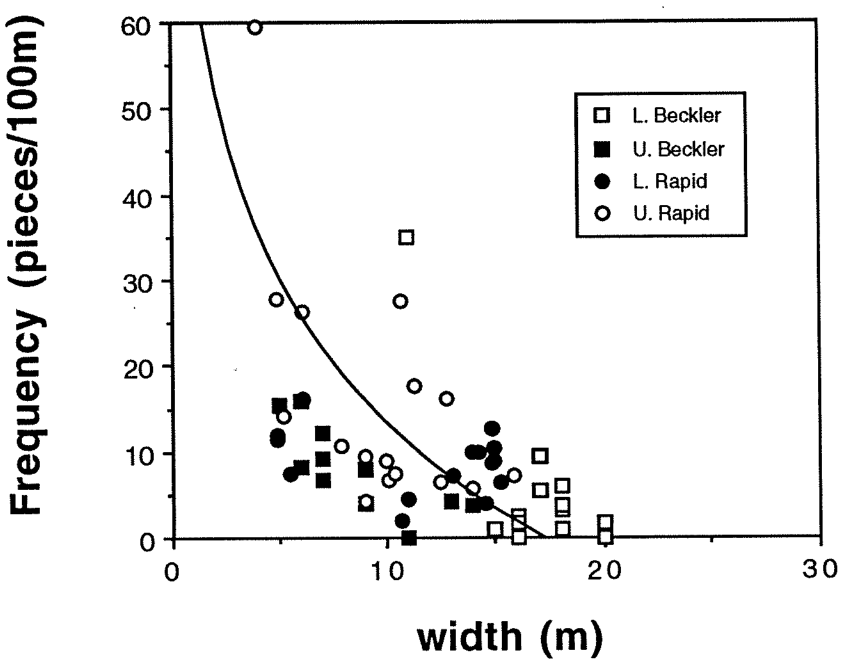

Figure 7. Frequency of large woody debris (LWD) as a function of channel widths in the main river channels of the lower and upper Beckler and the lower and upper Rapid rivers. The regression equation for LWD 100 m^{-1} and channel widths (m) is y = 69.8 - 56.4* Log(x) where $r^2 = 0.48$, n = 63 and $p = 0.05$.

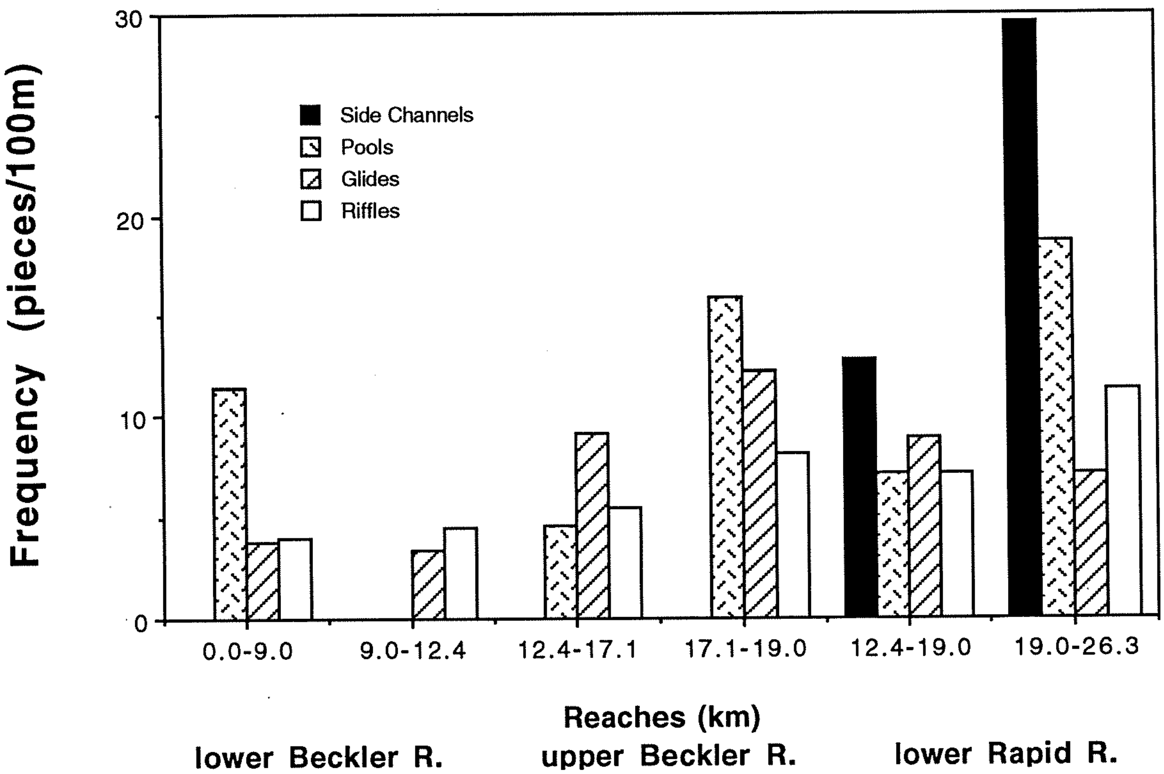

Figure 8. Frequency of LWD 100 m^{-1} in riffle, glide, pool and side channel habitats of the main river channels of the lower and upper Beckler and the lower and upper Rapid rivers. For the lower Beckler River, the downstream reach extends from 0.0–9.0 km and the upstream reach from 9.0–12.3 km. The upper Beckler River's downstream reach extends from 12.3–17.1 km and the upstream reach from 17.1–19.0 km. The lower Rapid River channel extends from 0.0–6.6 km above the Beckler River confluence and the upper channel from 6.6–13.9 km.

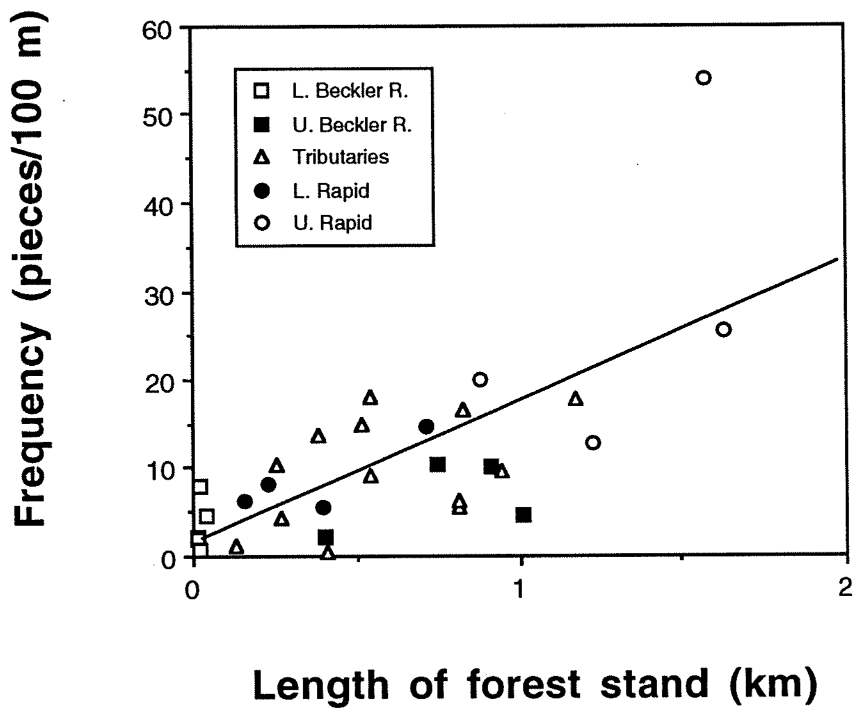

Figure 9. Frequency of LWD 100 m^{-1} in stream channels as a function of the reach length (km) of large riparian trees (diameter >0.61 cm) adjacent to the channel. The regression equation for LWD and riparian trees is $y = 1.29 + 16.0(x)$, where $r^2 = 0.49$, $n = 31$ and $p = 0.05$.

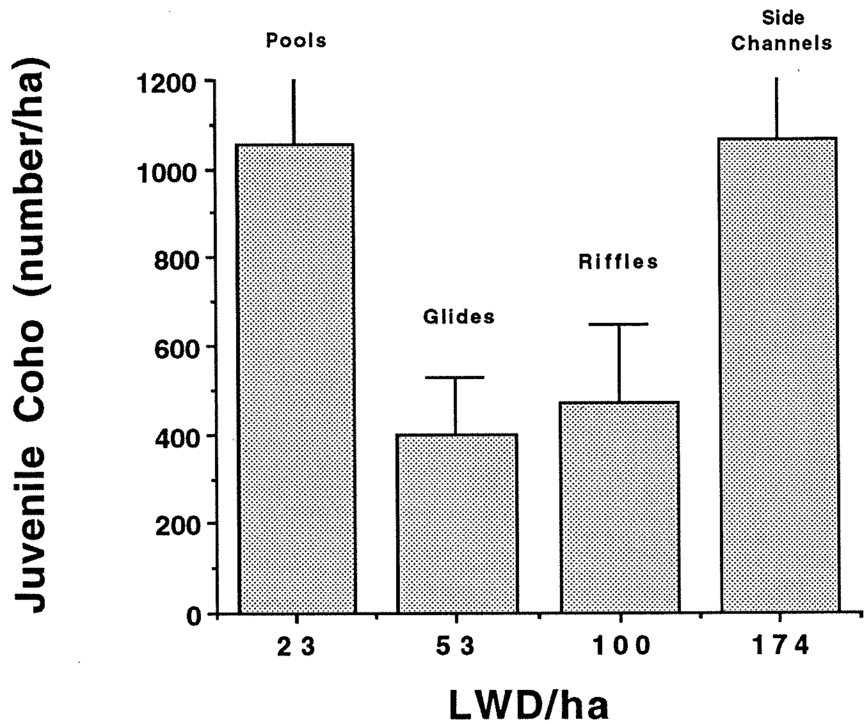

Figure 10. Number of juvenile coho salmon ha^{-1} and the occurrence of LWD ha^{-1} in riffle, glide, pool and side channel habitat areas of the main river channel of Rapid River. Population estimates based on August and September snorkel surveys. Error bars represent standard errors.

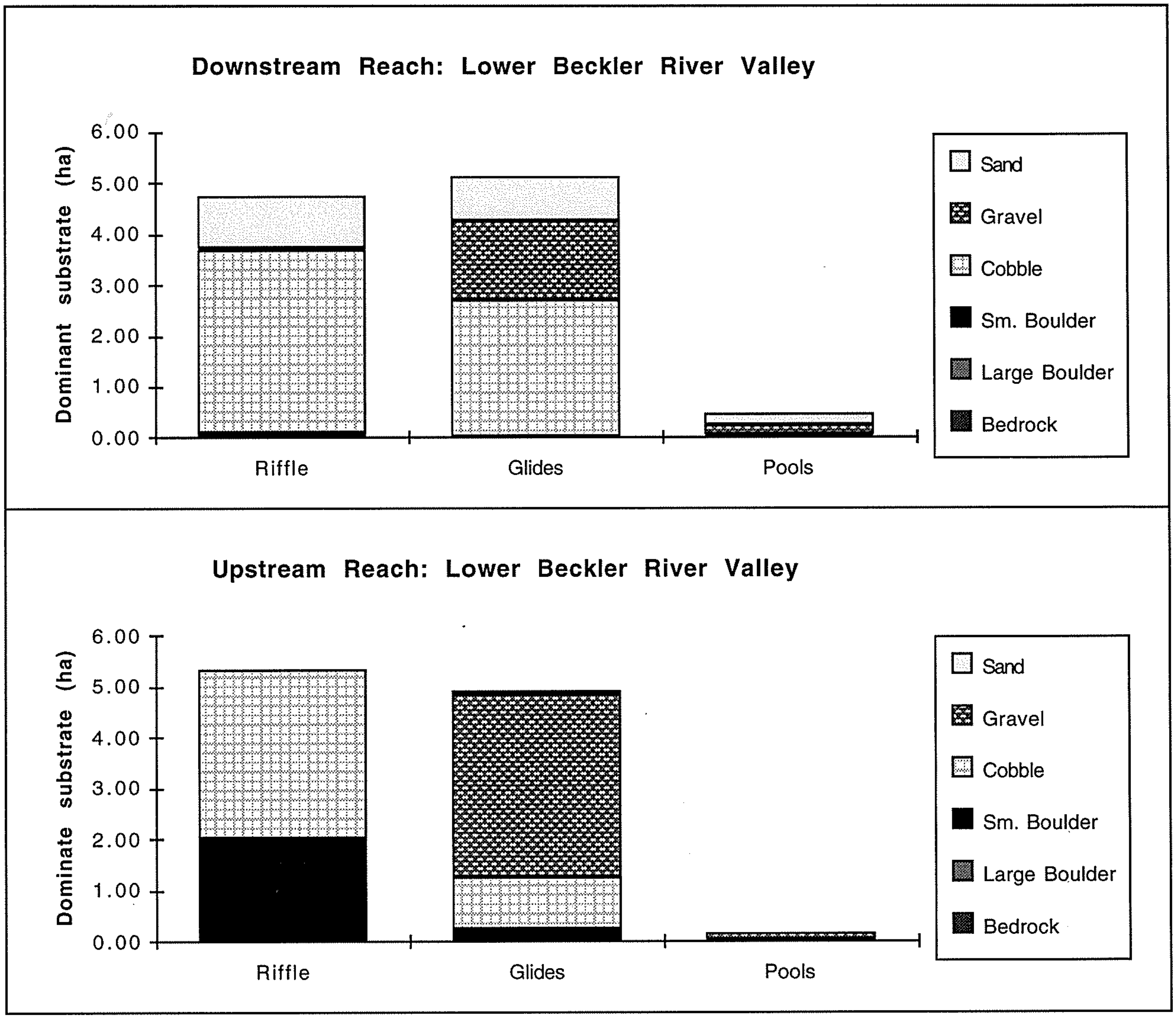

Figure 11. Distribution of the dominant bottom substrate sizes occurring within riffle, glide, and pool habitat areas of two reaches of the main river channel of the lower Beckler River. Size categories include sand (<2 mm), gravel (2–64 mm) cobble (64–256 mm), small boulders (256–1016 mm), large boulder (>1016), and bedrock. The downstream reach extends from 0.0–9.0 km and the upstream reach from 9.0–12.3 km along the lower Beckler River.

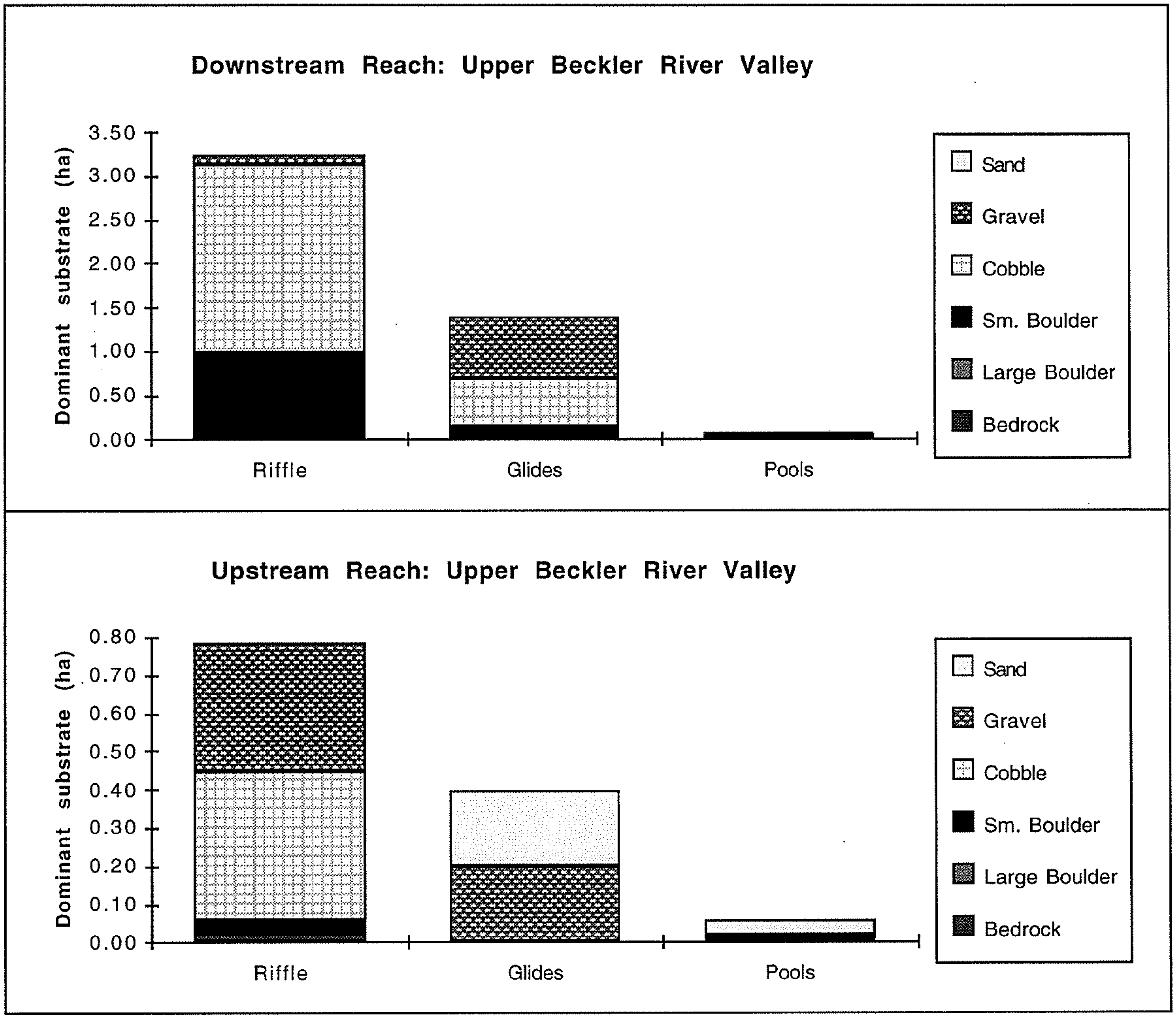

Figure 12. Distribution of the dominant bottom substrate sizes occurring within riffle, glide, and pool habitat areas within two reaches of the main river channel of the upper Beckler River. The downstream reach extends from 12.3–17.1 km and the upstream reach from 17.1–19.0 km along the upper Beckler River. The substrate size categories are the same as Figure 11.

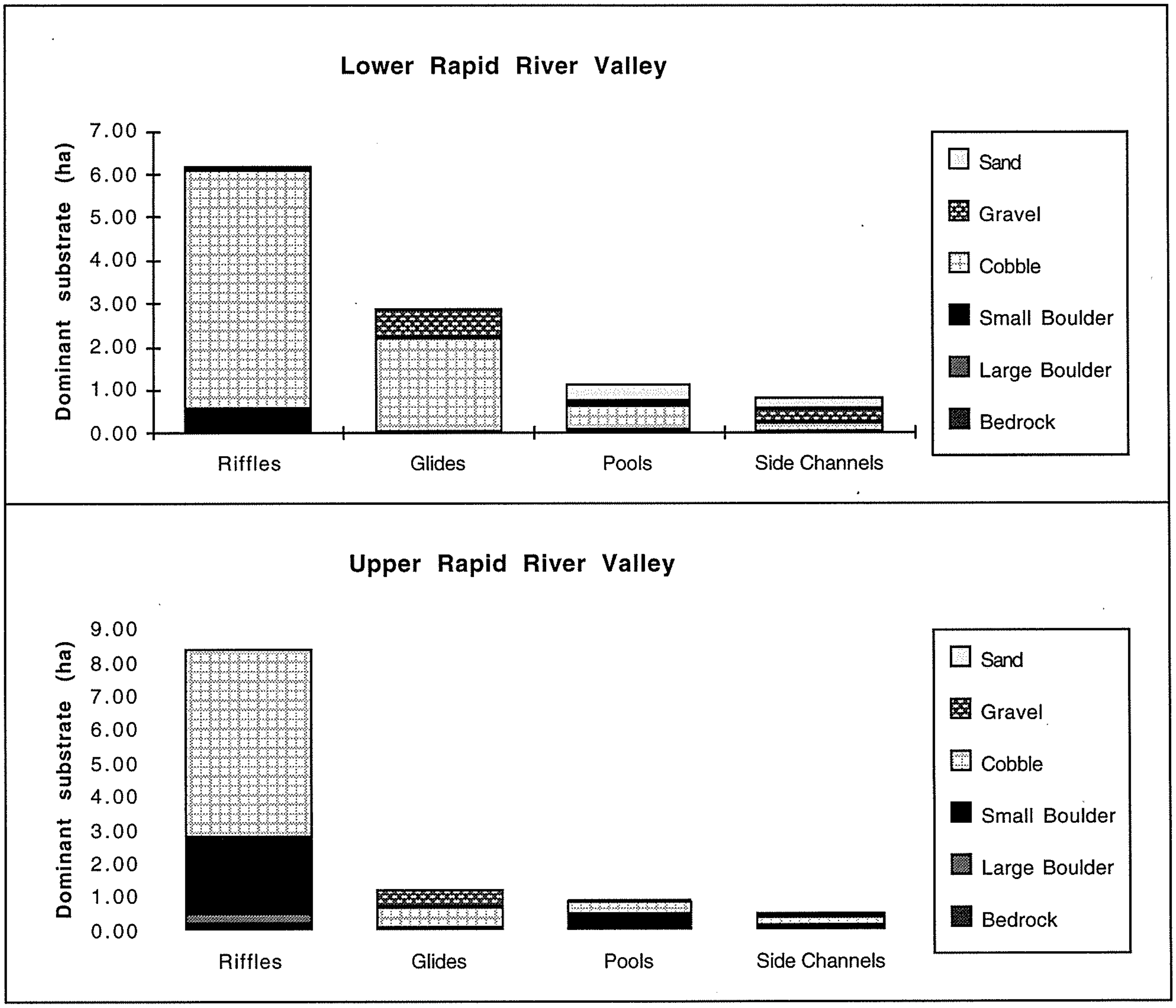

Figure 13. Distribution of the dominant bottom substrate sizes occurring within riffle, glide, pool, and side channel habitat areas within the lower and upper Rapid River. The lower river channel extends from 0.0–6.6 km above the confluence with the Beckler River and the upper channel from 6.6–13.9 km. The substrate size categories are the same as Figure 11.

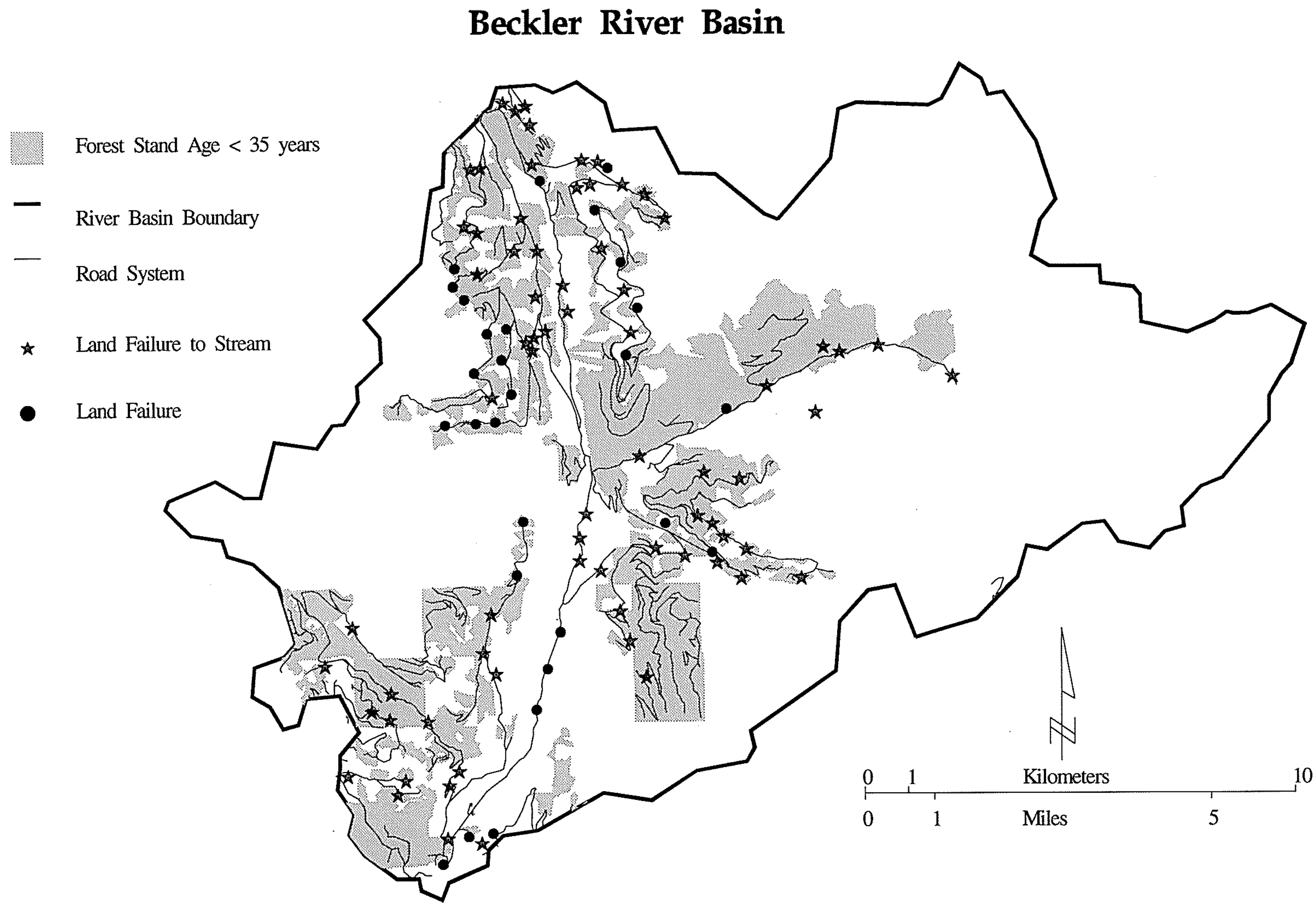

Figure 14. Spatial distribution of land failure sites, immature forest stands (age <35 years), and roads in the Beckler River drainage. The land failures are the total sites occurring between 1970 and 1990. The sites with star symbols indicate land failures reaching stream channels. The immature forests are considered as potentially unstable areas because minimal vegetative regeneration of roots and canopy cover provides inadequate hydrologic recovery (S. Woolley, Mt. Baker-Snoqualmie National Forest, pers. comm.; Sidle et al. 1985).

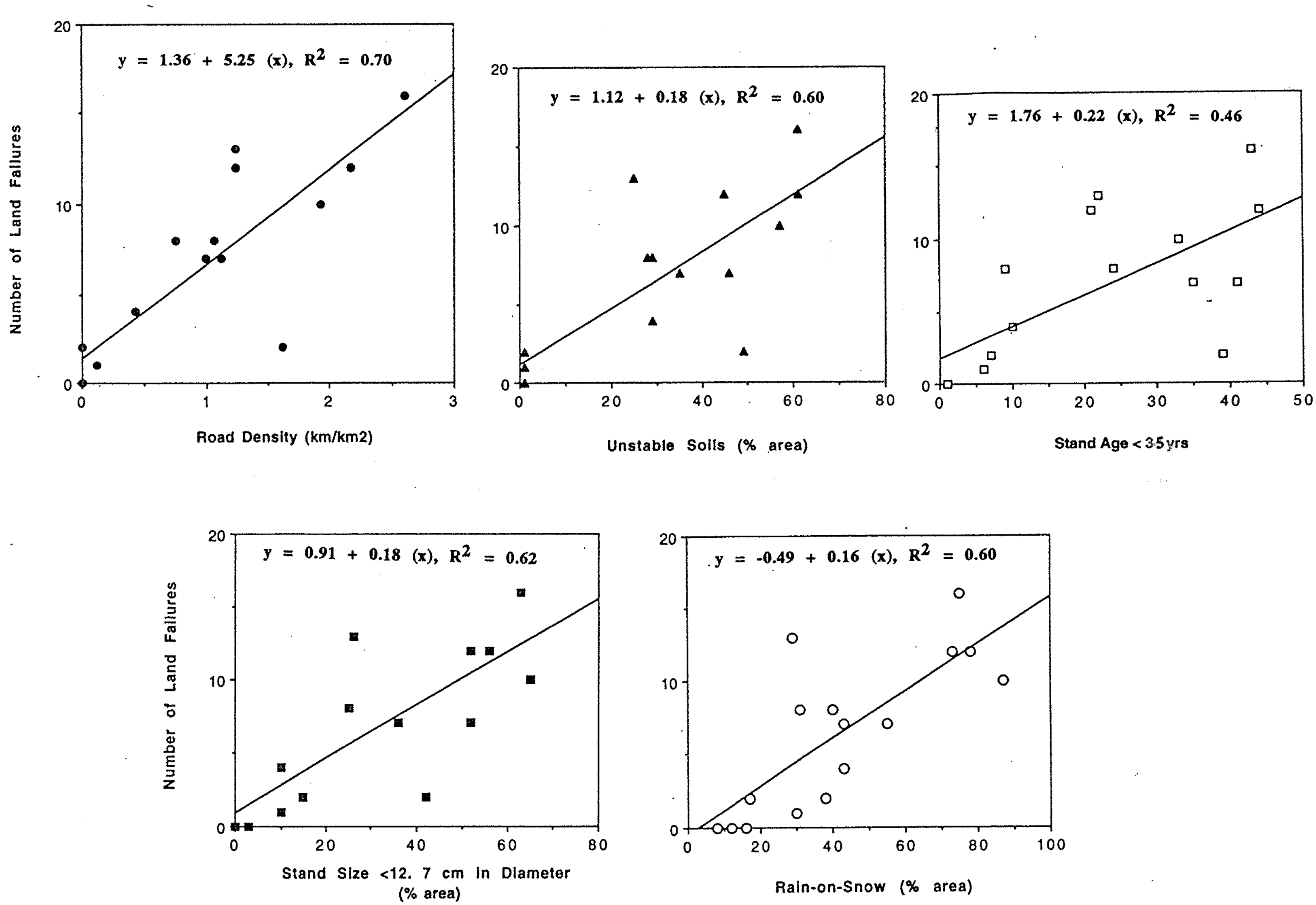

Figure 15A-E. Number of land failures as a function of roads, unstable soils, immature forest stands, small sized stands, rain-on-snow, and road densities in 16 tributary watersheds of the Beckler River drainage. The unstable soils represent soil areas with the greatest potentials for yielding sediments to streams (USDA Forest Service 1972). The small-sized forest stands are defined as trees with diameter <12.7 cm (dbh). The rain-on-snow is based on the range of elevations (305 to 1067 m) which has the highest frequency of rain-on-snow events in the central Cascades Mts. of Washington (Coffin 1991). The immature forest stands are defined in Figure 14. Panels A to E describe land failures as dependent variables, the respective dependent variables and regression equations, where (A) = road density (km km^{-2}); (B) = unstable soils (% area); (C) = immature forest stands (% area); (D) = small-sized forest stands (% area); and (E) = rain-on-snow (% area). The regression relationship are significant at the $p = 0.05$ level.

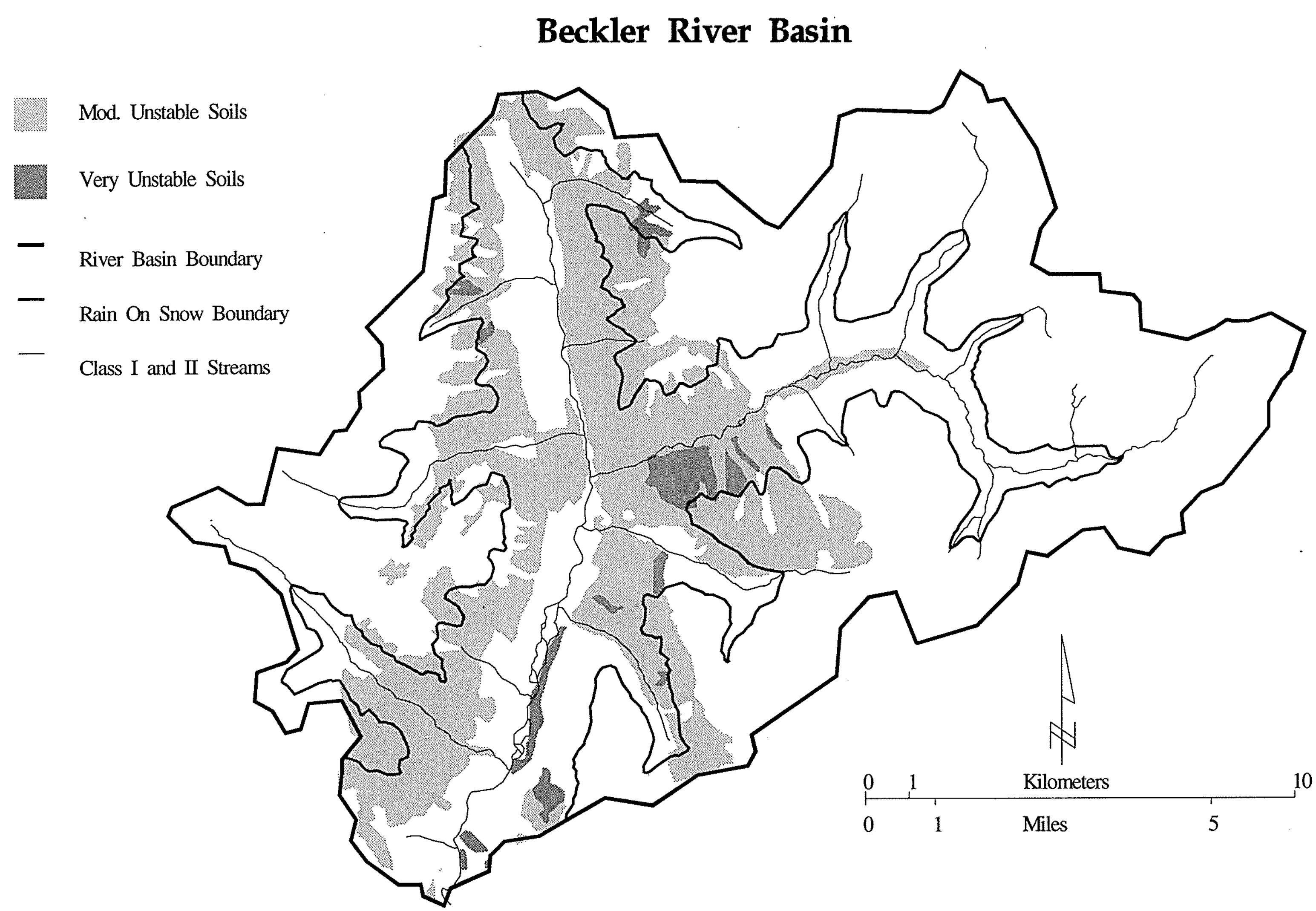

Figure 16. Spatial distribution of moderately and very unstable soils, rain-on-snow areas and Class I and II streams in the Beckler River drainage. Descriptions of Class I and II streams, unstable soils, and rain-on-snow areas are the same as in Figures 1 and 15, respectively.

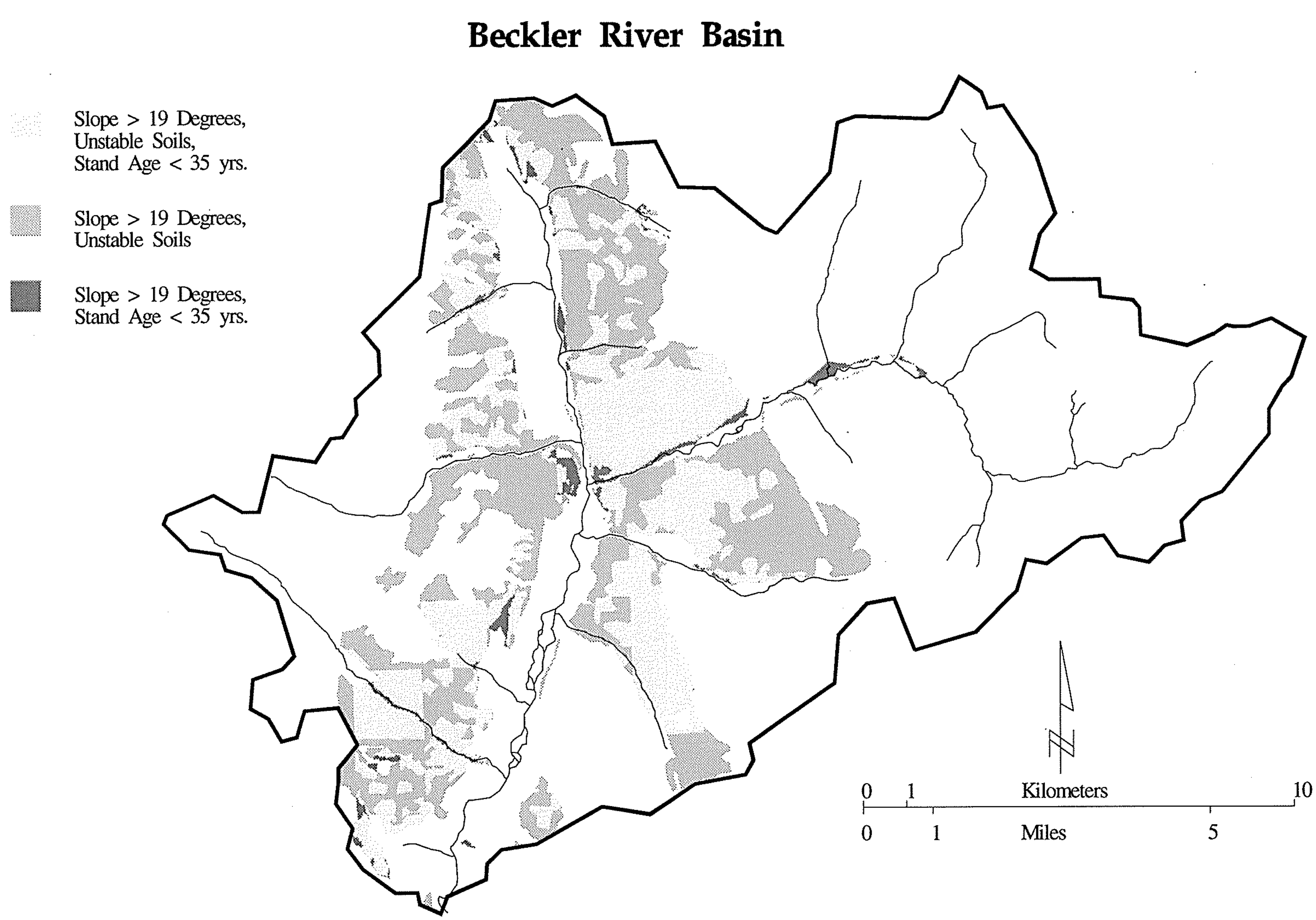

Figure 17. Overlapping distributions of immature forests, unstable soils, and critical terrain slopes in the Beckler River drainage. The areas of overlap suggest highly unstable terrain locations. The locations of the unstable soils and critical slopes (>19°) are based on the soil Resource Inventory (USDA Forest Service 1972) and GIS layers of terrain slopes. Descriptions of immature forest stands and unstable soils are defined in Figures 14 and 15.

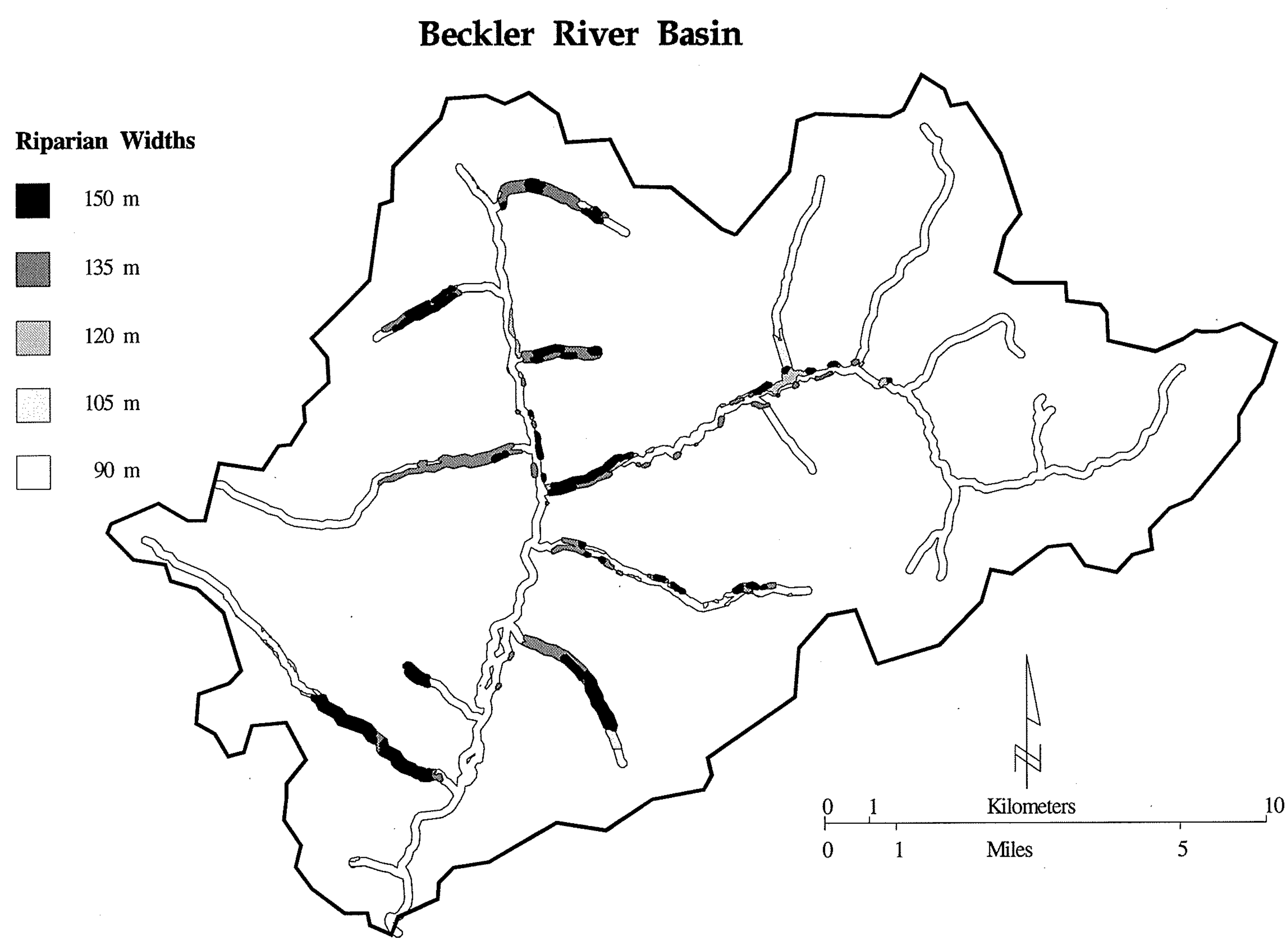

Figure 18. Modifications to the riparian reserve widths for Class I and II streams in the Beckler River drainage. The riparian reserve widths are 90-m fixed widths on each side of fish-bearing streams (USDA Forest Service 1994b). The modifications are based on the locations of overlapping distributions of immature forests (age <35 years), unstable soils, and terrain slopes (>19°) within the 90-m widths. Descriptions of Class I and II streams, immature forest stands, unstable soils, and terrain slopes are defined in Figures 1, 14, 15 and 17.

TABLES

Table 1. Physiographic characteristics of the subwatersheds in the Beckler River basin. Letters in parenthesis indicate subwatershed management codes of the Skykomish Ranger District, Mt. Baker-Snoqualmie National Forest.

	Lower Beckler River					Upper Beckler River					Rapid River					
	Bolt (A)	Eagle (B)	Un-named (C)	Harlen (D)	Johnson (E)	4th July (G)	Bull-bucker (F)	Wind-fall (H)	Boulder (I)	Ever-green (J)	Rapid (K)	Meadow (L)	N.F. Rapid (M)	M.F. Rapid (N)	Pete (O)	Joan (P)
Drainage area (km^2)	13.7	18.0	26.6	10.1	19.8	18.6	15.3	12.7	6.6	12.9	31.4	10.6	14.3	16.3	24.7	8.7
Total stream length (km)[a]	41.7	88.4	89.3	41.2	77.4	85.5	34.7	34.8	22.5	60.5	120.2	49.2	61.0	74.9	108.6	35.0
Drainage density ($km\ km^{-2}$)	3.0	4.9	3.4	4.1	3.9	4.6	2.3	2.7	3.4	4.7	3.8	4.6	4.3	4.6	4.4	4.0
Channel gradient (%)[b]	6-25	6-30	26-67	2-25	2-13	10-15	21-55	28-70	8-15	4-12	2-4					
Stream Class[c]																
Class I & II (km) (km)	5.6	10.0	13.0	4.5	7.1	8.5	6.7	4.2	3.6	3.7	11.7	4.9	6.6	9.0	10.1	3.4
Class III & IV (km)	36.1	78.4	76.3	36.7	70.3	77.0	28.0	30.6	18.9	56.8	108.5	44.3	54.4	65.9	98.5	31.6

[a]Total length for stream Classes I, II, III and IV as defined by the USDA Forest Service (Gregory and Ashkenas 1990).
[b]Range of gradients from channel stability surveys (Skykomish Ranger District).
[c]Class I and II streams (fish-bearing) and Class III and IV (non fish-bearing).

Table 2. Characteristics of large woody debris (LWD) and study reaches of select fish-bearing river channels and tributary streams in the Beckler River Basin compared to streams of undisturbed regions of western Washington (Bilby and Ward 1989) and southeast Alaska (Robison and Beschta 1990).

Characteristic	Beckler River Basin	Western Washington	Southeast Alaska
Reach length (m)	322–2100	74–715	335–1530
Reaches measured (N)[a]	23	22	5
Channel gradient (%)	2.0–25.0	2.0–18.0	0.8–2.5
LWD length (m)	>8.0	4.0–14.0	6.7–8.4
LWD diameter (m)	0.3–0.9	0.3–0.7	0.5–0.6
LWD frequency (LWD 100 m^{-1}) by channel width[b]			
<7 m	14	50	25
7 - 10 m	8	33	41
>10 m	7	14	38
LWD volume (m^3) by channel width			
<7 m	0.2–1.3[c]	0.2–1.0[d]	1.4–1.5
7 - 10 m	0.3–1.7	0.6–2.2	1.5
>10 m	0.3–0.9	2.2–5.2	1.8–2.2

[a]Reaches measured in the Beckler River basin form the Beckler and Rapid rivers and Johnson, Harlen and Evergreen creeks.
[b]Average LWD 100 m^{-1}.
[c]LWD volumes in Beckler River channels (m^3) calculated as (length) · (π) · (diameter/2)^2.
[d]Data for debris volume, length and diameter for western Washington streams estimated from channel width relationships (Bilby and Ward 1989).

Table 3. Unstable bank and channel conditions for rivers and tributary streams of the lower Beckler, upper Beckler and Rapid rivers. Unstable conditions are percent of the channel lengths surveyed during low streamflows. All surveys in 1993 except for Boulder Cr. in 1992 and Harlen Cr., the Beckler and Rapid rivers in 1991. Criteria used to establish stability included fair to poor scores after Pfankuck (1975). Symbol* = channel length surveyed (km).

	Lower Beckler				Upper Beckler						Rapid	
Unstable conditions	Beckler River	Bolt Creek	Eagle Creek	Harlen Creek	Beckler River	Wind-fall Cr.	Boulder Creek	4th July Creek	Bull-bucker	Everg-green Cr.	Lower	Upper
Banks												
Landform slopes		64	75	47		82	100	20	73	88		26
Mass wasting	38	56	3	71		33		24		56	31	10
Debris jams	38	37	19	95	38	91	33	60	38	100	31	52
Vegetative protection		37	13	51		27		27				
Rock & log obstructions		37	3	71		49		7	11	40		10
Erosion	100	45	17	57	38	58	33	9	23	16	31	22
Deposition	28	45	5	64	28	18	22	16		56		10
Channel												
Consolidation	72	37	3	4	72	18	18		12	40		10
Unstable substrates	54	45		4	38		73	84	12	12		10
Scouring	84	45	3	64	38	27	51			12		10
*Total km	12.4	3.0	8.9	4.1	4.7	1.5	1.5	5.2	2.4	4.0	5.6	12.3

APPENDIX I.

GIS commands for modification of riparian reserve widths (USDA Forest Service 1994 b). The ARC commands are for the ARC module of ARC/INFO.

```
/* The following are ARC commands for use in the ARC module of ARC/INFO.
/* Comments begin with /*
/* aa is baddirts i.e. the soils identified as risky
/* bb is badslopes i.e. the slopes defined as critical
/* cc is ageclass1 i.e. the youngest ageclass
/*
intersect bb aa ab poly #
intersect cc aa ac poly #
intersect cc bb bc poly #
intersect ab cc threerisk poly #
union aa bb orisk
union bb orisk oorisk
union cc oorisk onerisk
union ab ac trisk
union bc trisk tworisk
clean onerisk
clean tworisk
clean threerisk
/*
dissolve tworisk tworisk2 aa# poly
dissolve threerisk threerisk2 aa# poly
dissolve aa aa2 aa# poly
dissolve bb bb2 bb# poly
dissolve cc cc2 cc# poly
dissolve ab ab2 aa# poly
dissolve ac ac2 aa# poly
dissolve bc bc2 bb# poly
/*
/* buffer the streams with baseline 90 meter buffer
/*
buffer 1_2only 1_2onlybuf DATA # 90 # line
```

```
/*
/* create a cover that shows where this buffer intersects areas
/* with three risks
/*
intersect 1_2onlybuf threerisk2 3riskbuf poly #
/*
/* buffer this new buffer OF THE INTERSECTION OF THE
/* BUFFER WITH THREE-RISK AREAS with an additional buffer of 60 meters.
/*
buffer 3riskbuf 3rbx # # 60 # poly
/*
/* for each two risk area, perform the previous action of finding where the
/* baseline buffer intersects  with two-risk areas then add on the
/* additional buffer
/*
intersect 1_2onlybuf ab abbuf poly #
intersect 1_2onlybuf ac acbuf poly #
intersect 1_2onlybuf bc bcbuf poly #
buffer abbuf abbufx # # 45 # poly
buffer acbuf acbufx # # 30 # poly
buffer bcbuf bcbufx # # 15 # poly
/*
/* display each of the covers after cleaning with different shading
/* it is best to lay down the 90 meter buffer with a light color
/* adding successively wider (and less extensive) buffers in darker colors
/*
```