AN ABSTRACT OF THE THESIS OF

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Title: Undercut Streambanks in Forested Headwater Streams of the Oregon Coast Range.

Abstract approved: ______________________________.
Robert L. Beschta

This study was undertaken to evaluate the occurrence and characteristics of undercut streambanks in forested headwater streams of the Oregon Coast Range. Undercut streambanks and associated reach characteristics were surveyed along 46 sample reaches (each 152 m in length) in 8 streams; all sample reaches occurred in unmanaged forested riparian areas. Drainage areas ranged from 0.3 to 16.6 km^2.

At each undercut location length, surface area, volume, low-flow (summertime) volume, and maximum horizontal depth were measured. Individual undercuts had surface areas ranging from 0.3 to 27.7 m^2 with a mean value of 2.6 m^2, and lengths ranging from 1.2 to 15.2 m with a mean value of 5.0 m.

The area of undercut streambanks ranged from 0.0 to 27.4 m^2 / 100 m of stream, with an average value of 6.5 m^2 / 100 m. The proportion of bankfull channel area undercut

ranged from 0.0 to 4.5 %, with an average value of 1.1 %. Reach length undercut ranged from 0.0 to 23.6 %, with an average value of 6.2 %. The values reported in this study are approximately mid-range in comparison to characteristics of undercut banks reported in studies from Alaska, Montana, and Wisconsin. The % of reach area covered by undercut streambanks in this study is approximately half of that provided by large woody debris.

Outside channel bends had approximately 6 times more undercut streambanks than inside bends or straight sections. Streams having a sinuosity index greater than 1.15 averaged approximately twice as much % stream length undercut and 3 times as much % surface area undercut than streams having a sinuosity index less than 1.15.

Number of undercuts and undercut characteristics were inversely correlated with channel gradient; significant differences occurring among 1 %, 2-4 %, and 5+ % channel gradient classes.

Streambanks ranging in height from 1-2 m had a higher occurrence of undercut streambanks than either lower or higher streambanks. Undercut streambanks were 4 times more common in "composite" than "non-composite" streambanks. Undercut characteristics appear to be correlated with valley segment type.

Channel widths were, on average, significantly narrower at undercut sites when compared to reach average channel widths. However, it does not appear that width characteristics are a cause of undercutting. Based on field observations it appears that flow obstructions (gravel bars, boulders, large woody debris) have little impact on undercut characteristics.

Both at-a-site and reach-level comparisons of undercut bank characteristics showed relatively strong correlations with streamside tree densities. Red alder (*Alnus rubra*) is the most prevalent species found in Coast Range riparian areas, and the most significant species in explaining reach-level differences in undercut characteristics. Sitka spruce (*Picea sitchensis*) is less common in riparian zones, but appears to be positively correlated with the proportion of reach area undercut.

UNDERCUT STREAMBANKS IN FORESTED HEADWATER STREAMS OF THE OREGON COAST RANGE

by

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A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Completed September 19, 1990

Commencement June, 1991

APPROVED:

Professor of Forest Engineering in charge of major

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Dean of Graduate School

Date thesis is presented September 19, 1990

Typed by Ed Salminen for Edward M. Salminen

ACKNOWLEDGEMENT

I want first of all to acknowledge my father and mother, William and Frances Salminen, for both the encouragement they gave me to pursue higher education, and the free hand to do whatever I chose in life. To all of my family I appreciate the love and respect that they have given me.

Thanks to Bob Beschta for the guidance and support that kept me going through those moments of doubt about this project. I appreciate his enthusiasm, and curiosity with life, the universe, and everything.

Thanks to the Forest Research Laboratory for providing the funds that made graduate school possible, and to the Alfred W. Moltke Fellowship which made graduate school a pleasure.

Finally I want to thank all the fine friends I've found since moving to Corvallis, particularly the "Bob Squad" and Bob Squad "wanna-be's". Thanks to Therese Glowacki and Curt Veldhuisen for their early examples of how to "do" graduate school. Last I want to thank my buddy Michele Chapin who has been my partner in a project infinitely more important and interesting than the one chronicled here.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

UNDERCUT STREAMBANKS IN FORESTED HEADWATER STREAMS OF THE OREGON COAST RANGE

INTRODUCTION

In the Pacific northwest, small streams associated with mature forests are often noted for their productive fisheries (Sedell et al., 1988). Yet fisheries and forest production may represent potentially conflicting resource goals. Management concerns have often focused on the effect of timber harvesting and road building on stream temperature, sediment input, and changes in peak flows (Harr et al., 1975; Brown, 1985). More recently, interest has shifted to the influence of forest management on large woody debris (LWD) (Maser et al., 1988).

The increasing level of concern of forest management effects on fisheries is reflected in recent amendments to Forest Practices Rules in Oregon regarding riparian area management (Oregon Department of Forestry, 1987) and the creation of the Timber, Fish, and Wildlife program in Washington state. Forest Practices Rules in Oregon, for example, allow for 50 percent of the canopy to be removed and require leaving at least ten square feet of conifer basal area / acre (Adams, 1988). Many states are revising forest practices rules to include riparian zone regulations that will promote bank stability and availability of large woody debris (Sullivan et al., 1987). Although forest practice rules apply to all timber harvests, there is considerable leeway in how they are applied (Everest et al., 1985). Of the 17,000 miles of fish-bearing streams in western Oregon 54 percent are on private lands, 34 percent on USDA Forest Service land, and 12 percent on Bureau of Land Management land (Sedell et al., 1988).

There is increased interest in the Oregon Coast Range in riparian area management. Issues include appropriate silvicultural methods for timber production, management strategies to produce and maintain large woody material for stream structural elements, and the development of in-stream fisheries habitat-improvement structures.

Various authors (Boussu, 1954; Hunt, 1969, 1988; Lewis, 1969; Bustard and Narver, 1975a, 1975b; Platts, 1983) identify undercut streambanks as an important fish habitat feature, providing protective cover. However, little is known about the distribution and characteristics of undercut streambanks in streams of western Oregon. The purpose of this study was to investigate undercut streambanks, by reach type (reaches defined by physical / vegetative characteristics), in forested headwater streams of the central Oregon Coast Range. This information may be useful for:

a) determining if undercut streambanks are an important source of protective cover in forested streams.

b) inferring, based on the reach characteristics where undercut streambanks are found, what mechanisms are responsible for their formation, and

c) speculating on how management activities may affect the frequency and magnitude of undercut streambanks.

Knowledge of the distribution of and the possible mechanisms responsible for undercut streambanks may be useful to managers interested in maintaining this important fish-habitat feature while pursuing other goals in riparian-area management. Specific objectives of this study are:

a) To determine the frequency of occurrence and physical characteristics of undercut streambanks.

b) To infer, based on at-a-site characteristics of undercut streambanks and associated reach characteristics, processes responsible for the occurrence of undercut streambanks.

This study was undertaken in forested headwater streams because they comprise the highest percentage of overall stream length, they are often impacted by forest-management practices, and they are productive for fisheries (Beschta and Platts, 1986; Sedell et al., 1988).

LITERATURE REVIEW

Important physical factors affecting fish habitat are temperature, cover, and magnitude and fluctuations in discharge (Hynes, 1972). In addition anadromous salmonids require access to the sea, clean gravel for spawning, low sediment concentrations for sight feeding, invertebrate organisms for food, and high dissolved oxygen content (Everest et al., 1985).

Cover provides shelter for fish, and may be the single most important factor affecting a fishery (Platts, 1983). Cover has been defined as areas in the stream where fish can rest and avoid predators (Arnette, 1976). Artificial "lies", which provide fish cover, have been used in English streams for many years (Boussu, 1954). Cover in streams can include aquatic and terrestrial vegetation, woody debris, large rocks and other submerged objects, deep water, turbulent water, and undercut banks (Binns and Eiserman, 1979). Large woody debris may be the most important source of cover in forested streams of the Pacific northwest (Everest et al., 1985).

Although cover may be a factor in selection or abandonment of spawning sites in small streams, it may be more important for the protection of juveniles from avian, terrestrial, and aquatic predators. In second- and third-order streams, abundance of juvenile steelhead and coho is correlated to cover (Everest et al., 1985).

Requirements for space, food, and cover change with time of year and species of fish (Chapman and Bjornn, 1969). An increase in food supply reduces territorial behavior, and consequently reduces spatial needs for juvenile coho (Chapman, 1966). Increased cover increases visual isolation and decreases spatial needs.

The availability of summer rearing habitat is influenced primarily by in-stream flow volumes (Everest et al., 1985). If sufficient in-stream flow exists, salmonids will seek physical microhabitat that provide deep slow-moving cool water with sufficient space, substrate of sufficient size, adequate food, and cover.

Function of Undercut Streambanks

Undercut streambanks provide fish cover and favorable conditions for increased fish biomass, particularly in small streams (Platts et al., 1987). Platts et al. (1987) also suggested that undercut streambanks are good indicators of how well banks are protected under different management practices.

Boussu (1954) studied the relationship of cover to trout populations in Trout Creek (drainage area (A) = 2 km^2, gradient (G) = 0.4 %), Gallatin County, Montana. Undercut banks were removed from two stream sections. Total pounds of fish declined by an average of 33 % whereas the untreated control section increased by 20 % over the same period.

Hunt (1969) investigated the effects of habitat alterations using wooden bank covers and current deflectors on trout populations in Lawrence Creek ($A = 17\ km^2$, $G = 0.2\ \%$), Wisconsin. Trout distributions were found to be positively correlated to the amount of undercut bank and amount of pool area (Hunt, 1988). Increases in undercut bank cover and pool area were credited for large decreases in overwinter mortality.

Bustard and Narver (1975a) studied the winter ecology of juvenile coho and steelhead in Carnation Creek ($A = 10\ km^2$, $G = 2.4\ \%$), Vancouver Island, British Columbia. They found that feeding and other activities were reduced and that at low water temperature most fish were found within one meter of cover. Large woody debris and undercut banks were the most common types of cover used by age 0 coho and age 1+ coho and steelhead. Only undercut banks that had a dense complex of roots were used. Rubble was the primary source of cover for age 0+ steelhead. During the coldest temperatures few fish could be located in the open; they were only found under logs and undercut banks. These responses seem to be characteristic of juvenile salmonids (Chapman and Bjornn, 1969).

Bustard and Narver (1975b) tested the winter habitat preference of juvenile cutthroat and coho using constructed sidepools along Dick Creek ($A = 1.2\ km^2$), Vancouver Island, British Columbia. Coho showed a strong preference to sidepools with overhanging cover. Cutthroat used both overhanging bank and rubble cover equally.

Models predicting trout standing crop (Binns and Eiserman, 1979; Lloyd, 1986) have been developed which include a measure of undercut streambank as a predictor variable.

Physical Processes Relevant to Streambank Form

Despite the importance of streambanks on sediment supply, channel form, and flood-plain development, relatively few field or laboratory studies on bank processes have been undertaken (Knighton, 1984). In addition, most studies have focused on large low-gradient alluvial rivers which differ from steepland channels in many respects.

The three main processes in bank erosion are (Hooke, 1979; Knighton, 1984):

a) Hydraulic shearing of bank material-- Often the dominant erosive process. Loss of bank material is affected by shear stress distribution and local turbulence. Maximum values of velocity and shear stress are often in the lower bank area, even during a bankfull event.

b) Slumping and rotational slipping-- Usually a result of reduced internal resistance due to bank moisture or removal of the lower bank by hydraulic action. Changes in river stage, seepage, or piping may influence this process.

c) Frost action-- Most important in widening existing cracks and disaggregating material which may then be eroded by hydraulic action or slumping.

Factors influencing bank erosion are presented in Table 1. Although hydraulic action and bank moisture content provide the required conditions for bank erosion, amounts of bank erosion depend on more than magnitude of flows alone. It is not possible therefore to define erosional threshold flows. The principal factors affecting bank erosion at a site are composition of the bank material, asymmetry of flow, and channel geometry, all of which interact to some extent (Knighton, 1984).

Hydraulics

The potential energy of water that is available for doing work in a stream is a function of the mass of water in the stream and its position (elevation) within the drainage (Beschta and Platts, 1986). As the water moves down through the stream system, potential energy is converted to kinetic energy which becomes available for sediment transport, bank erosion, and channel scour. However, more than 95 percent of the kinetic energy of a stream is dissipated as heat as a result of turbulent flow (Morisawa, 1968).

Table 1. Factors influencing bank erosion.

Factor	Relevant characteristics
Flow properties	Magnitude, frequency and variability of stream discharge
Bank material composition	Size, gradation, cohesivity and stratification of bank sediments
Climate	Amount, intensity and duration of rainfall; frequency and duration of freezing
Subsurface conditions	Seepage forces, piping; soil moisture levels
Channel geometry	Width and depth of channel; height and angle of bank; bend curvature
Biology	Type, density and root systems of vegetation; animal burrows
Human-induced factors	Urbanization, land drainage, reservoir development, boating

From Knighton (1984).

Stream power is the rate of potential energy expenditure / unit length of channel (Knighton, 1984) and is the product of specific weight of water, discharge, and channel gradient. Narrowing of channel banks may cause acceleration of water, increasing the unit stream power of the flow. Increased bank resistance due to root systems, logs, boulders, and other large roughness elements along a channel tend to reduce stream power by dissipating energy as turbulence (Beschta and Platts, 1986). This concept of stream power is useful for understanding the erosive capability of water in open channels (Beschta and Platts, 1986).

Channel bank and bed processes respond to the varying magnitude and frequency of discharge, and the resulting spatial distribution of velocity and shear stress (Thorne and Lewin, 1979). Thorne and Lewin (1979), working in the River Severn ($A = 375\ km^2$, $G = 0.2\ \%$), Wales, discovered, through the use of bed load tracers, that relatively small floods of about one-half bankfull were able to scour banks at bend apices, while much larger floods were required to produce bank scour at inflection points.

Secondary currents are an important component in the spatial distribution of streambank erosion. Bathurst et al. (1979) identify two types of secondary currents. Stress induced currents result from streamwise vorticity (spiral flow about the primary axis) generated as a result of turbulent flow and are usually found in straight channels. Skew-induced currents result from flow through curved stream sections and are characterized by both a downstream velocity component and a transverse current component which combine to cause a spiral or helicoidal flow pattern (Knighton, 1984). Secondary currents distort the distribution of the isovels, changing the distribution of boundary shear stress.

Secondary velocities are usually an order of magnitude lower than primary velocities (Bathurst et al., 1979). The strength of secondary velocities in bends is influenced by Reynold's number (Knighton, 1984), position in the bend, radius of curvature-to-width ratios, width-to-depth ratios, and deflection of the arc angle of the bend, all of which vary with discharge. Bathurst et al. (1979) indicated that secondary velocities are relatively weakest (with respect to primary flows) at low and high discharges and relatively strongest at medium discharges.

There also exists in some bends a small cell of reverse rotation at the outer bank in addition to the main cell of secondary circulation (Thorne et al., 1985). The effect of these cells is to move high velocity water away from the bank at the water surface, reducing the velocity gradient and causing the maximum shear stress to occur below the water surface (Bathurst et al., 1979). These minimum shear stresses occur near the junction of the bed and bank.

Between bends the cell of secondary circulation decays and is replaced by one rotating in the opposite direction (Knighton, 1984). This process occurs as a new cell grows beneath the old one at the inflection point, resulting in divergent flow at the surface and convergent flow at the bed (Knighton, 1984).

Channels with wide shallow cross-sections may have relatively high capacity for bank erosion due to steep velocity profiles near the bed (Beschta and Platts, 1986). Riffles tend to be wider than pools due to bed-height increases, thus flows are directed towards the bank and can produce undercutting (Knighton, 1984).

Several researchers (Bagnold, 1960; Hickin, 1974; Hickin and Nanson, 1975; Begin, 1981) have investigated the relationship of radius of channel curvature (Rc) to channel width (W) in studies of river meanders. Bank erosion increases with decreasing Rc:W ratios, reaching a maximum value in the approximate range of 2 to 3, below which erosion decreases. Bagnold (1960) attributes the decrease in bank erosion rates in streams having Rc:W ratios less than 2 to flow separation along the convex inner bend resulting in local eddying and energy dissipation.

Bank material

Richards (1982) identifies several problems in modelling the effect of bank sediment on channel form. First, erodibility is a function of particle size and shape in non-cohesive grains, but is confounded by interparticle bonds in cohesive material. Second, sediment composition varies both longitudinally along a reach, and vertically within a bank, and can't be represented by a weighted average of properties. Third, resistance of bank material will vary depending on bank vegetation, moisture conditions, and the presence of any protective material (collapsed bank) along the bank. Finally, bank erosion occurs in two primary modes; loss of individual grains or aggregates, and sudden large-scale bank failures. Grain-by-grain erosion will occur quite frequently, whereas mass movements occur in response to many factors and with less frequency (Christian, 1988).

Banks having a high silt-clay content are more resistant to fluvial erosion than non-cohesive banks (Knighton, 1984). Schumm (1960) investigated the width-to-depth ratio of alluvial channels in relation to the sediment types of the channel and banks. Width-to-depth ratio was found to decrease with increasing percentage of silt and clay in channel banks, presumably due to its effect on cohesive strength. Richards (1982) indicates the primary control on cross-sectional channel shape is the nature of the perimeter sediments, although this relationship is not easily quantifiable.

Hickin and Nanson (1975) predict that the rate of lateral migration will decrease as bank height increases due to the greater amount of material that must be removed.

Thorne and Tovey (1981) however attribute bank failure in some composite banks (e.g. banks consisting of cohesionless material overlain by cohesive silt/clay) to hydraulic action in the lower bank leading to undercutting, and failure of the upper bank due to cantilever action.

The internal strength of a bank can be reduced due to wetting (Knighton, 1984) and the additional weight of saturated banks can increase the potential for failure (Christian, 1988). Positive pore water pressure can also reduce the grain to grain friction. In composite banks along the River Severn ($A = 375\ km^2$, $G = 0.2\ \%$), Wales, Thorne and Tovey (1981) reported that the soils were usually well-drained, and positive pore water pressures were small.

Thorne and Lewin (1979) classified banks as cohesive, non-cohesive, and composite. Composite banks are common for alluvial banks formed by a meandering river. Composite bank stability is controlled by the weakest material (Knighton, 1984).

Thorne and Lewin (1979) investigated bank processes associated with composite banks on the River Severn in Wales. Non-cohesive lower layers were typically 0.3 to 2 m thick. Cohesive upper layers were typically 0.5 to 1 m thick. The authors concluded that the size and stability of overhanging blocks depended on the thickness of the cohesive material and the engineering properties of the soil, and that fluvial processes were insignificant in comparison. Removal of the lateral earth pressure on the exposed surface, resulting in the development of cracks away from the edge of the channel, together with drying and desiccation at the surface, were presented as being among the critical factors in failure. Fluvial processes are important however in controlling the rate of bank retreat through removal of failed blocks and material along the base of the bank.

Thorne and Tovey (1981) give three principal mechanisms responsible for cantilever (overhang) failure as:

a) Shear failure, occurring when the weight of the overhang overcomes the shear strength of the soil.

b) Beam failure, occurring when the moment of the weight of the overhang around the neutral axis exceeds the resistive moments of the soil in tension and compression.

c) Tensile failure, occurring when the tensile stress of the overhang exceeds tensile strength of the soil.

Beam failures were the most common form of failure that they observed. Shear failures were only observed in sandy soils having low cohesive strength, or where vegetation was absent. Tensile failures were only observed where the thickness of the overhang exceeded 0.8 meters. Tensile failures left remnant root-bound blocks. Stability analysis, based on a static equilibrium approach, is restricted by the complex nature of flowing water and sediment, and the stochastic nature of stress peaks associated with river flow (Thorne and Lewin, 1979).

Uniqueness of headwater streams

Steepland channels differ from lowland channels in several ways (Lisle, 1987):

a) Steepland channels are high-gradient (> 1 %).

b) Steepland channels are often not self-formed due to confining valley walls, terraces, and bedrock control.

c) Hill slope processes may be of greater importance than fluvial processes in shaping channel features of steepland streams.

Steep valley walls commonly constrain the development of floodplains in headwater streams to narrow, discontinuous strips along the channel, or prevent their development entirely (Sullivan et al., 1987). Although both hillslope and channel processes affect channel shape, local obstructions are also a factor. The influence of an obstruction on local hydraulics generally increases as its length and width increases relative to channel width. Woody debris has a variable role with respect to bank protection. In some instances woody debris may protect banks from erosion, while in others it can divert flow into banks (Sullivan et al., 1987).

Lisle (1986), in a study in Jacoby Creek ($A = 36$ km^2, $G = 1$ %), Northwestern California, found that large streamside obstructions and bedrock bends tended to control the location and spacing of pools and gravel bars. Bars were found to develop one bed-width above an obstruction, and 3 to 4 bed-widths below. Obstructions wider than one-third the channel width tended to form pools that spanned the channel, while those that were less than one-third channel width formed scour-holes at the obstruction. Bank erosion generally occurred at the obstruction or in areas below where the channel widens. Streamside obstructions included large woody debris, rock outcrops, and rooted projections.

Influence of Vegetation

The influence of vegetation on channel form and processes has often been ignored in many studies because it is not easily quantifiable (Richards, 1982; Hickin 1984; Knighton, 1984; Thorne and Osman, in press) or easy to account for statistically (Richards, 1977; Hickin, 1984). Furthermore, vegetation controls are scale dependent; in very small streams the effect of vegetation may be overwhelming while in large rivers it may be less important (Hickin, 1984).

Vegetation complicates bank stability analysis by creating anisotropic bank material properties and random variations in properties (Thorne and Osman, in press). Vegetation may increase bank stability by reinforcing banks, or decrease stability through the added weight of trees. The presence of plants therefore makes it very difficult to create a deterministic model of bank stability (Thorne and Osman, in press).

Arguments over the role of riparian vegetation have traditionally evaluated the effects of vegetation versus no vegetation (Hickin, 1984). Variations in the influence of different quantities and qualities of vegetation have not been addressed.

Three important influences of vegetation on channel form and processes are increased flow resistance, increased bank strength, and changes in local hydraulics due to in-stream woody material (Hickin, 1984). Vegetation within the channel increases channel roughness and decreases the energy available to erode streambanks (Richards, 1977). Beschta and Platts (1986) noted that the fibrous root systems of grass are susceptible to being washed clean of soil particles. Vegetation with woody root systems however (combined with grass, forbs, etc.) create banks with more surface roughness and serve as a more resistant barrier to high velocities and turbulence. Furthermore, the long life span of many tree species means that individual trees may influence bank stability for long periods of time.

Channel width

Hickin (1984) stated that since vegetation increases sediment strength by root binding, and that critical tractive force theory implies that bank slope is a function of shear strength, we would reason that well-vegetated banks would have a low width-to-depth ratio. Most studies support this conclusion. Richards (1977) found that on the River Fowey, England, width-to-depth ratios were less than half of that predicted by Schumm's silt-clay relationship. The difference was attributed to the effect of vegetation on bank material cohesion.

Channel widths decreased as much as 50 percent over a 15-year period following a major disturbance (recurrence interval >= 100 years) along the middle fork of the Willamette River (A = 670 km^2), Oregon (Lyons and Beschta, 1983). A possible explanation for this trend is the regrowth of riparian vegetation.

Brice (1964) used channel width as a measure of streambank erodibility for a section of the Calamus River (A = 2,500 km^2, G = 0.1 %), Nebraska. The section was nearly uniform with respect to channel gradient and discharge. Low sinuosity indices (1.0 to 1.4) were associated with high and low bank erodibilities, and high sinuosity indices (1.4 to 2.1) were associated with intermediate erodibility. Differences in erodibility were attributed to streambank vegetation class (described only as "swamp vegetation").

Groeneveld and Griepentrog (1985) found that groundwater extraction along the Carmel River (A = 660 km^2) in California was responsible for decline of riparian tree vegetation and a 670 % increase in channel width in some areas.

Studies on the relative effects of tree-root strength versus grass-root strength on channel width yield varying results. Sullivan et al. (1987) indicated that channels are narrower in meadows with dense herbaceous vegetation as compared to channels running through forests where roots are less dense. Dense networks of grass roots may stabilize banks and form narrower channels than in stream sections flowing through forests where larger tree roots are less able to bind bank material (Richards, 1982).

Zimmerman et al. (1967), in a study of several headwater streams in northern Vermont ($A = 0.5$ to $2.1\ km^2$), noted that channel width did not increase in a downstream direction. They attributed this primarily to the effect of streamside vegetation. At points where drainage area was greater than 13 km^2 and annual flows exceeded 5.7 m^3s^{-1}, the effect of vegetation on channel shape was marginal. In one study stream ($A = 2.1\ km^2$) channels were clearly wider in forest and narrower in sod. Although smaller width-to-depth ratios in sod-lined banks supports the idea that sod adds more cohesive strength to the soil than trees, it is possible that these larger width-to-depth ratios are the result of greater above-ground disturbance (blow-down of streamside trees) in forested streams.

In contrast, Charlton et al. (1978) found that when channel width was plotted against bank-full discharge (log-

log plot) for gravel-bedded rivers in England, grass-lined banks averaged 30 percent wider and tree-lined banks 30 percent narrower than the best-fit line.

For a small (A = 4.72 km^2) stream in England, Murgatroyd and Ternan (1983) found that channel widths within a forested section were three times greater than predicted by drainage area-to-channel width relationships for non-forested reaches. Bank erosion in forested reaches was attributed to suppression by the forest of the thick sod layer and to in-channel log and debris jams. The authors attribute the differences between their observations and those of Charlton et al. (1978) to the influence of scale on bank processes: Charlton et al. were working in rivers 10 to 60 m wide. At that size, the influence of log jams and sod rooting on bank form appears to be less important.

Hey and Thorne (1986) developed equations for channel width as a function of discharge for 62 gravel-bed rivers in England, ranging in bankfull discharge from 4 to 420 m^3s^{-1}. Statistically significant equations were developed based on bank vegetation type; channels with grass-lined banks were found to be 1.8 times wider than tree-lined banks.

From the review of the literature it is unclear what the relative effect of grass vs. tree vegetation is on channel width. However, scale-effects may provide some explanation for the conflicting trends that have been observed.

Bank stability

Vegetation provides a mechanism for stabilizing eroded banks and maintaining channel stability (Beschta and Platts, 1986). Smith (1976), working in a glacial meltwater river in Alberta, showed that bank sediment having 16 to 18 percent root volume by weight with a 5-cm thick root mat, had 20,000 times more resistance to erosion than similar banks without roots.

Thorne and Tovey (1981) observed that grass roots near the surface formed mats that reinforced the tensile strength of the soil. They reported that cohesive strength decreased with depth, reaching a minimum at the base of the root zone (about 2.5 m) and remained fairly constant or increased slightly thereafter. Most tensile failures occurred at the base of the root zone.

Oliver and Hinkley (1987) have reported that undercut banks fail in areas with small amounts of deep roots, particularly tree roots, or where an undercut is below the root zone. Platts (1981), in a study on the effects of sheep grazing in riparian areas in Idaho, found that heavily-grazed sections had about one-third the amount of undercut streambank than lightly-grazed sections.

Swanson et al. (1984), in a study of small streams (average width = 4.5 m) on Prince of Wales Island, Southeast Alaska, reported that undercut streambanks provided 4.5 times more cover in forested channels than in channels within clear-cut areas. Possible reasons for reduction in undercut streambanks include mechanical crushing of streambanks during forest harvest operations and aggradation of stream channels. In the two forested reaches surveyed, 1.8 and 5.8 percent of the total channel area was covered by overhanging streambanks. They noted that streambank soils were reinforced by both woody and herbaceous vegetation.

Bohn (1989) concluded that riparian vegetation cover reduced soil temperature fluctuations and decreased the number of days soil temperatures fell below 0 degrees C along Gance Creek (elevation 2000 m), northeastern Nevada. Riparian vegetation cover appeared to reduce the number of freeze-thaw cycles along the streambank face, thus maintaining the strength of the streambank soil.

Studies dealing with the effect of vegetation on lateral migration of rivers have shown that root-bound banks have greater resistance to erosion than unvegetated banks (Hickin, 1984). In comparisons of reaches having similar discharge, channel slope, curvature, bank material, and bank height, a river flowing through unvegetated floodplains may erode at twice the rate as one flowing through naturally forested floodplains.

Loss of root strength

Ziemer (1981) studied the role of root stability, and loss of stability following harvesting, on forested slopes in the Klamath mountains in northern California. Roots reinforced soil by anchoring into bedrock and providing shear and tensile strength. Root strength decreased over time in cut roots and increased in new and existing live roots. The relative reinforcement provided by decaying cut roots, and existing live roots, was found to reach a minimum value approximately seven years after clear-cutting. However, the applicability of hillslope root studies to riparian vegetation is not known.

Although the importance of vegetation to bank stability has been well established, the question of root-strength loss after harvesting in riparian areas has not been adequately investigated (Sullivan et al., 1987).

Plant communities

Oliver and Hinckley (1987) indicated that the character of riparian forests depends on the frequency and magnitude of disturbance, the ability of a species to tolerate anaerobic or drought periods, local soil conditions, and the types of species available. The result is a vegetation mosaic consisting of patches of wetland species mixed with upland species. Riparian forests also tend to be sparse relative to upland forests, with many natural openings.

Hackley (1989) reported on the relationship of streambank stability (measured as a community-type stability index) to riparian area plant community type and grazing use in the Salmon River drainage, Idaho. Plant communities were identified using continuous bank transects. Stability index was defined as the length of stable banks by community type within a subreach. Bank stability categories included stable, depositional, or cut/slough. Although bank stability was significantly ($p < 0.01$) correlated with plant community type, the model accounted for only a small proportion of the variation in bank stability. Hackley suggested that plant community type is correlated to soil stability factors; xeric communities for example tend to be found on cohesionless sands, gravels, and cobbles which are very susceptible to erosion.

Platts and Nelson (1989) studied streambank characteristics (bank angle, undercut, and stream shore depth) and associated riparian vegetation in grazed and ungrazed pastures along Big Creek (mean annual discharge = $0.44\ m^3s^{-1}$) in Northeastern Utah. Their analysis suggested that, in the absence of grazing, similar riparian plant communities would be expected to promote similar physical streambank characteristics. Riparian vegetation in their study was composed primarily of sedges and gramanoids.

In summary, there are several points that can be gleaned from the literature, relevant to undercut streambanks: Undercut streambanks are important in providing protective cover for fish. Hydraulic processes that affect the distribution of shear stress affect bank erosion processes. Bank material composition affects the resistive strength of banks. In particular, percent silt/clay and heterogeneity (composite structure) affect bank strength. Headwater stream processes differ from lowland channels in that they are high-energy regimes, often affected by upland processes.

The role of vegetation in bank stability has not been adequately addressed. Results from studies on the effect of grass species and tree species on channel width are conflicting. Some studies conclude that channels are wider with grass-lined banks, other studies indicate channels are wider with tree-lined banks. It is clear, however, that riparian vegetation increases the resistive strength of streambanks. It is not clear how resistive strength changes over time with the loss of riparian vegetation.

HYPOTHESIZED MODEL OF UNDERCUT STREAMBANKS

Undercut streambanks are hypothesized to be the product of a differential application of erosional forces acting on the streambank and resistive forces offered by the streambank. A uniform application of erosional or resistive forces in a vertical plane may alter the rate of bank retreat, but not result in undercutting. A differential application of forces (Figure 1) is believed to be necessary for undercut streambanks to form and persist.

The erosional force exerted by the fluid on the bed and banks is the boundary shear stress. Average boundary shear stress can be estimated at a cross-section as:

$$\tau = \gamma R G$$

Where γ = the specific weight of water, R = the hydraulic radius, and G = channel gradient. The magnitude of boundary shear stress will increase as channel gradient and hydraulic radius (or channel depth) increases. Locally higher values of boundary shear stress may result from asymmetry of flow with respect to the streambank, caused primarily by channel curvature and local variations in the channel cross-section. Additional areas of locally higher boundary shear stress may include scour around in-stream obstructions.

The resistive strength of a streambank is believed to be a function of soil particle cohesion, weight of

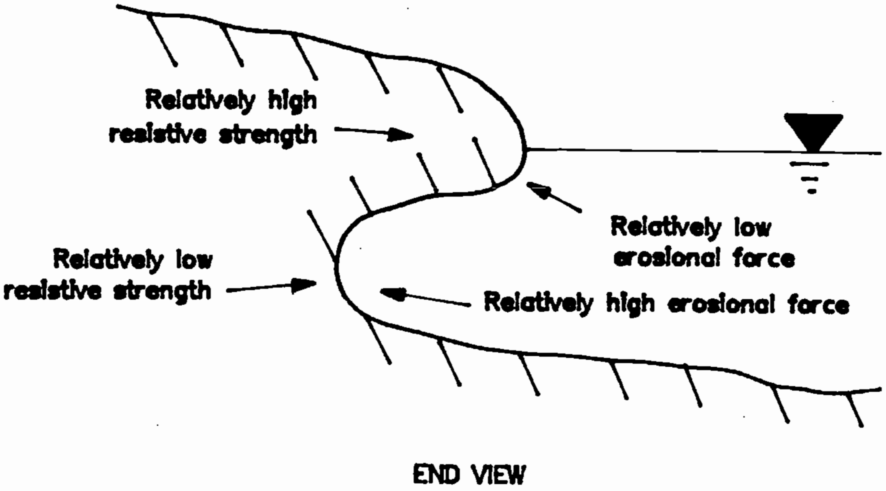


Figure 1. Hypothesized differential applications of bank resistive strength required for undercut formation / persistence.

particles relative to stream competence, and reinforcement by roots. Factors contributing to the relative differences in resistive strength may include composite bank structure and the rooting characteristics associated with streamside vegetation.

Bank height may also influences resistive strength of the streambank. Low banks may be more susceptible to disturbance from more frequent flood events than higher banks, resulting in a reduction in vegetation and the associated resistive strength of the roots. In low bank areas tree roots may penetrate the entire soil profile, providing uniform strength properties. High bank areas may be susceptible to failure due to the increased weight of the overhanging banks.

STUDY AREA

This study was conducted in eight study streams in the central Oregon Coast Range (Figure 2). All study reaches are located within undisturbed riparian areas on lands managed by the Siuslaw National Forest. The Rock Creek study reaches are within the Rock Creek Wilderness. The Cummins Creek study reaches are within the Cummins Creek Wilderness. The Flynn Creek study reaches are located within the Flynn Creek Research Natural Area. The Mill Creek study reaches are within the City of Toledo Watershed. The remaining study reaches are located within basins that have had some level of timber harvest in the past.

Climate

The climate of the Oregon Coast Range is characterized as having cool wet winters and warm dry summers. Climate is primarily controlled by marine air masses releasing precipitation as they move over the Coast Range (Schlicker et al., 1974). Approximately 200 to 300 cm of precipitation fall annually, 90 percent as rain (Corliss, 1973). Basin relief and geographic location affect variability in total amounts of precipitation; rainfall along the crest of the Coast Range may be twice that of areas along the coast or in the Willamette valley (Beschta,

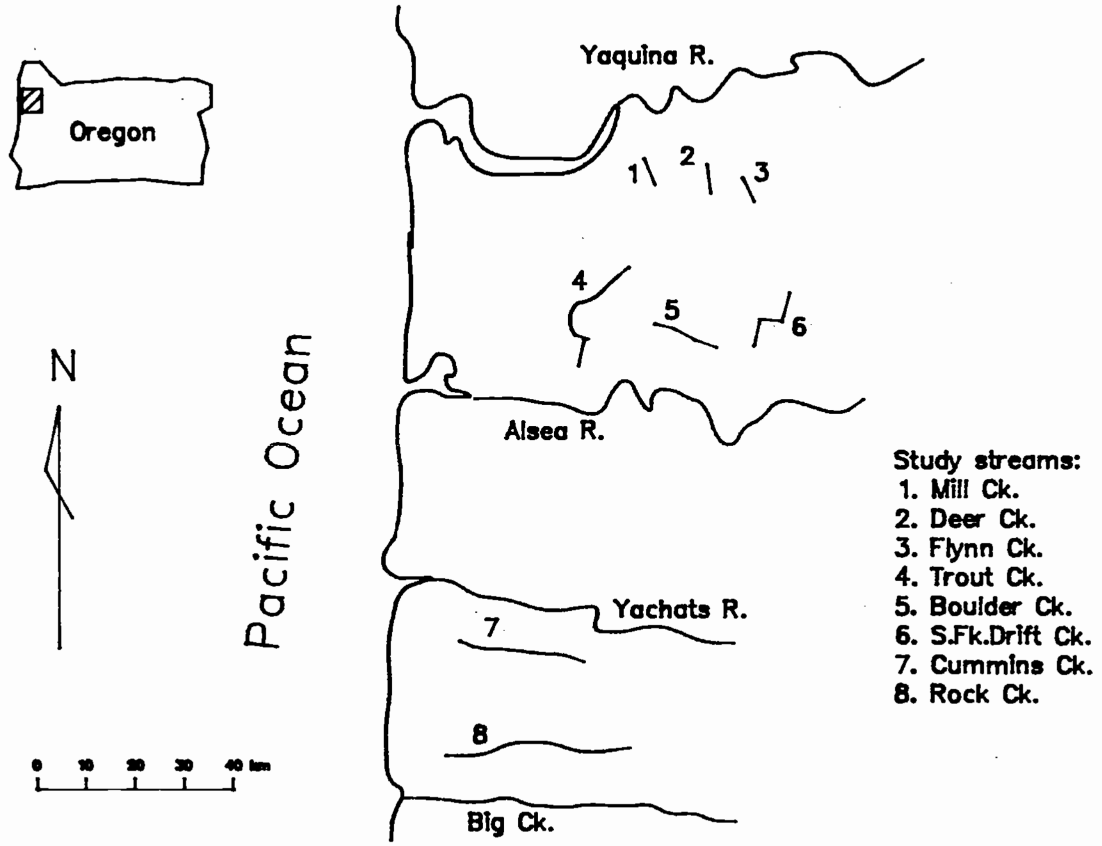


Figure 2. Location of study streams.

1989).

Mean daily temperatures at Newport are 6.8 degrees C for the month of January, and 14.3 degrees C for the month of August. Mean daily temperatures at Valsetz are 2.9 degrees C for January, and 16.2 degrees C for August (Corliss, 1973).

Geology

The Oregon Coast Range is bounded to the north by the Columbia River, to the south by the Klamath Mountains, to the east by the Willamette valley, and to the west by the Pacific Ocean. The general crestline of the range is about 460 m elevation. Mary's Peak, elevation 1,249 m, is the highest point in the range.

The geology of the Coast Range is dominated by older Cenozoic marine and estuarine sedimentary rock with areas of intrusive igneous rock (Baldwin, 1981). Rock and Cummins Creeks are located on Yachats basalt from the late Eocene epoch. Yachats basalt is made up of a heterogeneous assemblage of subaerial and submarine volcaniclastic rocks and flows, with occasional sandstone and siltstone interbeds (Schlicker et al., 1974). The area is characterized by a series of east-west linear canyons eroded by small streams, suggesting structural control (Schlicker et al., 1974).

The remaining study streams are located on rhythmically bedded micaceous and arkosic sandstone, and sandy siltstone of the Flournoy formation (Baldwin, 1981). Beds grade upward from medium-grained sandstone to fine-grained sandstone and siltstone (Baldwin, 1981). The area is intruded by dikes and sills of igneous material.

Soils

Soils in the Rock and Cummins Creek areas are of the Formader-Klickitat-Hembre complex, and the Neskowin-Salander complex (Patching, 1987). The soils are predominately well-drained loams, silt loams, and sandy loams derived from igneous parent material. Some streamside areas are classified as Fluvent units. Fluvent units are characterized as being low-gradient, consisting of highly-stratified sand, silt, and gravel, 100 to 150 cm or more in depth (Patching, 1987).

Soils in the remaining study areas are of the Bohannon-Slickrock association (Corliss, 1973). These soils are well-drained gravelly loams and gravelly clay loams, derived from sandstone parent material. Some streamside areas are classified as colluvial and alluvial land. Streamside areas are low-gradient, consisting of loamy alluvial and colluvial material that has moved from the side slope areas, and are generally 0.3 to 1.0 m deeper than soils of the surrounding slopes (Corliss, 1973).

Stream Segments

Frissell et al. (1986) presented a hierarchical stream classification system for categorizing similar stream habitats over a range of spatial scales. The major division is the stream system, consisting of an entire stream basin. The next finer level of resolution is the stream segment. Stream segments are typed according to slope, valley form, lithology, and soils (Frissell and Liss, 1986), and occur at a linear spatial scale on the order of 100's of meters. Different stream segment types will give rise to characteristic reach, pool/riffle, and microhabitat systems.

Stream segments within the study streams can be typed as bedrock canyons, colluvial canyons, alluviated canyons, and terrace-bound valleys (Frissell and Liss, 1986; Frissell, personal communication, Oregon State University, Corvallis, 1989). Characteristics of these stream segments are include in Appendix A.

Vegetation

Vegetational zones are based on the potential climax vegetation of a site (Franklin and Dyrness, 1987). The two major vegetational zones in the Oregon Coast Range are the Sitka spruce (*Picea sitchensis*) zone, and the western hemlock (*Tsuga heterophylla*) zone (Franklin and Dyrness, 1987). The Sitka spruce zone runs in a narrow band along the coast, extending inland only a few kilometers, except where it runs up river valleys. The western hemlock zone runs east from the boundary with the Sitka spruce zone.

Overstory tree species common to both zones include western hemlock, Douglas-fir (Pseudotsuga menziesii), grand fir (Abies grandis), western redcedar (Thuja plicata), red alder (Alnus rubra), and bigleaf maple (Acer macrophyllum). Sitka spruce is a common species in the Sitka spruce zone, but found only occasionally in the western hemlock zone. Riparian areas are dominated by red alder and, within the Sitka spruce zone, Sitka spruce.

Understory vegetation consists primarily of salmonberry (Rubus spectabilis), stink currant (Ribes bracteosum), Oregon-grape (Berberis aquifolium), devil's club (Oplopanax horridum), vine maple (Acer circinatum), red elderberry (Sambucus racemosa), and salal (Gaultheria shallon).

Disturbance plays an important role in the forests of the Oregon Coast Range. Much of the central Coast Range forests were destroyed by wildfires in the mid-1800's. Hence, most upland forest stands are less than 150 years old. Many riparian stands are considerably younger than adjacent upland stands due to disturbance associated with large magnitude flood events and mass soil failures. The largest peak flows on record occurred in 1965 in some streams in or near the study area (Deer Creek, Lyndon

Creek), and in 1972 in other streams (Needle Branch, Flynn Creek).

Fisheries

Sport fishing is a popular recreational activity in Coast Range streams. Common fish species found in headwater streams include steelhead (<u>Oncorhyncus gairdneri</u>), cutthroat trout (<u>O. clarki</u>), and coho salmon (<u>O. kisutch</u>).

METHODS

Sample Reach Selection

Forty-six sample reaches, each 152 meters (500 feet) in length, were evaluated. A 152 m reach length was chosen because it was felt that this was an adequate length of stream to capture representative reach characteristics. The total sample of reaches were selected to cover a range of channel gradients, drainage areas, and valley segment types. Individual reaches were selected to keep channel gradient and valley segment type constant within the reach. Reaches were also selected to avoid major tributary junctions (resulting in major changes in drainage area) within the reach. The procedure for selecting sample reaches was:

a) Locate sections of stream on topographic maps and aerial photographs that appeared to be homogeneous with respect to channel gradient and riparian vegetation, and which covered a range of drainage areas.

b) Walk through the stream sections and determine where the major changes in channel gradient, valley segment type, and riparian vegetation occurred.

c) Randomly locate a starting point for sample reaches, within a given stream section, using a random number table.

Field Procedures

Stream reaches were sampled in an upstream direction from the randomly-chosen starting point. Three types of information were collected:

a) Information collected continuously throughout the reach.

b) Information collected systematically at 15.3-m (50-ft) intervals.

c) Information collected at sites with undercut streambanks.

Sample reaches were surveyed during summertime low-flow conditions.

Measurements of Undercut Streambanks

For the purposes of this study undercut streambanks are defined as any portion of the bank where the ratio of the horizontal "depth" of undercut to vertical depth of undercut (Figure 3a) is greater than or equal to 0.5, and where the longitudinal length of the undercut (Figure 3b) is greater than 1.0 meter. Although somewhat arbitrary, this criterion was necessary to discriminate between a vertical streambank and an undercut streambank.

Characteristics of undercut streambanks that were measured include the following:

a) Length of undercut: Straight-line longitudinal

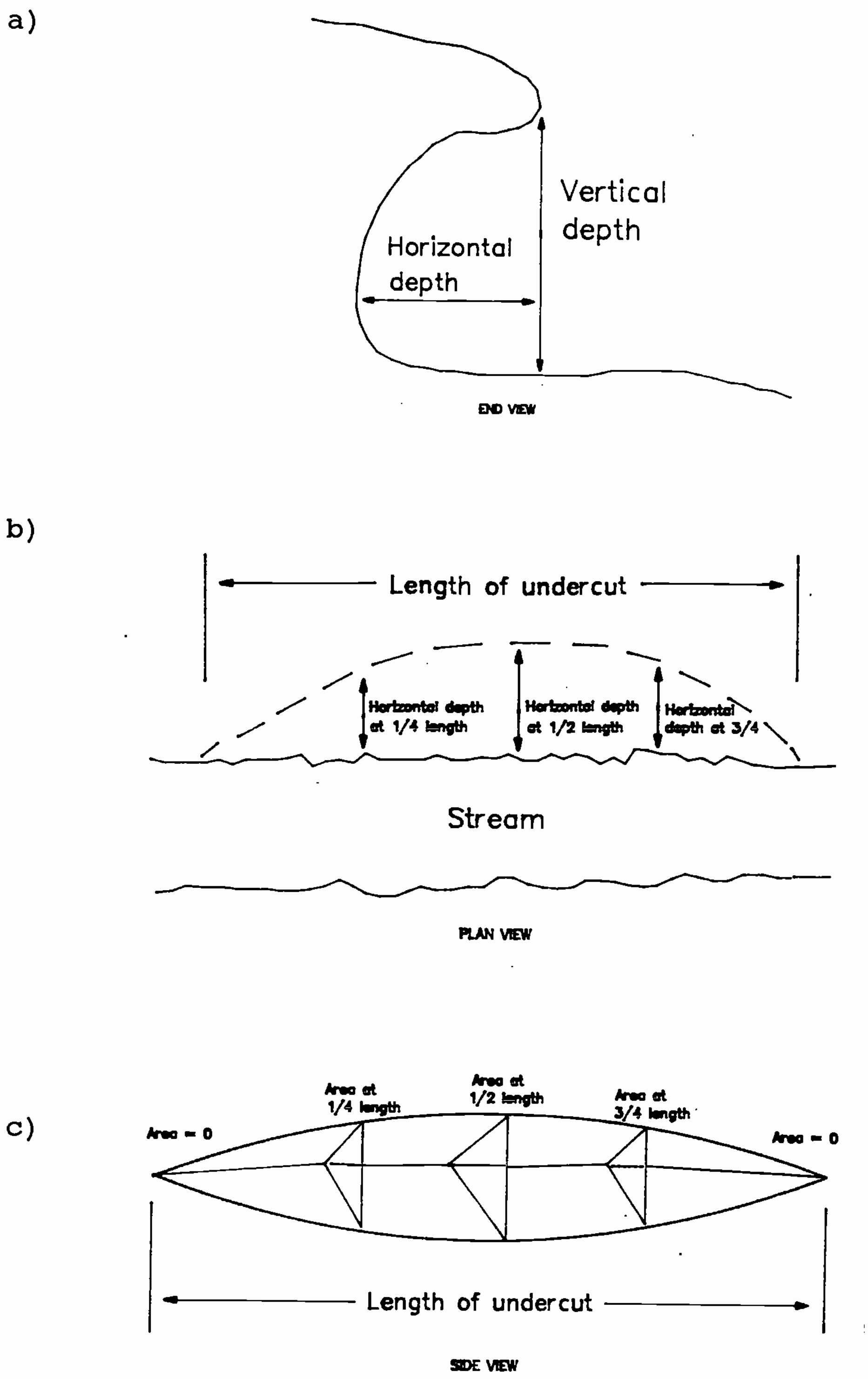


Figure 3. Definitions of undercut streambanks.

distance of each undercut.

b) Surface area under an overhanging bank: The horizontal "depth" of undercut was measured at 1/4, 1/2, and 3/4 of the longitudinal length (Figure 3b). The "surface area" under the overhanging bank was determined trigonometrically using these measurements.

c) Volume of undercut: The volume of each undercut was calculated trigonometrically using the horizontal and vertical depth measurements at 1/4, 1/2, and 3/4 of the longitudinal length, determining a cross-sectional area, averaging these areas, and multiplying by the length of the undercut (Figure 3c).

d) Maximum horizontal depth of undercut.

e) Volume of undercut usable at low flows: This measurement was used to index the amount of usable fish habitat under an overhanging bank at low (summertime) flows. The volume of each undercut that is occupied by water at low flows was determined by measuring the water surface height at the point of maximum horizontal undercut (Figure 4), determining the cross-sectional area occupied by water (if any), and multiplying by the length of undercut.

f) Channel habitat-type adjacent to undercut streambanks: Habitat-types include pools, riffles, and cascades (Bisson et al., 1982). This was used to illustrate the low-flow energy regime at undercut sites, and their potential suitability as fish

End view:

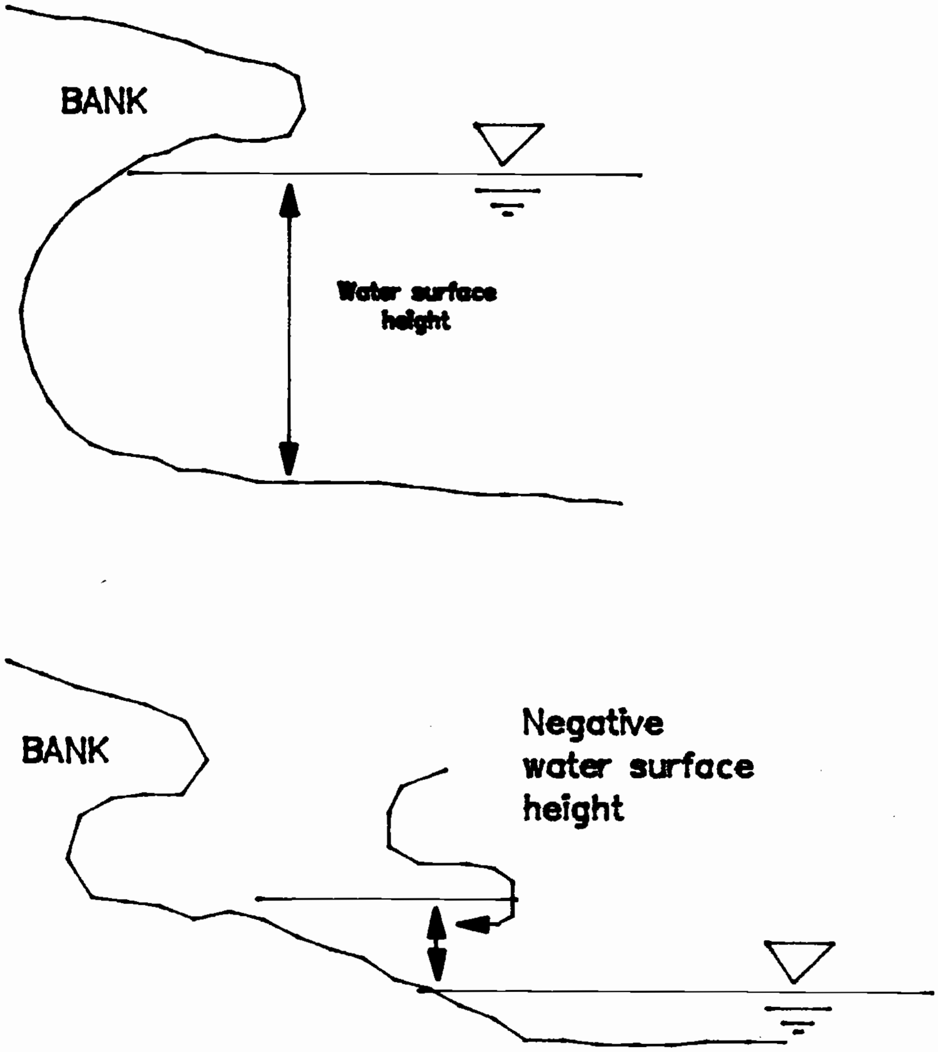


Figure 4. Definition of water surface height at undercut streambanks.

habitat.

Variables Characterizing Stream Reaches

Measured variables characterizing stream reaches included:

a) Valley segment type: The valley segment type (Bedrock canyon, colluvial canyon, alluviated canyon, terrace-bound valley) was determined for each reach.

b) Stream power index: The drainage area at the midpoint of each reach was determined from USGS quadrangle maps. Drainage area was used in computations of stream discharge associated with a two-year recurrence interval (Q_2). Q_2 is assumed to approximate bankfull flow (Leopold et al., 1964). Stream power index was computed as the product of Q_2 and channel gradient.

Harris et al. (1979) give equations for estimating Q_2 in the Oregon Coast region based on drainage area (A) in square miles, percent area of lakes and ponds (ST), and precipitation intensity (I) in inches. Area of lakes and ponds was zero for all study streams, therefore the equation reduces to:

$$Q_2 = 4.59\ (A)^{0.96}\ (I)^{1.91} \qquad (\%\ S.E. = 33)$$

Precipitation intensity was determined from isopluvial maps (Harris et al., 1979).

c) Channel gradient: The average channel gradient for each reach was determined by measuring the percent slope from riffle-crest to riffle-crest along the length of the reach.

d) Channel sinuosity: Knighton (1984) defines a sinuosity index as:

$$S = \frac{\text{segment length along channel centerline}}{\text{straight-line distance between endpoints}}$$

The sinuosity index is assumed to be correlated with higher bank shear stress in outside bends.

e) Bank height: The vertical thickness of the bank material for the two primary bank material types (if more than one type was present), was determined for both banks, at 15.3-m intervals, and at each undercut site along the reach. The bottom and top of the bank was defined as those two points which have a prominent change in slope when viewed in end view (Figure 5). Locations where the bank height was equal to the valley-wall height were arbitrarily assigned a bank height of 30 m.

After beginning the field work it was decided to also measure bankfull height, consequently only 29 sample reaches have measurements of bankfull height. Bankfull height was measured as the vertical distance from the bottom of the bank to the lower limit of perennial vegetation (Williams, 1978).

End view:

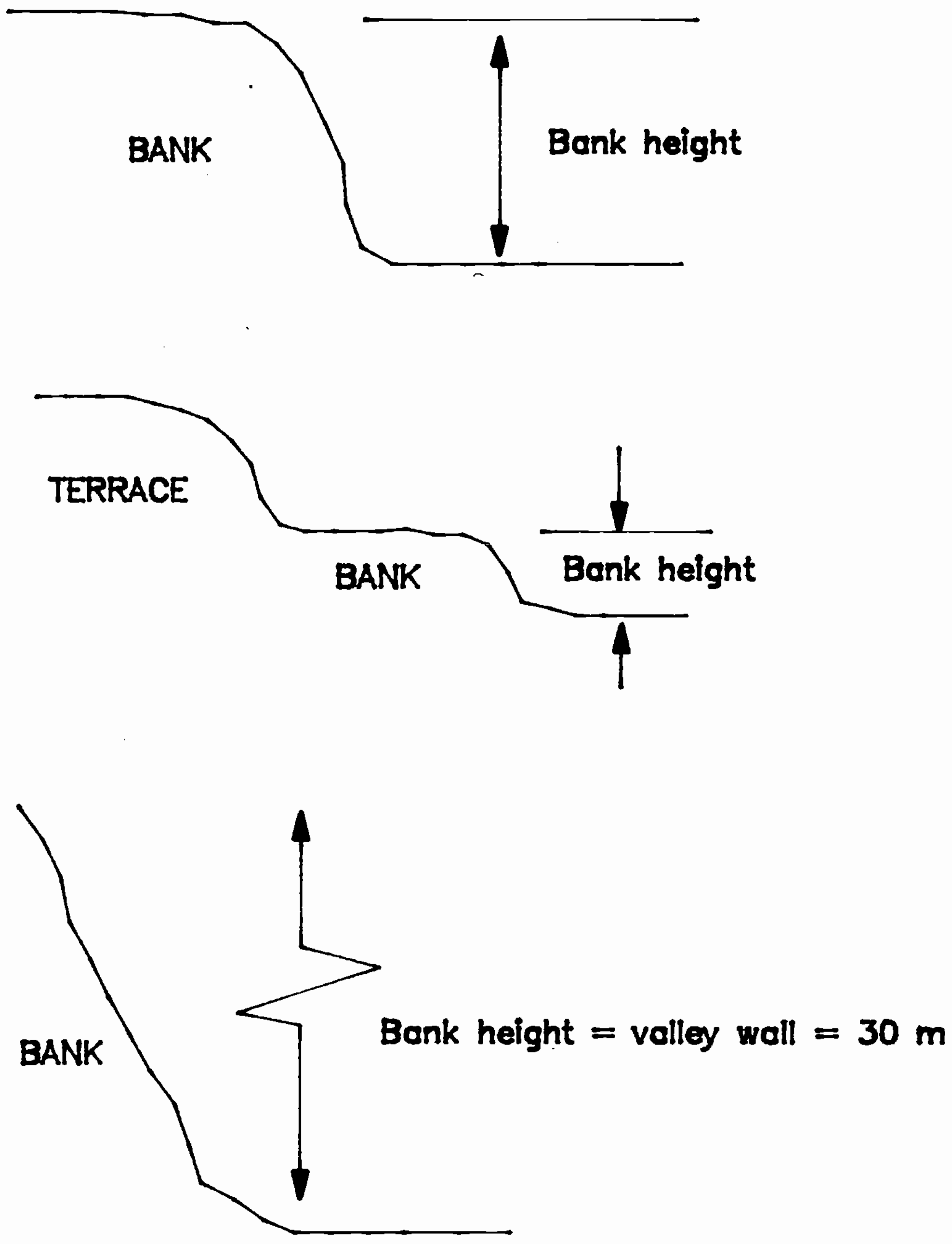


Figure 5. Definition of bank height.

f) Bank material type: The primary bank material composition (clay, loam, sand, gravel, rubble, boulder, bedrock, woody debris) was determined for the two main layers (if more than one layer was present) of each bank at 15.3-m intervals, and at undercut sites along the sample reach.

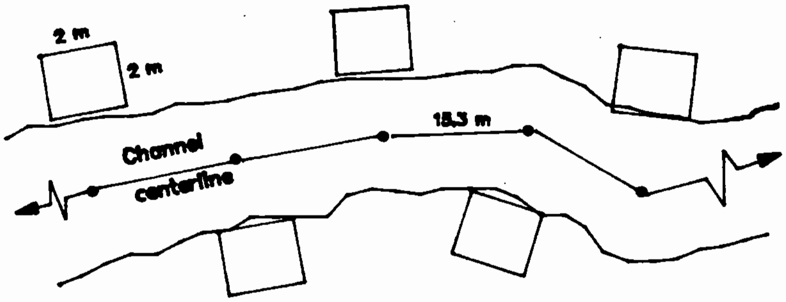
g) Channel curvature: Each undercut site was classified as being located along an outside bend, inside bend or straight section of channel. Information on curvature was also recorded at 15.3-m intervals throughout the reach. Boundary shear stress is expected to be greater at the outside of bends.

h) Bankfull width: Bankfull width was determined at 15.3-m intervals along each reach and at the point of maximum horizontal depth at undercut sites.

i) Shrub density: Species and percent cover was estimated for the two main shrub species on a 2-m x 2-m plot on alternating sides of the channel at 15.3-m intervals along the reach (Figure 6a). This information was also collected at a 2-m x 2-m plot located at the point of maximum undercut at each undercut site (Figure 6b).

j) Tree density: Tree density for each sample reach was determined by measuring the species, diameter, and distance from plot center of trees within a 6-m (19.7-ft) radius plot whose plot center was located at the edge of the channel on alternating sides of the

a) Plan view:



b) Plan view:

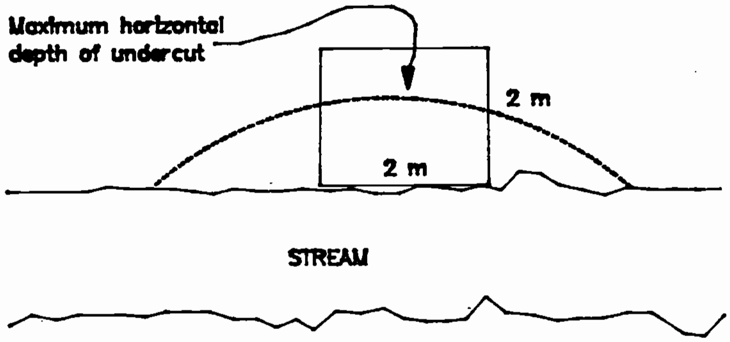


Figure 6. Definition of shrub sample plots.

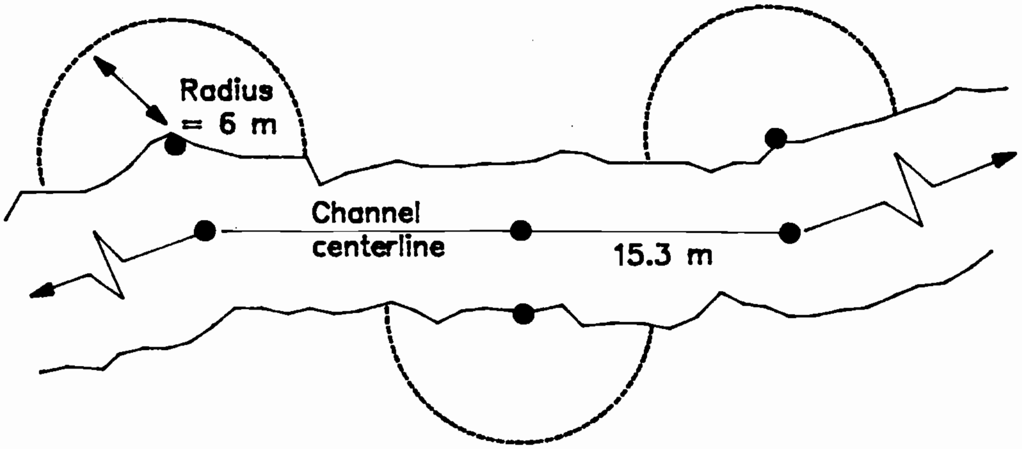
channel at 15.3-m intervals (Figure 7a). The rationale for choosing a 6-m radius was that Smith (1964) suggested that the ratio of root-spread to crown width for forest-grown trees in the Pacific northwest ranged from 0.6 for red alder to 0.9 for Douglas-fir. Sample trees had crown-widths averaging approximately 8 to 10 m.

The area of each plot was determined from the channel sinuosity maps (Figure 7b). Basal area / hectare was calculated at each plot and averaged for the reach.

Basal area / hectare was also determined at undercut sites, using the edge of the streambank at the point of maximum horizontal depth of undercut as the plot center.

k) Obstructions: At each undercut site the presence, position, and possible influence of any obstructions (gravel bars, boulders, LWD) relative to the undercut streambank was recorded.

a) Plan view:



b) Plan view:

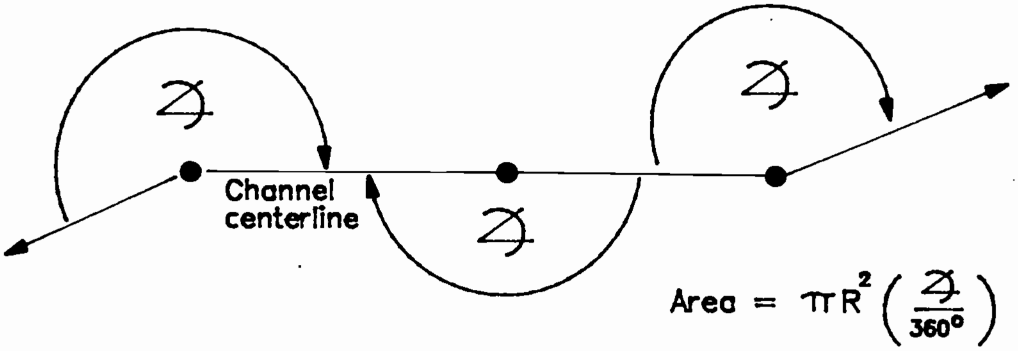


Figure 7. Definition of tree sample plots.

RESULTS AND DISCUSSION

Distribution of Undercut Streambanks

Undercut streambank characteristics

Undercut streambanks are summarized by at-a-site values and reach totals. A total of 175 individual undercuts were evaluated in 46 reaches. Physical and vegetative characteristics of sample reaches are summarized in Table 2. Undercut characteristics for sample reaches are summarized in Table 3; average at-a-site values are summarized in table 4. It should be noted that the length of undercut / 100 m represents both streambanks. Reach area is defined as the product of reach length along the channel centerline and average reach width. Complete summaries of at-a-site and reach undercut characteristics are included in Appendix B.

One-third of all undercuts had less than one percent of their volume usable at low flows (Figure 8).

Comparison with other studies

Few studies exist that focus primarily on the characteristics of undercut streambanks in undisturbed streams. The information that does exist was usually collected as part of studies of forest harvesting effects on riparian habitat (e.g. Koski et al., 1984; Swanson et al., 1984), fish population studies (e.g. Lewis, 1969), or

Table 2. Physical and vegetative characteristics of sample reaches.

Reach	Average bankfull width (m)	Sin-uos-ity indx	Val. seg. type	Channel gradient (%)	Drain-age area (km^2)	Tree basal area/ha (m^2/ha)	Shrub cover (%)
MILL 1	5.2	1.14	ALC	2	4.0	6	17
MILL 2	4.0	1.04	CLC	4	3.1	10	32
MILL 3	3.6	1.03	CLC	5	2.9	8	75
MILL 4	3.0	1.06	CLC	5	1.0	0	87
DEER 1	4.1	1.14	ALC	2	3.2	1	62
DEER 2	3.9	1.01	CLC	8	3.1	6	74
DEER 3	4.5	1.31	TBV	1	2.6	37	18
DEER 4	3.7	1.49	TBV	1	2.3	49	15
DEER 5	4.5	1.20	TBV	1	2.3	59	18
DEER 6	3.9	1.16	TBV	2	1.3	8	50
FLYNN 1	1.7	1.19	ALC	4	0.3	23	65
FLYNN 2	2.8	1.39	ALC	2	1.2	6	55
FLYNN 3	3.4	1.09	CLC	5	1.6	55	30
FLYNN 4	4.7	1.16	TBV	1	3.8	21	117
TROUT 1	9.1	1.05	CLC	2	16.6	8	48
TROUT 2	6.7	1.04	BRC	3	12.1	5	32
TROUT 3	8.6	1.15	ALC	1	11.7	1	29
TROUT 4	8.0	1.12	CLC	2	10.9	22	49
TROUT 5	6.7	1.10	CLC	2	8.8	9	59
TROUT 6	6.1	1.10	CLC	2	4.0	10	40
TROUT 7	3.3	1.18	ALC	4	1.8	0	94
BOULDER 1	6.1	1.16	CLC	4	3.6	30	86
BOULDER 2	6.6	1.04	BRC	5	6.1	0	87
BOULDER 3	7.6	1.03	CLC	3	8.5	30	46
BOULDER 4	9.5	1.01	BRC	4	10.2	14	60
BOULDER 5	8.8	1.01	ALC	3	10.6	28	28
S.FORK 1	7.0	1.11	ALC	4	7.4	29	25
S.FORK 2	6.1	1.07	CLC	4	3.5	5	27
S.FORK 3	4.3	1.11	ALC	5	1.4	16	54
S.FORK 4	3.3	1.04	CLC	11	0.5	3	22
CUMMINS 1	6.4	1.08	ALC	3	4.7	17	53
CUMMINS 2	8.4	1.13	ALC	2	10.1	26	14
CUMMINS 3	7.3	1.13	ALC	2	13.9	20	0
CUMMINS 4	7.4	1.26	ALC	3	8.8	83	18
CUMMINS 5	9.9	1.06	ALC	3	11.2	51	5
CUMMINS 6	9.4	1.04	ALC	2	15.8	23	5
CUMMINS 7	10.1	1.03	ALC	2	14.7	14	9
CUMMINS 8	10.4	1.09	ALC	2	12.2	73	7
ROCK 1	7.9	1.07	ALC	3	14.1	31	14
ROCK 2	8.7	1.03	CLC	3	12.2	45	13
ROCK 3	8.2	1.02	ALC	4	8.8	103	5
ROCK 4	6.8	1.06	CLC	4	6.1	21	19
ROCK 5	6.0	1.08	BRC	8	4.5	11	52
ROCK 6	5.5	1.04	CLC	5	3.3	25	14
ROCK 7	5.1	1.14	CLC	9	1.8	5	37
ROCK 8	3.6	1.17	BRC	21	0.8	3	42

BRC = bedrock canyon
CLC = colluvial canyon
ALC = alluvial canyon
TBV = terrace-bound valley

Table 3. Summary of reach-level undercut characteristics (n = 46 sample reaches).

Characteristic	Mean	Minimum	Maximum	Standard deviation
Undercut banks (# / 100 m)	2.5	0.0	7.9	2.1
Length undercut (m / 100 m)	12.4	0.0	47.2	12.7
Area undercut (m^2 / 100 m)	6.5	0.0	27.4	7.3
Reach area undercut (%)	1.1	0.0	4.5	1.2
Volume undercut (m^3 / 100 m)	1.8	0.0	6.5	2.1
Low-flow usable volume undercut (m^3 / 100 m)	0.5	0.0	3.3	0.7
Low-flow usable volume undercut (% of total vol.)	13.5	0.0	57.4	15.3
Maximum horizontal depth undercut (m / 100 m)	1.2	0.0	4.6	1.1

Table 4. Summary of at-a-site undercut characteristics (n = 175 undercuts).

Characteristic	Mean	Minimum	Maximum	Standard deviation
Length of undercut (m)	5.0	1.2	15.2	3.2
Area of undercut (m^2)	2.6	0.3	27.7	3.1
Volume of undercut (m^3)	0.7	0.1	6.4	1.1
Low-flow usable volume of undercut (m^3)	0.1	0.1	1.5	0.2
Low-flow usable volume of undercut (% of total vol.)	20.4	0.1	100.0	26.1
Maximum horizontal depth of undercut (m)	0.9	0.2	4.6	0.6

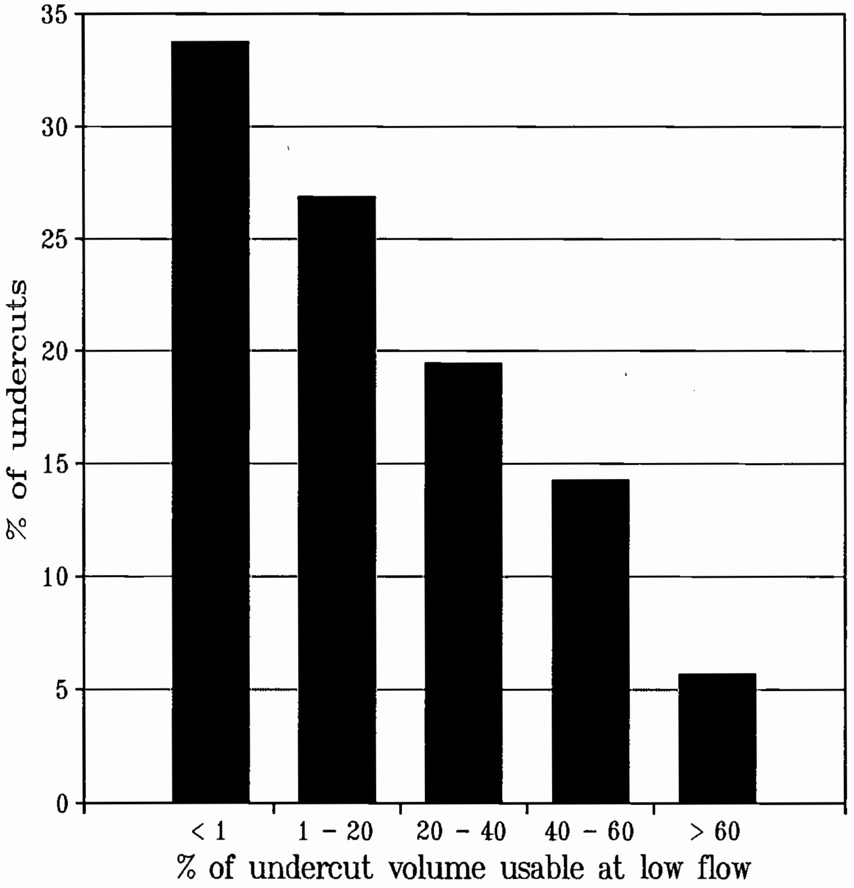


Figure 8. Frequency distribution of undercut volumes usable at low (summertime) flows.

population response to habitat manipulation (e.g. Boussu, 1954; Hunt, 1969), and may not represent an unbiased sample of conditions in those systems.

Results are usually expressed as percent length of bank undercut, area undercut, or percent reach area undercut. The characteristics from this study as well as several studies in southeast Alaska, western Montana, and Wisconsin are summarized in Table 5. Only Hunt (1969) expressed undercut streambanks as a percent of length undercut. The average percent of length undercut for reaches in this study were approximately the same as in the reaches studied by Hunt.

Average area undercut / 100 m was approximately the same for this study and the studies from Montana, Wisconsin, and one of the clear-cut reaches in southeast Alaska. The remaining studies averaged more area undercut / 100 m than this study. However, the range of area undercut / 100 m for this study exceeded all other studies reported here.

Average values for percent reach area undercut for this study are either the same or lower than is indicated for all other studies except for one set of clear-cut conifer reaches in southeast Alaska.

Comparison with large woody debris cover

Comparisons between values of undercut streambank cover determined in this study and values of large woody

Table 5. Comparison with undercut characteristics from other studies.

Location / riparian vegetation	Length of channel (m)	Number of reaches sampled		Drain-age area (km^2)	Channel width (m)	Channel gradient (%)	Length UC (%)	Area UC (m^2/ 100m)	Reach area UC (%)
THIS STUDY									
(1) Oregon Coast Range Red alder/Sitka spruce	6995	46	AVG	6.4	6.1	3.9	6.2	6.5	1.1
			MIN	0.3	1.7	1.0	0.0	0.0	0.0
			MAX	16.6	10.4	21.0	23.6	27.4	4.5
			STD	4.8	2.3	3.4	6.3	7.3	1.2
OTHER STUDIES									
(2) Southeast Alaska Old-growth conifer	540	18	AVG	-	6.5	1.5	-	23.7	3.6
(2) Southeast Alaska Clear-cut conifer	540	18	AVG	-	5.6	1.3	-	10.0	1.8
(2) Southeast Alaska Clear-cut with buffer	540	18	AVG	-	7.8	1.4	-	17.3	2.2
(3) Southeast Alaska Old-growth conifer	400	2	AVG	< 5	4.5	5.0	-	16.5	3.8
			MIN	< 5	4.2	3.0	-	8.6	1.8
			MAX	< 5	4.8	7.0	-	24.4	5.8
			STD	-	0.4	2.8	-	11.1	2.8
(3) Southeast Alaska Clear-cut conifer	370	2	AVG	< 5	4.1	5.5	-	4.6	0.9
			MIN	< 5	1.7	4.0	-	0.7	0.4
			MAX	< 5	6.5	7.0	-	8.5	1.3
			STD	-	3.4	2.1	-	5.5	0.6
(4) Western Montana Open conifer/grassland	190	19	AVG	700.0	8.0	0.6	-	4.7	2.2
			MIN	-	-	-	-	0.0	0.0
			MAX	-	-	-	-	22.6	5.7
			STD	-	-	-	-	5.8	1.5
(5) Western Montana Sedge/grass/willow	217	13	AVG	1.8	3.2	0.4	-	5.6	2.7
			MIN	-	1.2	-	-	0.0	0.0
			MAX	-	5.6	-	-	13.4	11.6
			STD	-	1.4	-	-	4.9	3.3
(6) Wisconsin Grass/alder/oak	3096	2	AVG	16.6	7.2	0.2	5.5	-	-
			MIN	-	7.0	-	5.0	-	-
			MAX	-	7.3	-	6.0	-	-
			STD	-	0.2	-	0.7	-	-

(1) This study
(2) Koski et al., 1984.
(3) Swanson et al., 1984.
(4) Lewis, 1969. Only pools were sampled
(5) Boussu, 1954.
(6) Hunt, 1969.

debris (LWD) cover reported in other studies are complicated by the small sample size of some studies (e.g. Swanson et al., 1984), or possible inaccuracies in converting volume estimates of LWD reported in other studies (e.g. Robison, 1988; Veldhuisen, 1990) to area estimates.

Area of cover and percent channel area cover provided by undercut streambanks in this study, and by LWD from other studies, are summarized in Table 6. Maximum and average values for both area of cover and percent channel area cover provided by undercut streambanks is exceeded in all cases by LWD cover. Veldhuisen's (1990) results are from many of the same streams investigated in this study. Comparisons between these two studies show that, while average and maximum values for area of cover and percent channel area covered are approximately double for LWD, they are still on the same order of magnitude. High values for LWD cover in reaches flowing through clear-cut areas in southeast Alaska result primarily from logging slash (Swanson et al., 1984).

Characteristics Associated With Undercut Streambanks

Channel curvature

Six times more undercut banks were found on outside channel bends than on inside bends or straight sections (Figure 9). Undercut characteristics followed the same

Table 6. Comparison of cover provided by undercut streambanks to cover provided by large woody debris.

Location / riparian vegetation	Length of channel (m)	Number of reaches sampled		Drainage area (km^2)	Channel Gradient (%)	Area of cover (m^2/ 100m)	Bankfull channel area covered (%)
THIS STUDY							
(1) Oregon Coast Range Red alder/Sitka spruce	6995	46	AVG	6.4	3.9	6.5	1.1
			MIN	0.3	1.0	0.0	0.0
			MAX	16.6	21.0	27.4	4.5
			STD	4.8	3.4	7.3	1.2
**							
LWD STUDIES							
(2) Oregon Coast Range Red alder/Sitka spruce	56550	25	AVG	45.4	1.9	16.4	2.2
			MIN	0.5	0.2	3.3	0.1
			MAX	170.0	8.9	46.3	9.0
			STD	55	2.1	11.0	2.3
(3) Southeast Alaska Spruce/hemlock/alder	3575	5	AVG	14.8	1.7	60.3	4.8
			MIN	0.7	0.8	15.6	3.4
			MAX	55.4	2.5	156.0	6.0
			STD	23.1	0.7	56.8	1.2
(4) Southeast Alaska Spruce/hemlock	400	2	AVG	< 5	5.0	32.1	6.9
			MIN	< 5	3.0	11.3	2.7
			MAX	< 5	7.0	52.8	11.0
			STD	-	2.8	29.3	2.9
(4) Southeast Alaska Clearcut	370	2	AVG	< 5	5.5	51.4	13.5
			MIN	< 5	4.0	24.8	12.0
			MAX	< 5	7.0	78.0	15.0
			STD	-	2.1	37.7	2.1

(1) This study
(2) Veldhuisen, 1990.
(3) Robison, 1988.
(4) Swanson et al., 1984.

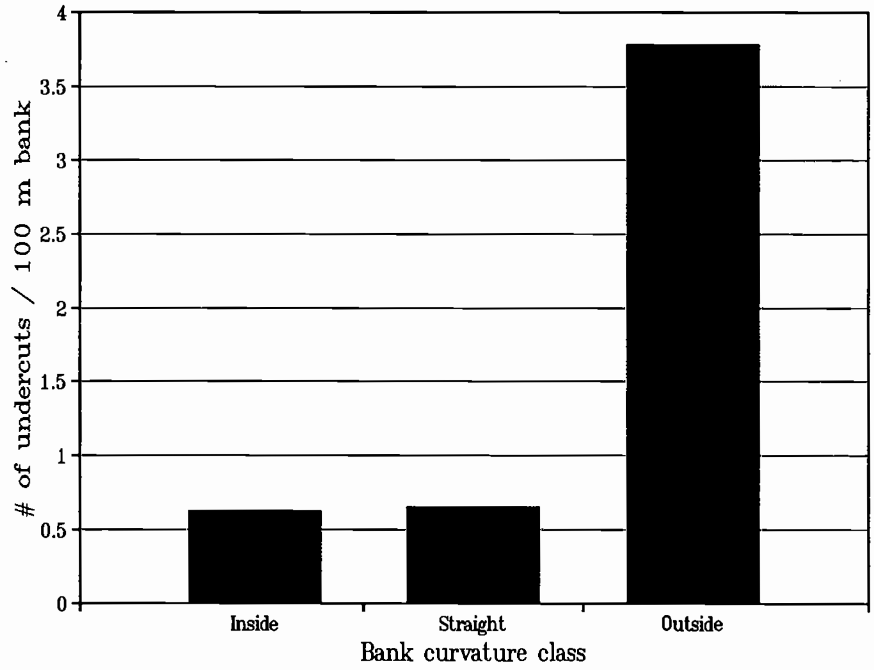


Figure 9. Number of undercuts / 100 m of stream, by curvature class.

trend (Table 7); numbers were normalized by total length of bank in each class. The prevalence of undercut banks on the outside bends may be a result of relatively high boundary shear stresses.

Channel sinuosity

Percent reach length undercut and percent reach surface area undercut were both significantly[1] higher in reaches having a sinuosity index greater than 1.15 (Figures 10a and 10b).

Reach-level analysis reveals that all undercut characteristics, with the exception of volume and usable volume undercut, are significantly and positively correlated with sinuosity index (Table 8). Coefficients of determination (i.e. r^2) ranged as high as 0.40, for the percent of reach area undercut, suggesting a relatively good relation with sinuosity index. Figure 11 is a plot of the percent of reach area undercut vs. sinuosity index.

Results from the at-a-site analysis (Table 8) show no relationship between individual undercut characteristics and reach sinuosity index.

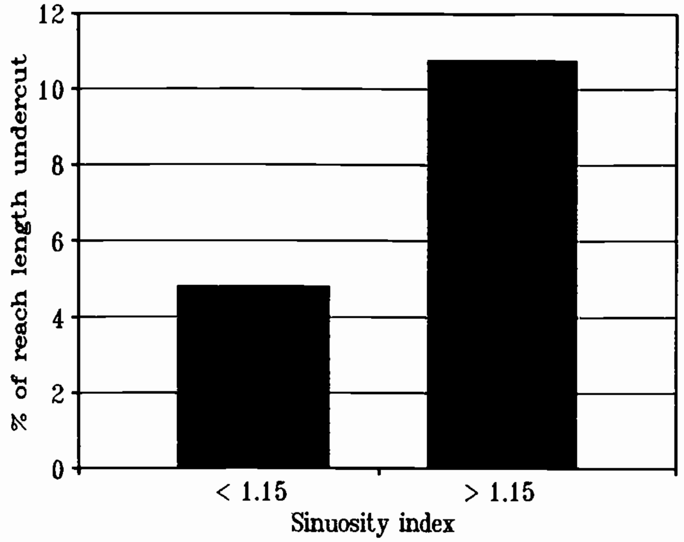
Several processes are associated with sinuous streams that may affect undercut streambank characteristics. Sinuous streams tend to be low-gradient systems. Overbank

[1] Significance was determined at the alpha ≤ 0.05 level throughout this study.

Table 7. Comparisons of characteristics at outside banks vs. inside banks and straight sections.

Characteristic	Number of times greater on outside vs. inside banks	Number of times greater on outside vs. straight banks
Number of undercuts	6	6
Area of undercut	12	9
Length of undercut	9	7
Volume of undercut	14	9
Low-flow usable volume of undercut	11	7

a)



b)

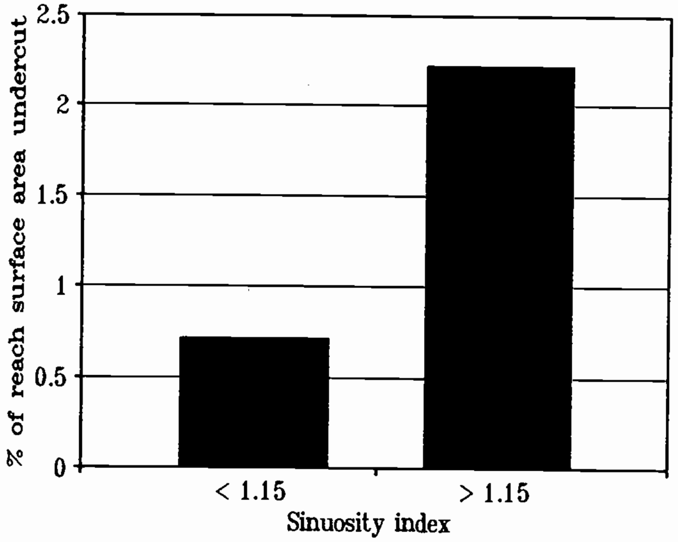


Figure 10. a) Average percent of reach length undercut and b) average percent of reach surface area undercut, by sinuosity class.

Table 8. Regression analysis of undercut characteristics on channel sinuosity index.

	Regression analysis		
Dependent variable	r^2	p-level	Slope
REACH ANALYSIS:			
Number of undercuts (#/100m)	0.27	0.000	positive
Length undercut (m)	0.23	0.001	positive
Area undercut (m^2)	0.11	0.027	positive
Reach area undercut (%)	0.40	0.000	positive
Volume undercut (m^3)	0.01	0.520	positive
Low-flow usable volume undercut (m^3)	0.08	0.065	positive
Low-flow usable volume undercut (% of total vol.)	0.14	0.012	positive
Maximum horizontal (m) depth undercut	0.13	0.014	positive
AT-A-SITE ANALYSIS:			
Length of undercut (m)	0.01	0.310	positive
Area of undercut (m^2)	0.00	0.590	negative
Volume of undercut (m^3)	0.03	0.036	negative
Low-flow usable volume of undercut (m^3)	0.00	0.970	negative
Low-flow usable volume of undercut (% of total vol.)	0.05	0.003	positive
Maximum horizontal depth of undercut (m)	0.00	0.980	positive

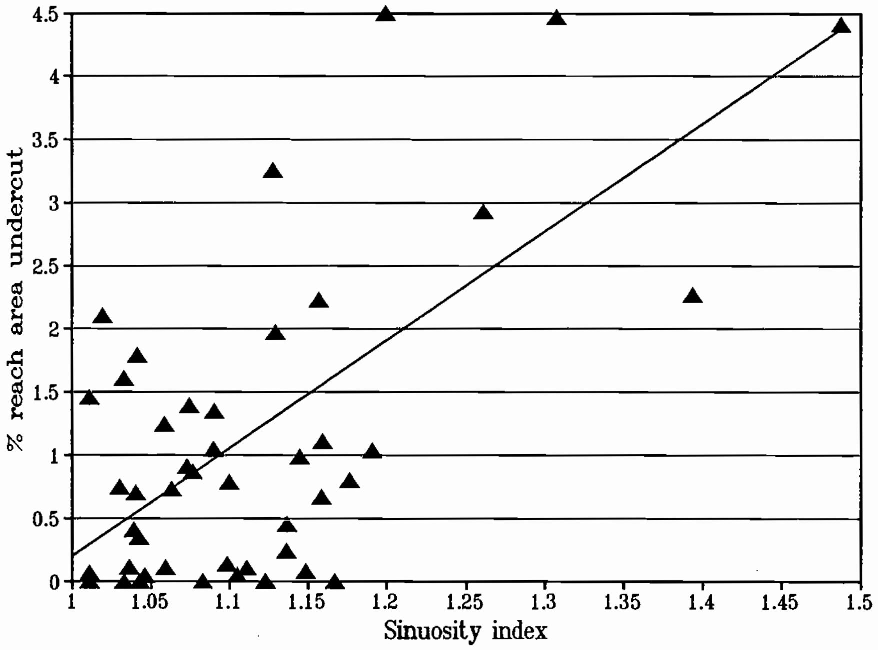


Figure 11. Plot of percent reach area undercut on reach sinuosity index.

flows will tend to be relatively lower energy, resulting in less disturbance of riparian vegetation. Bank material in sinuous streams is often fine-grained cohesive silts and clays. Sinuous streams have a lower radius of channel curvature, resulting in more opportunities for shear stress to be directed at the bank.

Habitat type (Bisson et al., 1982) was recorded at all undercut sites and at systematic intervals throughout sample reaches. The distribution of habitat-types by channel curvature class for the 46 study reaches is given in Table 9. Numbers were normalized by the total length of stream sampled in each curvature class. Sixty-two percent of all riffles and 72 percent of all pools occurred in straight channel sections in reaches having a sinuosity index less than 1.15. The distribution of habitat-types by curvature class changes in streams having a sinuosity index greater than 1.15. Riffles occurred equally in straight and curved sections. However, approximately 2/3 of all pools occurred in curved sections in relatively sinuous streams.

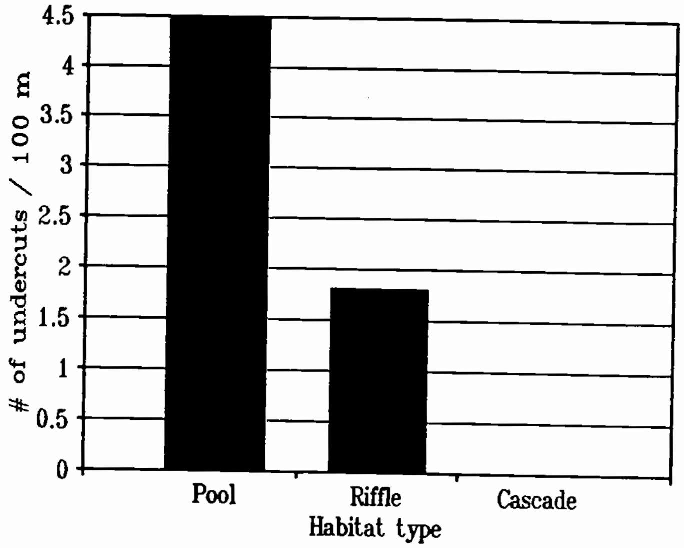
No undercuts were found in the cascade habitat type. The number of undercuts and area undercut associated with pools are more than double those in riffles (Figures 12a and 12b). The greater number of undercuts found in pool areas may be due to the higher percentage of pools found on channel bends in relatively sinuous reaches and the associated hydraulic conditions favorable to undercutting

Table 9. Distribution of habitat-types by channel curvature class.

	REACHES WITH A SINUOSITY INDEX > 1.15 (n = 35)		REACHES WITH A SINUOSITY INDEX > 1.15 (n = 11)	
	% of habitat-types in:		% of habitat-types in:	
Channel unit	straight sections	curved sections	straight sections	curved sections
Riffle	62	38	52	48
Pool	72	28	36	64

Too few cascade habitat-types occurred in sample reaches to provide meaningful values.

a)



b)

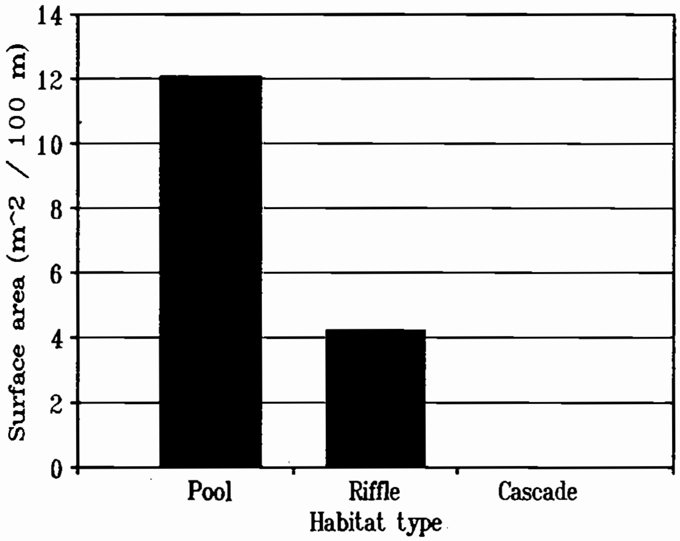


Figure 12. a) Average number of undercuts and b) average surface area of undercuts, per 100 m of channel, by habitat-type.

in these areas.

Channel gradient

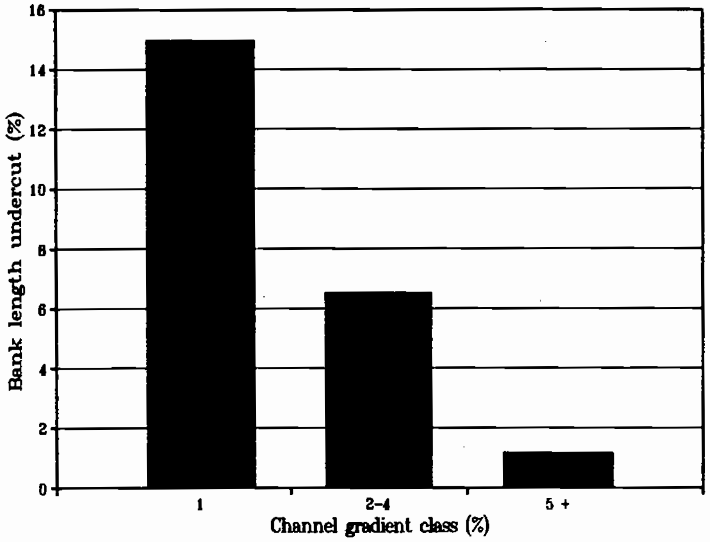
The average percent of bank length undercut / reach and the percent of reach surface area undercut / reach, respectively, by channel gradient class are given in Figures 13a and 13b. Differences between classes were significant.

At the reach level all undercut characteristics were significantly and negatively correlated with channel gradient (Table 10). Coefficients of determination (r^2) ranged from 0.09 to 0.23. A low amount of the variation in undercut characteristics is explained by predictive equations based on channel gradient alone.

At-a-site analysis reveals that only length of undercut and percent usable volume were significantly correlated with channel gradient (Table 10). Local channel gradient does little to explain variations in individual undercut characteristics.

One possible process-level explanation for this inverse relationship between gradient and presence of undercut streambanks is that high-gradient reaches may be devoid of bank-side vegetation due to high-energy overbank flows at these sites. Total basal area/hectare was found to be significantly lower in the steepest (> 5%) channel gradient classes as compared to the 2-4 percent class; no significant difference was found between the 2-4 percent

a)



b)

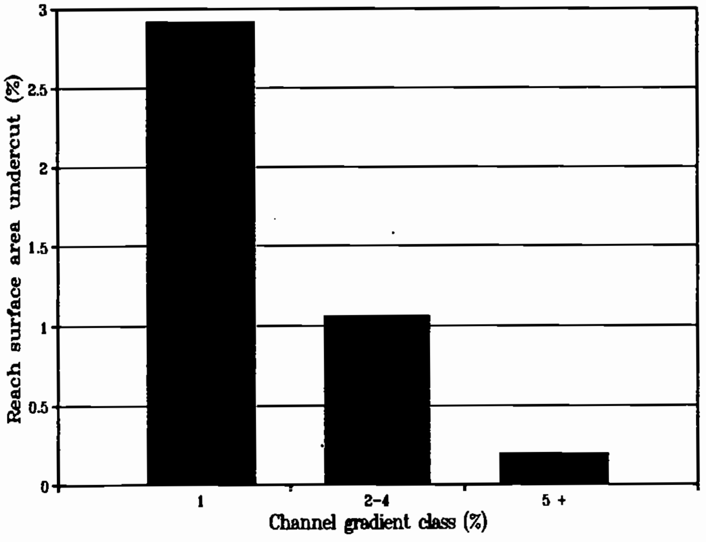


Figure 13. a) Average percent of bank length undercut and b) average percent of reach surface area undercut, by channel gradient class.

Table 10. Regression analysis of undercut characteristics vs. channel gradient.

Dependent variable	Regression analysis r^2	 p-level	 Slope
REACH ANALYSIS:			
Number of undercuts	0.23	0.001	negative
Length undercut	0.19	0.003	negative
Area undercut	0.15	0.007	negative
Reach area undercut (%)	0.16	0.006	negative
Volume undercut	0.12	0.020	negative
Low-flow usable volume undercut	0.11	0.027	negative
Low-flow usable volume undercut (% of total vol.)	0.09	0.018	negative
Maximum horizontal depth undercut	0.16	0.006	negative
AT-A-SITE ANALYSIS:			
Length of undercut	0.02	0.045	negative
Area of undercut	0.01	0.312	negative
Volume of undercut	0.00	0.933	negative
Low-flow usable volume of undercut	0.01	0.190	negative
Low-flow usable volume of undercut (% of total vol.)	0.03	0.024	negative
Maximum horizontal depth of undercut	0.01	0.139	negative

class and the 1 percent gradient class (t-test analysis). However, the total basal area / hectare of red alder significantly decreased with increasing channel gradient. Lower densities of bank-side vegetation in these streams would not have been apparent if no recent overbank flows had occurred.

The channel sinuosity index and channel gradient are not independent variables. Sinuosity and channel gradient were significantly and negatively correlated in this study with an r^2 of 0.26.

Stream power index

The affect of stream power index was analyzed at the reach level and at-a-site using simple linear regression. Undercut characteristics were the dependent variables and stream power index was used as the independent variable. Reach stream power index was not significantly correlated to any reach-level undercut characteristics.

At-a-site values of undercut area, volume, and usable volume were significantly and positively correlated with at-a-site stream power index. However, the low r^2 values (0.04, 0.08, and 0.03 respectively), although significant, indicate that at-a-site stream power index does little to explain the variation in these undercut characteristics.

The poor correlation between stream power and undercut characteristics supports the idea that local hydraulic variation (i.e. increased boundary shear stress due to channel curvature and channel gradient) and bank reinforcement processes are more influential on bank form than total energy expenditure.

Bank height

Reach-level analysis of bank height effects on undercut characteristics were not possible due to the method used of arbitrarily assigning valley-wall sites a bank height of 30 meters and the resulting inability of determining a meaningful average reach bank height. Valley-wall sites were also removed from at-a-site analysis (5 occurrences).

The area of undercut streambank / 100 m of bank, by bank height class is given in Figure 14. The distribution by bank height class of other at-a-site undercut characteristics (length, volume, usable volume, / 100 m) are similar in appearance. Streambanks having bank height in the 1- to 2-meter range appear to have higher values for all undercut characteristics.

All at-a-site undercut characteristics were significantly and positively correlated to bank height, except for usable volume and percent usable volume (Table 11). Coefficients of determination (r^2) values however ranged from 0.02 to 0.07, suggesting that bank height does little in explaining variation in individual undercut characteristics. Log-log transformation of the data improved the relationships slightly. The positive

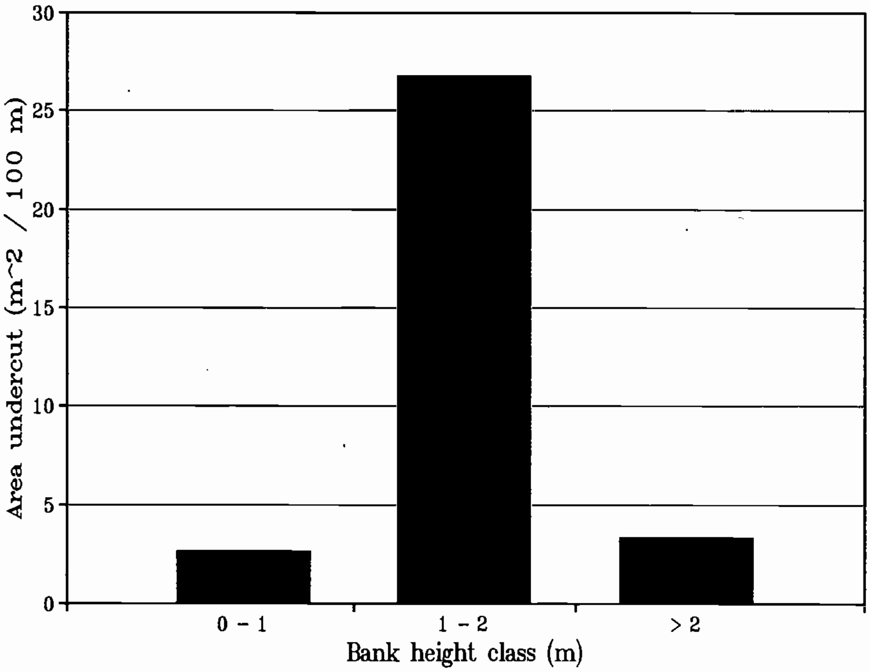


Figure 14. Area of streambank undercut / 100 m, by bank height class.

Table 11. Regression analysis of at-a-site undercut characteristics vs. streambank height.

	Regression analysis		
Dependent variable	r^2	p-level	Slope
UNTRANSFORMED VARIABLES:			
Length of undercut	0.03	0.031	positive
Area of undercut	0.04	0.009	positive
Volume of undercut	0.07	0.000	positive
Low-flow usable volume of undercut	0.02	0.058	positive
Low-flow usable volume of undercut (% of total vol.)	0.02	0.081	positive
Maximum horizontal depth of undercut	0.04	0.014	positive
LOG - LOG TRANSFORMED VARIABLES:			
Length of undercut	0.04	0.014	positive
Area of undercut	0.11	0.000	positive
Volume of undercut	0.18	0.000	positive
Low-flow usable volume of undercut	0.07	0.005	positive
Low-flow usable volume of undercut (% of total vol.)	0.00	0.930	positive
Maximum horizontal depth of undercut	0.12	0.000	positive

Valley-wall sites were not included in this analysis. Only undercut characteristics having non-zero values were used in the log-log analysis.

relationship of undercut characteristics to bank height does not contradict the apparent preferred range of bank height discussed above because at-a-site values only apply to the population of undercuts, not non-undercut locations.

Bankfull height was measured in 29 of the sample reaches. The difference between bank height and bankfull height is a measure of the height of bank material above bankfull flow. The area undercut / 100 m, by bank height minus bankfull height class (Figure 15), is similar in appearance to Figure 14. Area undercut appears to be greatest in locations where bank height minus bankfull height is approximately 1.0 to 1.5 meters. Other at-a-site characteristics (length, volume, usable volume, / 100 m) have a similar distribution by bank height minus bankfull height class. Only volume of undercut was significantly correlated with at-a-site bank height minus bankfull height ($r^2 = 0.04$).

The apparent preferred bank height range of 1- to 2-meters (1- to 1.5-m above bankfull) is probably attributable to disturbance regime and rooting characteristics of streamside trees. Low banks would be more susceptible to disturbance from overbank flows, consequently limiting the development of streamside trees. Minore and Smith (1971) found that red alder, western redcedar, and Sitka spruce could all tolerate sites having winter water tables less than 15 cm deep. Water table location is therefore probably not as important in

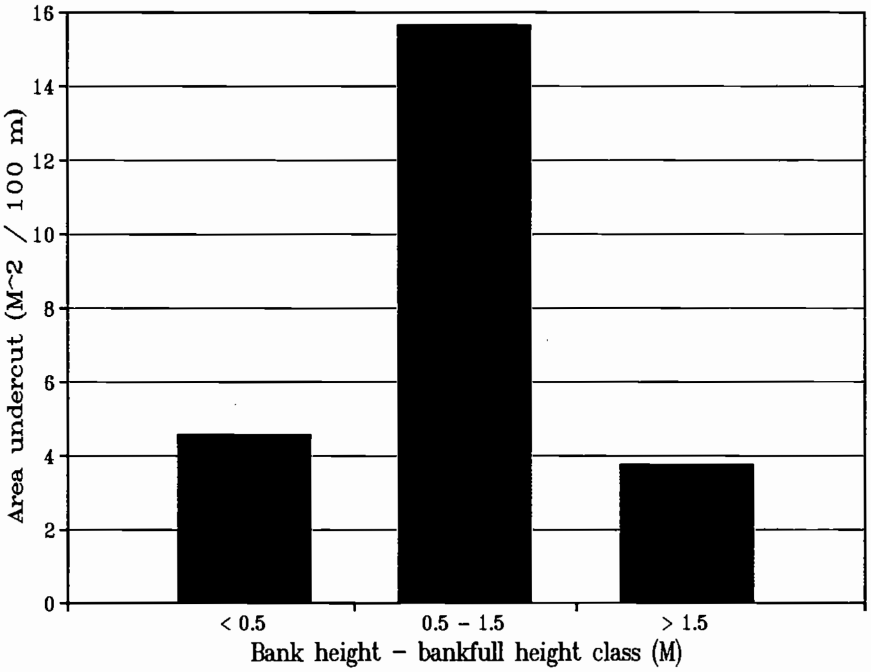


Figure 15. Area undercut / 100 m, by bank height - bankfull height class (n = 112 undercuts, 29 reaches, 4,4 km of stream).

restricting tree growth as disturbance. T-tests comparing total basal area/hectare between individual undercut locations support this theory of disturbance effects on streamside vegetation; total basal area/hectare was significantly lower between undercut sites less than 1-m high and undercut sites 1-2 m high.

A possible scenario explaining the apparent preference of undercuts to form and persist in banks 1 to 2 m thick is illustrated in Figure 16. The root mass in banks less than 1 m thick may be uniformly distributed throughout the soil profile, adding resistive strength equally at all depths. The literature reviewed by Perry (1982) suggests that the bulk of root systems normally occur in the top meter or soil. Banks 1 to 2 m thick have a root-reinforced top layer, and a relatively weak lower bank area. High banks (> 2 m) may fail due to the excessive weight of the overhang and vegetation.

Bank material

Bank bottom-material types were predominately loam, gravel, rubble, and boulder/bedrock (Table 12). The distribution of undercuts / bank bottom-material type, normalized for total length of bank in each class, were lower for the boulder / bedrock class but showed no preference for any other material type (Figure 17). Undercut characteristics (length, area, volume, usable volume, / 100 m) show similar distributions as number of

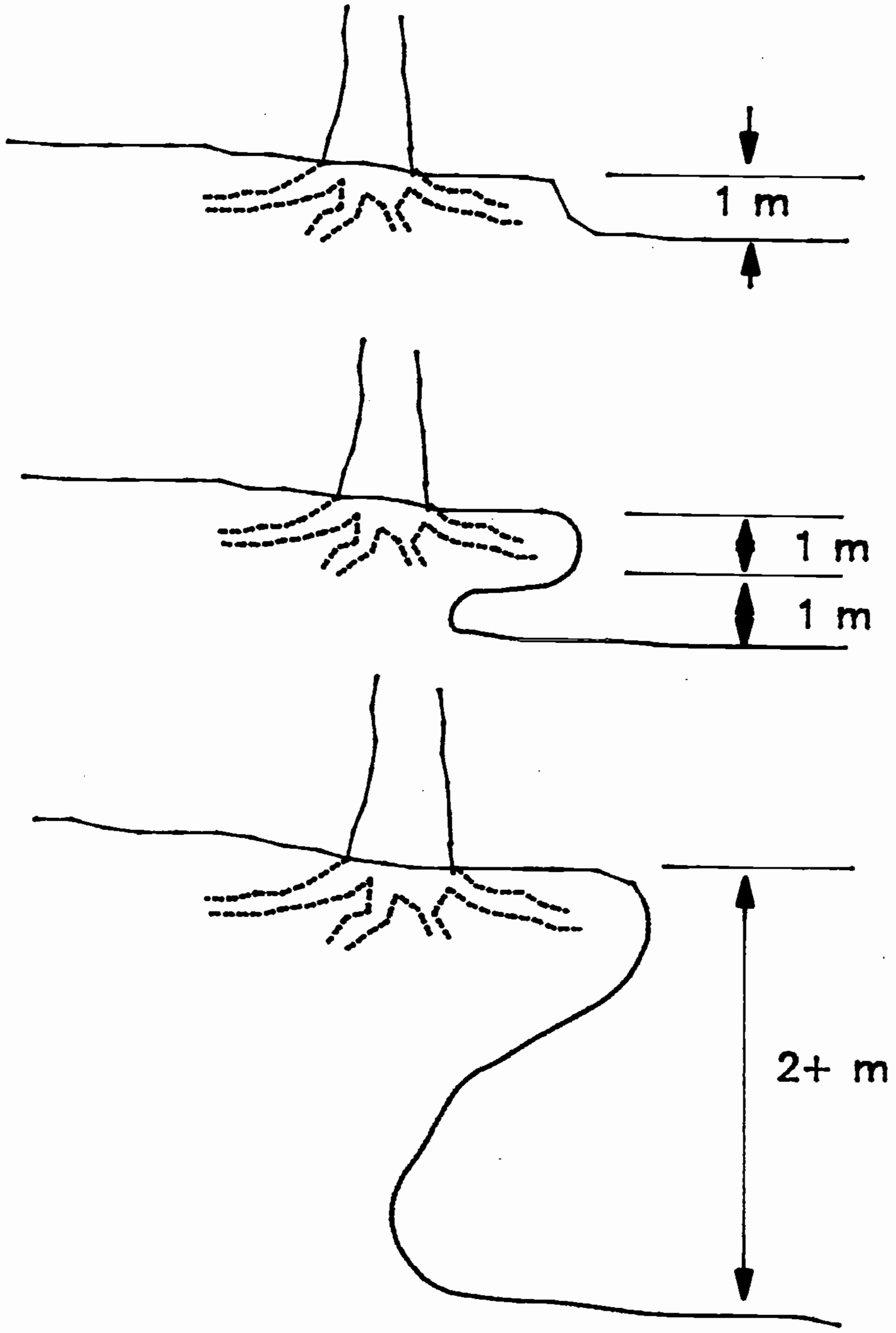


Figure 16. Possible rooting patterns in banks of varying height.

Table 12. Distribution of bank material types in sample streams (total length sampled = 7 km).

Bank material type	TOP MATERIAL: % of total bank length in class	BOTTOM MATERIAL: % of total bank length in class
Clay	0.0	0.5
Loam	55.4	26.1
Sand	2.2	2.2
Gravel	12.2	20.7
Rubble	16.0	28.5
Boulder	6.4	10.8
Bedrock	3.3	7.6
LWD	4.5	3.6
Total	100.0	100.0

Bottom material was used as top material type if only one layer was present.

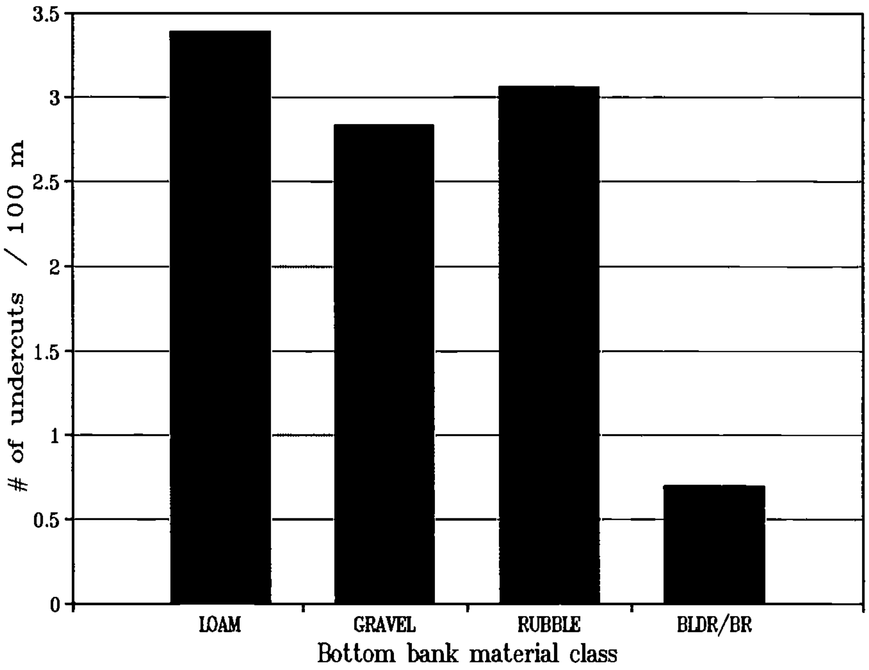


Figure 17. Number of undercuts / 100 m of streambank, by bottom bank-material class.

undercuts.

Essentially all undercuts had loam bank top-material. Banks having loam top-material made up 55 percent of the total length of bank in the streams studied, but other bank top-material types were represented (Table 12).

Undercut streambanks were almost four times more common in composite than non-composite banks (Figure 18, Table 13). Undercut characteristics (length, area, volume, usable volume) follow the same trend.

The presence of undercut streambanks appear to be correlated to the relative resistivity found in composite banks having a cohesive silt layer above a less cohesive gravel, rubble, or boulder/bedrock layer.

Channel width

A dimensionless percent difference in width was calculated at each undercut as:

$$\frac{(\text{width @ UC} - \text{reach average width}) \times 100}{\text{reach average width}}$$

The frequency distribution of % difference in width at undercut sites is given if Figure 19. The distribution is approximately normal and the mean difference in width (- 8 %) is significantly less than zero (t-test analysis). Sixty-six percent of all undercuts were narrower, and 34 percent wider, than the reach average.

From the distribution of percent difference in bankfull widths it appears that undercut streambanks are

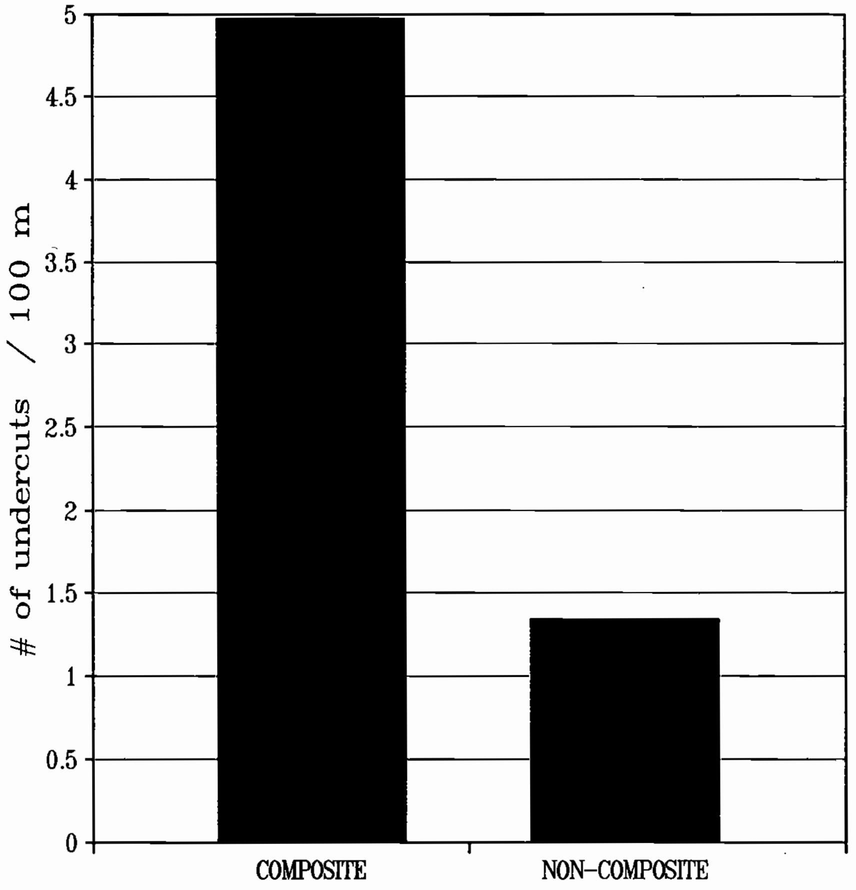


Figure 18. Number of undercuts / 100 m of streambank for composite vs. non-composite banks.

Table 13. Comparison of undercut characteristics in composite vs. non-composite banks.

Characteristic	# of times greater in composite banks
Number of undercuts	3.7
Length undercut	4.3
Area undercut	5.5
Volume undercut	8.1
Low-flow usable volume undercut	5.4

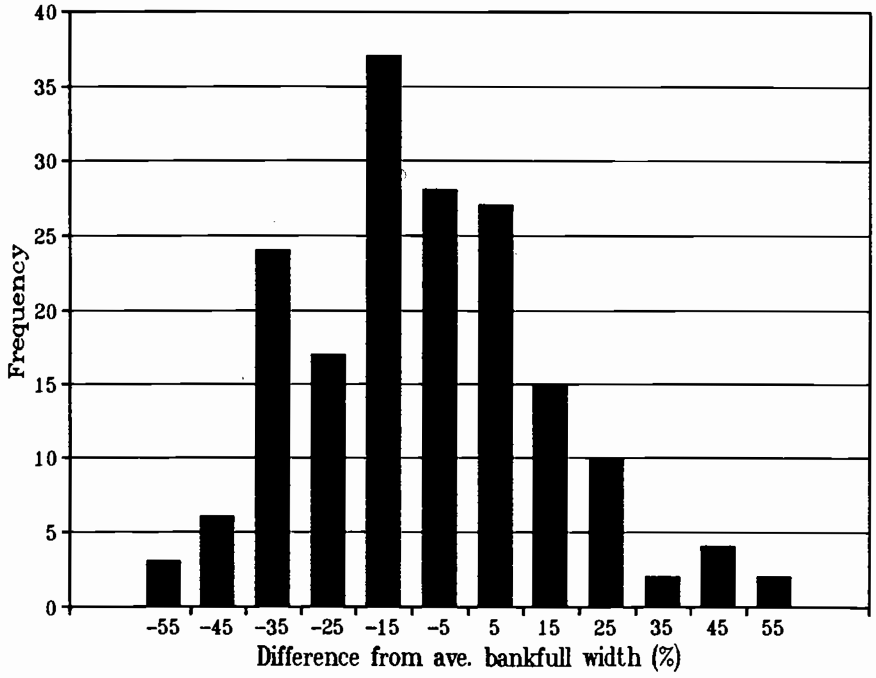


Figure 19. Frequency distribution of differences between bankfull widths at undercuts to reach average bankfull widths (n = 175 undercuts).

not associated with narrower-than-average channel locations.

Shrub density

Percent differences between shrub cover at undercut sites and reach average percent shrub cover were calculated as:

$$\frac{\underline{(\%\ \text{cover @ UC} - \text{reach average}\ \%\ \text{cover})}}{\text{reach average}\ \%\ \text{cover}} \times 100$$

The percent difference in shrub cover between undercut sites and reach average cover is illustrated in Figure 20. Fifty-four percent of all undercuts had lower than average, and 46 percent had higher than average, percent cover.

Analysis of undercut characteristics on percent shrub cover consisted of a simple regression model using average total percent cover and a multiple regression model, using average percent cover by shrub species, as the independent variables. Salmonberry and Stink currant were the two most common shrub species present, and were considered as separate independent variables in the multiple regression analysis. All other species were placed in a single category.

Reach-level analysis shows that all undercut characteristics, except for percent usable volume, are significantly and negatively correlated with total percent shrub cover (Table 14). All undercut characteristics are significantly and negatively correlated with percent cover

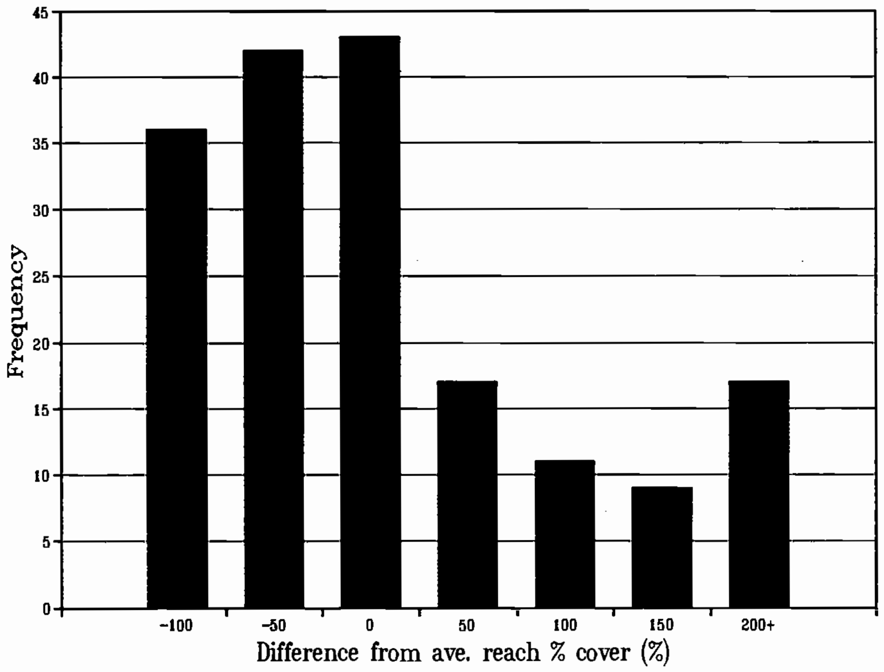


Figure 20. Frequency distribution of differences between shrub cover at undercuts in comparison to reach average percent shrub cover (n = 175 undercuts).

Table 14. Regression analysis of undercut characteristics vs. reach average percent shrub cover (n = 46 reaches).

Dependent variable	Regression analysis $r^2 (R^2)$	p-level	Slope
SIMPLE REGRESSION MODEL: Independent variable total % cover			
Number of undercuts	0.14	0.011	negative
Length undercut	0.25	0.000	negative
Area undercut	0.31	0.000	negative
Reach area undercut (%)	0.17	0.005	negative
Volume undercut	0.34	0.000	negative
Low-flow usable volume undercut	0.22	0.001	negative
Low-flow usable volume undercut (% of total vol.)	0.04	0.180	negative
Maximum horizontal depth undercut	0.17	0.004	negative
MULTIPLE REGRESSION MODEL: Independent variables: % salmonberry, % stink currant, % other cover			
Number of undercuts	0.21	0.005	negative
Length undercut	0.27	0.001	negative
Area undercut	0.30	0.000	negative
Reach area undercut (%)	0.18	0.010	negative
Volume undercut	0.31	0.000	negative
Low-flow usable volume undercut	0.21	0.005	negative
Low-flow usable volume undercut (% of total vol.)	0.17	0.014	negative
Maximum horizontal depth undercut	0.19	0.008	negative

by species as well, using the multiple regression model. There appears to be no improvement, based on r^2 and R^2 values, from using the multiple regression model over the simple regression model.

At-a-site analysis (Table 15) yields similar results as the reach-level analysis, however the low r^2 and R^2 values (0.01 to 0.07) indicate that percent shrub cover does little to explain the variation in individual undercut characteristics.

The inverse relationship of shrub cover and undercut characteristics is counter-intuitive, and is probably due to the interaction of shrub and tree vegetation. Average total percent shrub cover is significantly and negatively correlated with average total basal area of the overstory vegetation ($r^2 = 0.23$). Regressing the logarithm of average total percent shrub cover on total basal area improves the relationship ($r^2 = 0.32$), suggesting that the decrease in shrub cover with increasing tree density is not a linear relationship.

Percent shrub cover may also be related to site conditions (accumulated alluvial material) or disturbance regime, associated with low-gradient channel reaches. However, no statistically significant relationship was found to exist between average total percent shrub cover, and either channel gradient or sinuosity index.

Table 15. Regression analysis of undercut characteristics vs. at-a-site percent shrub cover (n = 175 undercuts).

Dependent variable	Regression analysis $r^2(R^2)$	 p-level	 Slope
SIMPLE REGRESSION MODEL: Independent variable total % cover			
Length of undercut	0.07	0.000	negative
Area of undercut	0.06	0.001	negative
Volume of undercut	0.05	0.002	negative
Low-flow usable volume of undercut	0.05	0.003	negative
Low-flow usable volume of undercut (% of total vol.)	0.02	0.044	negative
Maximum horizontal depth of undercut	0.05	0.003	negative
MULTIPLE REGRESSION MODEL: Independent variables: % salmonberry, % stink currant, % other cover			
Length of undercut	0.06	0.003	negative
Area of undercut	0.05	0.009	negative
Volume of undercut	0.04	0.018	negative
Low-flow usable volume of undercut	0.04	0.027	negative
Low-flow usable volume of undercut (% of total vol.)	0.01	0.164	negative
Maximum horizontal depth of undercut	0.03	0.034	negative

Streamside tree density

Because streamside tree density was assumed to be correlated with rooting density, the size of trees and their distance from the bank were hypothesized as being important variables related to the occurrence and extent of undercut streambanks. Several measures of streamside tree density were used in analyzing the influence of riparian tree vegetation on undercut characteristics at both the reach and at-a-site levels. Basal area, basal area / hectare (total basal area adjusted for plot size), sum of diameters, basal area / distance, basal area per hectare / distance, and sum of diameters / distance were all considered in the initial analysis. Basal area / hectare (BA), and basal area per hectare / distance (BA/D) yielded the best relationships with undercut streambanks, and will be the only variables reported.

Analysis consisted of simple and multiple regression models. Simple regression analysis considered the relation of undercut characteristics to BA and BA/D for all species lumped together. Multiple regression analysis considered the relation of undercut characteristics to BA and BA/D by species.

Reach level analysis indicated, for the simple regression model, that all undercut characteristics except percent usable volume are significantly and positively correlated with both BA and BA/D (Table 16). Breaking the independent variables down by species, and using multiple

Table 16. Simple linear regression analysis of undercut characteristics vs. reach basal area / hectare.

Dependent variable	Regression analysis r^2	p-level	Slope
INDEPENDENT VARIABLE: Reach BA			
Number of undercuts	0.22	0.001	positive
Length undercut	0.30	0.000	positive
Area undercut	0.34	0.000	positive
Reach area undercut (%)	0.25	0.000	positive
Volume undercut	0.32	0.000	positive
Low-flow usable volume undercut	0.22	0.001	positive
Low-flow usable volume undercut (% of total vol.)	0.02	0.750	positive
Maximum horizontal depth undercut	0.12	0.018	positive
INDEPENDENT VARIABLE: Reach BA/D			
Number of undercuts	0.26	0.000	positive
Length undercut	0.28	0.000	positive
Area undercut	0.33	0.000	positive
Reach area undercut (%)	0.23	0.001	positive
Volume undercut	0.30	0.000	positive
Low-flow usable volume undercut	0.18	0.003	positive
Low-flow usable volume undercut (% of total vol.)	0.00	0.850	positive
Maximum horizontal depth undercut	0.12	0.020	positive

BA = reach basal area per hectare
BA/D = reach basal area per hectare / distance

regression analysis, improves most of the relationships (Table 17).

Not all of the independent variables in the multiple regression model (Table 17) are significant at the alpha $\leq$ 0.05 level. Variables having highest p-values were removed one at a time until only the significant variables remain. For percent of reach length undercut the final form of the equation retains only BA of red alder as an independent variable, and has an r^2 value of 0.47. The equation for total area undercut retains both BA of red alder and Sitka spruce and has an R^2 value of 0.37. The equation for number of undercuts / 100 m yielded the best results, suggesting that presence of trees determines where undercuts occur, but that the size of individual undercuts is more variable. The final form of the equation retained only BA of red alder and had an r^2 value of 0.50. The plot of number of undercuts / 100 m on BA of red alder is given in Figure 21. Results using BA/D yielded equations of the same general form as BA.

Western redcedar and western hemlock were only minor components of a few reaches, and Douglas-fir was essentially non-existent. Sitka spruce appeared in only 6 reaches, but was associated with large undercuts, hence its significant effect on area of undercut, but not length or number. Bigleaf maple was the second most common species found in study streams, but apparently was not present in sufficiently varying densities to have a significant

Table 17. Multiple regression analysis of undercut characteristics vs. reach average basal area / hectare.

Dependent variable	Regression analysis R^2	p-level	Slope
INDEPENDENT VARIABLES: Reach BA by species			
Number of undercuts	0.49	0.000	positive
Length undercut	0.45	0.000	positive
Area undercut	0.37	0.000	positive
Reach area undercut (%)	0.31	0.002	positive
Volume undercut	0.34	0.001	positive
Low-flow usable volume undercut	0.18	0.028	positive
Low-flow usable volume undercut (% of total vol.)	0.00	0.920	positive
Maximum horizontal depth undercut	0.12	0.081	positive
INDEPENDENT VARIABLE: Reach BA/D by species			
Number of undercuts	0.41	0.000	positive
Length undercut	0.34	0.001	positive
Area undercut	0.36	0.001	positive
Reach area undercut (%)	0.19	0.023	positive
Volume undercut	0.36	0.001	positive
Low-flow usable volume undercut	0.18	0.029	positive
Low-flow usable volume undercut (% of total vol.)	0.00	0.950	positive
Maximum horizontal depth undercut	0.13	0.075	positive

BA = reach basal area per hectare
BA/D = reach basal area per hectare / distance

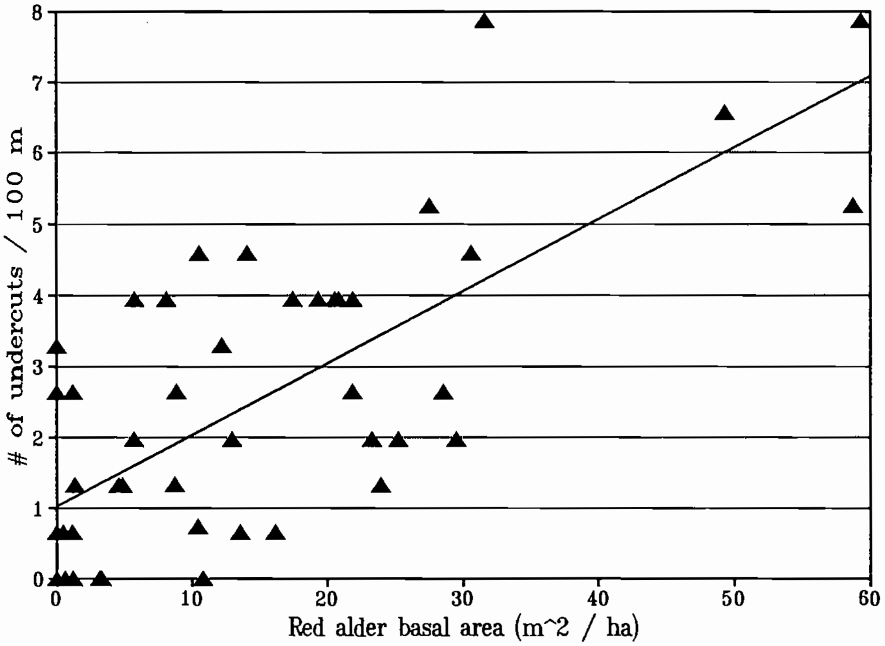


Figure 21. Number of undercuts / 100 m vs. basal area / hectare for red alder.

effect. Red alder was the most common tree species, appearing at different density levels in every reach that had tree species. Red alder would therefore be expected to be most closely correlated to undercut characteristics.

Percent differences between BA at undercut sites and reach average BA was calculated as:

$$\frac{(\text{BA @ UC} - \text{reach average BA}) \times 100}{\text{reach average BA}}$$

The percent difference in BA between undercut sites and reach BA (Figure 22) indicates that 88 percent of all sites had a higher than average BA. Undercut locations appear to be strongly linked with the presence of streamside trees.

Results of at-a-site analysis using the simple regression model show that all undercut characteristics except percent usable volume are significantly and positively correlated with both BA and BA/D (Table 18). Although r^2 values are low, they are higher than for any other independent variables analyzed so far at the at-a-site level.

Results using the multiple regression model (Table 19) yielded the highest R^2 at-a-site relationships reported in this study. All characteristics, except percent usable volume were significantly and positively correlated with both BA and BA/D segregated by species. BA/D was generally better than BA in explaining differences in at-a-site undercut characteristics, and may be due to the decrease in tree roots with distance from the tree.

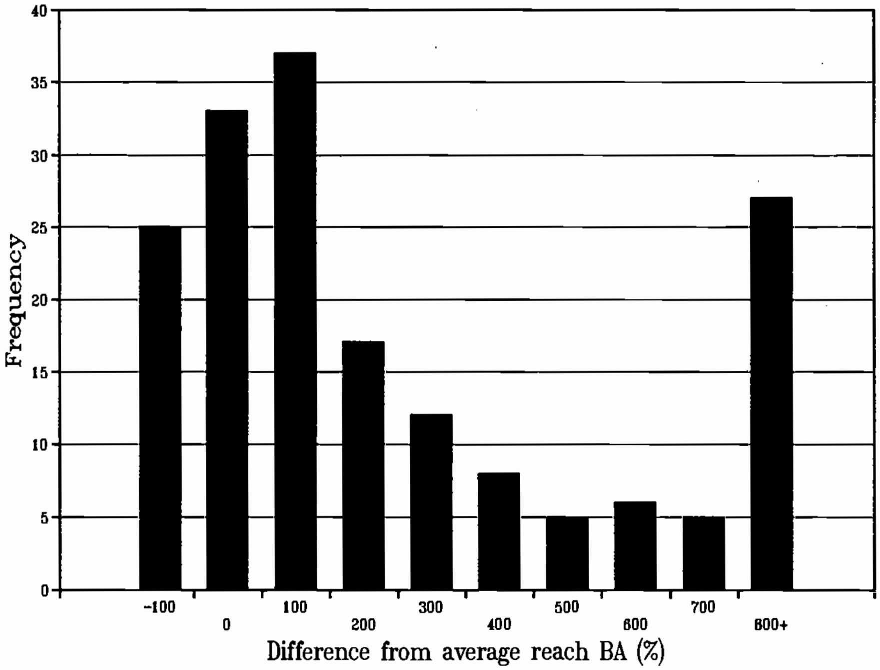


Figure 22. Frequency distribution of differences between basal area / hectare at undercuts in comparison to reach average basal area / hectare (n = 175 undercuts).

Table 18. Simple linear regression analysis of undercut characteristics vs. at-a-site average basal area / hectare.

Dependent variable	Regression analysis r^2	p-level	Slope
INDEPENDENT VARIABLE: At-a-site BA			
Length of undercut	0.16	0.000	positive
Area of undercut	0.20	0.000	positive
Volume of undercut	0.20	0.000	positive
Low-flow usable volume of undercut	0.03	0.027	positive
Low-flow usable volume of undercut (% of total vol.)	0.00	0.970	positive
Maximum horizontal depth of undercut	0.14	0.000	positive
INDEPENDENT VARIABLE: At-a-site BA/D			
Length of undercut	0.03	0.018	positive
Area of undercut	0.10	0.000	positive
Volume of undercut	0.08	0.000	positive
Low-flow usable volume of undercut	0.05	0.002	positive
Low-flow usable volume of undercut (% of total vol.)	0.01	0.291	positive
Maximum horizontal depth of undercut	0.10	0.000	positive

BA = reach basal area per hectare
BA/D = reach basal area per hectare / distance

Table 19. Multiple regression analysis of undercut characteristics vs. at-a-site average basal area / hectare.

Dependent variable	Regression analysis R^2	p-level	Slope
INDEPENDENT VARIABLE: At-a-site BA by species			
Length of undercut	0.27	0.000	positive
Area of undercut	0.31	0.000	positive
Volume of undercut	0.39	0.000	positive
Low-flow usable volume of undercut	0.09	0.001	positive
Low-flow usable volume of undercut (% of total vol.)	0.04	0.244	positive
Maximum horizontal depth of undercut	0.22	0.000	positive
INDEPENDENT VARIABLE: At-a-site BA/D by species			
Length of undercut	0.10	0.000	positive
Area of undercut	0.38	0.000	positive
Volume of undercut	0.44	0.000	positive
Low-flow usable volume of undercut	0.09	0.005	positive
Low-flow usable volume of undercut (% of total vol.)	0.00	0.252	positive
Maximum horizontal depth of undercut	0.22	0.000	positive

BA = reach basal area per hectare
BA/D = reach basal area per hectare / distance

As in the reach level analysis, not all of the independent variables in the multiple regression model are significant at the alpha ≤ 0.05 level. The final form of the model for area of undercut included hemlock, big leaf maple, and Sitka spruce BA/D as significant variables ($R^2 = 0.38$). Correlations among tree species were not significant. Volume of undercut on BA/D by species yielded the same three tree species as being significant variables, and had an R^2 value of 0.44. Although red alder appears to be an important variable influencing the occurrence of undercut streambanks at the reach level, other species appear to be more important in explaining differences between size of individual undercuts.

Valley segment type

The four stream segment types represented in these study streams are terrace-bound valleys (TBV), alluviated canyons (ALC), colluvial canyons (CLC), and bedrock canyons (BRC). The average number of undercuts and the area of undercuts / 100 m of each valley segment type are shown in Figures 23a and 23b respectively.

Number of undercuts / 100 m were significantly greater between TBVs and ALCs, and between ALCs and CLCs. Number of undercuts / 100 m were not significantly different between CLCs and BRCs, suggesting that there is little difference, with respect to the physical characteristics influencing occurrence of undercut streambanks, between

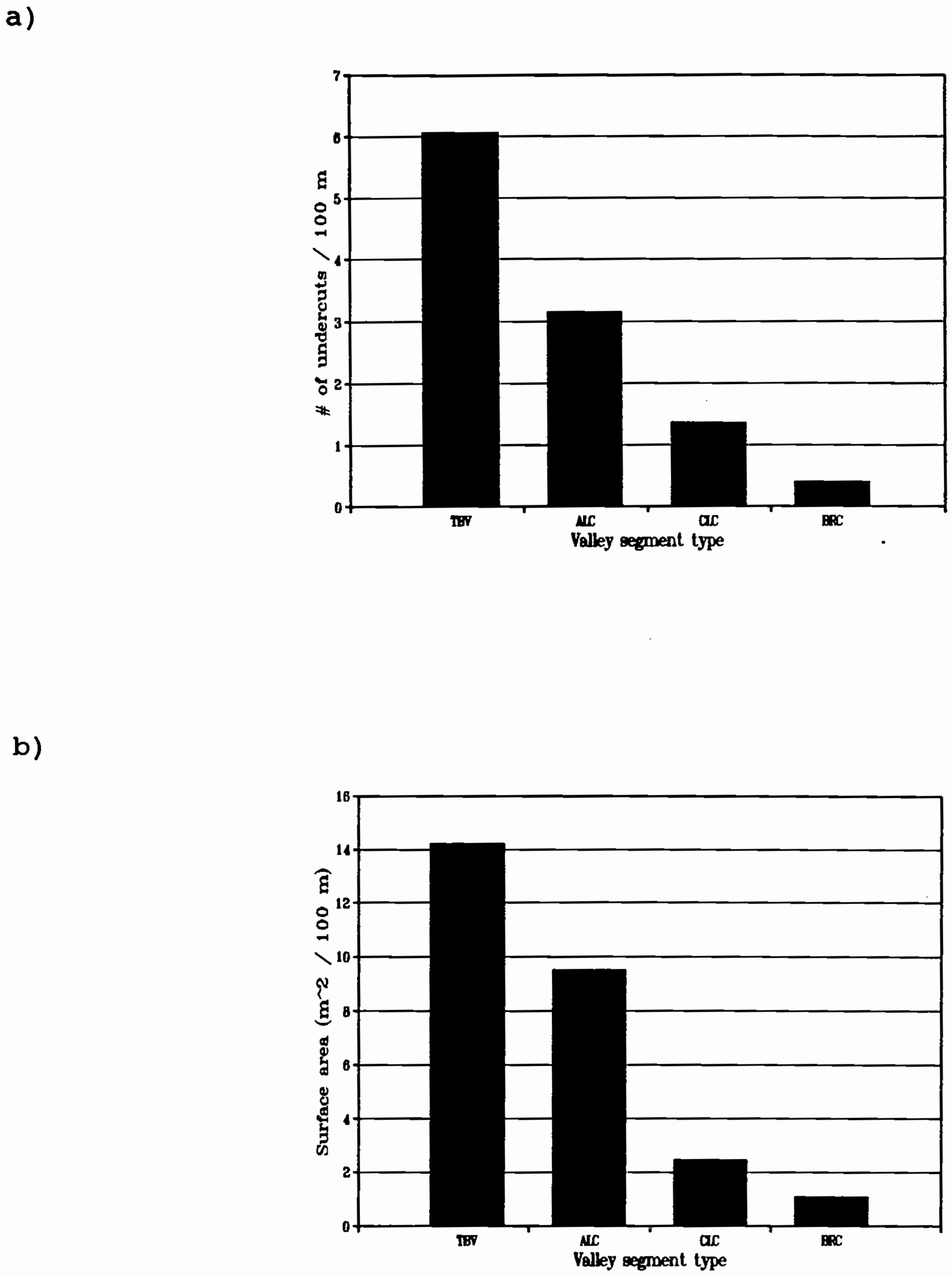


Figure 23. a) Average number of undercuts and b) average area undercut, per 100 m, by valley segment type.

these two valley segment types. Area undercut / 100 m is significantly different between ALCs and CLCs, and between TBVs and CLCs. Area undercut / 100 m is not significantly different between TBVs and ALCs, or between CLCs and BRCs.

Valley segment types may integrate many of the characteristics discussed above that are associated with undercut streambanks. TBVs are generally low-gradient, low energy, relatively sinuous reaches having banks composed of fine-grained and often composite bank material. Riparian tree vegetation is often well-developed in TBVs. In contrast, BRCs tend to be high-gradient, high energy reaches with coarse bank material and very little stream-side tree development.

Obstructions

The estimated association of in-stream obstructions (gravel bars, boulders, LWD) with undercut streambanks are summarized in Table 20. Percent frequency for each obstruction type is Segregated by primary and secondary categories. Only 1 percent of all undercut streambanks surveyed were estimated to have been associated with LWD as the primary cause, and none with gravel bars or boulders. Gravel bars, boulders, and LWD were estimated as secondary causal agents at 3, 1, and 5 percent of the undercut sites respectively.

Table 20. Estimated association of in-stream obstructions with undercut streambanks.

	Percent frequency of occurrence	
Obstruction	Primary cause	Secondary cause
Gravel bars	0	3
Boulders	0	1
LWD	1	5

SUMMARY AND CONCLUSIONS

Summary of Results

The area of undercut streambanks for reaches in this study ranged from 0.0 to 27.4 m^2 / 100 m of reach, with an average of 6.5 m^2 / 100 m. The percent of reach area undercut ranged from 0.0 to 4.5 percent, with an average of 1.1 percent. The percent of reach length undercut ranged from 0.0 to 23.6 percent with an average value of 6.2 percent. These values are approximately mid-range compared with studies from Alaska, Montana, and Wisconsin. The percent of reach area covered by undercut streambanks is approximately half of that provided by LWD in Oregon Coast Range streams.

Several process-level channel characteristics appear to be influential in the distribution of undercut streambanks characteristics:

1) Outside bends have a higher occurrence of undercut streambanks. The greater numbers of undercut streambanks found on outside bends are probably attributable to higher boundary shear stresses due to the flow being directed at the bank.

2) High-gradient stream reaches have less frequent occurrences of undercut streambanks. The inverse relationship between channel gradient and occurrence of undercut streambanks may be due to more frequent

disturbance in the streamside zone from over-bank flows, and the resulting lower densities of streamside trees.

3) Streambanks that are 1 to 2 meters in height (0.5 to 1.5 meters above bankfull height) have higher levels of undercut streambanks than both lower and higher banks. Less-frequent occurrences of undercut banks in low bank areas may be attributable to root-reinforcement throughout the entire soil profile and/or lower tree densities due to more frequent disturbance. Less-frequent occurrences of undercut banks in high bank areas may be attributable to failure of overhangs.

4) Areas with composite streambanks are apparently more susceptible to undercutting.

5) Streamside tree vegetation reinforces overhanging banks and is the single most important factor, based on regression analysis, in explaining variations between individual undercuts. Red alder is the most significant species in explaining reach-level differences in the number and percent length of undercuts. The percent of reach area undercut is also influenced by density of streamside Sitka spruce.

6) Percent shrub cover appears to be negatively correlated with undercut characteristics. This result is probably explained by the inverse relationship between tree density and percent shrub cover.

7) Based on field observations it appears that flow obstructions (gravel bars, boulders, LWD) do not have a significant impact on undercut streambank characteristics.

Valley segment type and channel sinuosity integrate many of the processes outlined above and are useful at the macro-scale level in understanding the distributions of undercut characteristics. Classification of valley segment type is based on many of the same characteristics associated with undercut streambanks including channel gradient, channel sinuosity, and substrate type.

Stream sections having a relatively high sinuosity index are usually low-gradient, have composite bank structure, more opportunity for the flow to be directed at the outside bank, and have well-developed riparian tree vegetation due to less-frequent disturbance and better site conditions for tree growth.

Two areas not addressed in this study that are important to understanding the distribution of undercut streambanks are the effects of disturbance history and the relationship of undercut streambanks to flow regime. The primary sources of disturbance in unmanaged riparian areas are floods, landslides, and wildfire. Although floods may directly erode banks and riparian vegetation, high flows also represent an important mechanism for causing undercut streambanks. Landslides may move colluvial material into the channel which may eventually fill undercut streambanks, and move trees and boulders into the channel which may in turn direct flows against the bank creating areas of scour. Wildfire may destroy riparian vegetation; eliminating root reinforcement and providing a large input of LWD which may produce bank scour.

The vertical height of most undercuts observed in this study was below bankfull height, suggesting that undercut banks form in flows lower than bankfull. Additionally, only six percent of all undercuts had greater than 60 percent of their volume occupied by water at low (summertime) flows (Figure 8), suggesting that undercut streambanks form during higher flows than those observed at the time of the study. Based on these two observations it appears that undercut streambanks form during flows approaching bankfull. Bankfull flows have a recurrence interval of 1.5 to 2 years (Leopold et al., 1964). Therefore, the flow conditions under which undercut streambanks can form occur in streams almost every year.

Interpolative Equations for Reach-Level Characteristics

Two interpolative equations were developed for percent of bank length undercut and percent of reach area undercut (Table 21). Coefficients of multiple determination (R^2) values were 0.67 and 0.66 respectively. All variables are significant at the alpha ≤ 0.05 level. Although the percent shrub cover is correlated with streamside tree

Table 21. Interpolative equations for percent of streambank length and percent of reach area undercut.

Equations	R^2
$L = -26.49 + 0.08CB + 27.20SI - 0.07TC + 0.19AB$	0.67
$A = -7.94 + 0.02CB + 7.75SI - 0.01TC + 0.02AB$	0.66

Where: L = Length of reach undercut (%)

A = Area of reach undercut (%)

CB = Percent composite bank

SI = Sinuosity index

TC = Average % shrub cover of reach

AB = Reach average red alder basal area / hectare density its inclusion appears to further refine the overall influence of streamside vegetation. The Interpolative equations presented here have not been tested and should be used with caution outside these study streams.

Implications for Streamside Management

The physical characteristics of streams (gradient, sinuosity, bank height and material) may be altered by dams, revetments, levees, and channelization, but these practices are not usually encountered in headwater streams or commonly associated with upland management practices. However, riparian vegetation is one component of these systems that is often altered.

Oregon's Forest Practices Rules (FPR) are intended to balance the protection of functions provided by riparian vegetation with the economic goals of landowners. Increased understanding of these functions should result in further refinements in the regulations. Examples include recent amendments to the FPR to maintain adequate densities of streamside trees for LWD recruitment.

Current FPR require leaving a minimum average of 9 trees, or 2.3 m^2ha^{-1} (10 ft^2ac^{-1}), of live conifers, and a minimum of 50 percent of the pre-operation canopy, in the streamside zone. With respect to conifer species it appears that retention of Sitka spruce is most important in maintaining undercut characteristics. In contrast, Douglas-fir was not found in the immediate streamside zone, and based on the reported intolerance of Douglas-fir to high water tables (Minore, 1970; Walters et al., 1980) would not be expected to be found there. Douglas-fir therefore appears to have little or no influence on undercut characteristics. Western hemlock and western redcedar would probably provide conditions favorable to undercut streambank development based on their tolerance to wet conditions, but they were not present in sufficient numbers to assess their influence.

With respect to hardwood species there are only minimal guidelines offered in the FPR as to what trees should be retained. Red alder is the major tree species found in Coast Range streams, and therefore showed the strongest correlation to undercut streambanks. Other hardwood species are probably also important in providing the conditions favorable to undercut streambank development. The results of this study indicate that retaining those trees relatively close to the channel, whose roots provide strength to streambank soils, should be an important consideration in identifying leave trees.

Land managers interested in establishing streamside trees that would improve the conditions for undercut streambank development might consider the following guidelines:

1) Low-gradient, sinuous stream sections would have the most favorable bank material and disturbance

regime for undercut development. Stream sections having relatively high sinuosity indices, or that occur in terrace-bound valley or alluviated canyon valley segment types, would be the most favorable and may often be determined from existing stream survey information.

2) Outside stream bends would experience the most favorable hydraulic conditions for undercut development and would be the best areas to establish streamside trees.

3) Streambanks 1-2 meters in height having a composite structure would be the best areas for establishing streamside trees.

4) Sitka spruce would be the best conifer species and red alder the best hardwood species to establish in streamside areas for promoting the occurrence of undercut streambanks.

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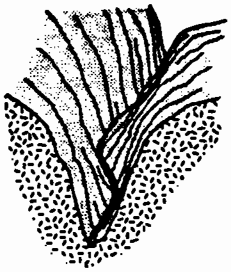
APPENDICES

APPENDIX A. Valley Segment Types (Frissell and Liss, 1986; Frissell, personal communication, Oregon State University, Corvallis, 1989).

BRC Bedrock Canyon

Valley width = 1-2 x active channel width (ACW)
Slope: Steep
Sinuosity: Low
Channel pattern: Straight
Width-to-depth ratio (W/D): Low
Substrate: Bedrock-dominated
LWD: Infrequent large jams

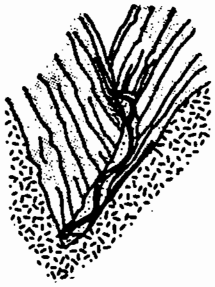


CLC Colluvial Canyon

Valley width = 1-2 x ACW
Slope: Steep
Sinuosity: Low
Channel pattern: Straight
W/D: Low
Substrate: Boulder-rich
LWD: Abundant single stems and frequent jams

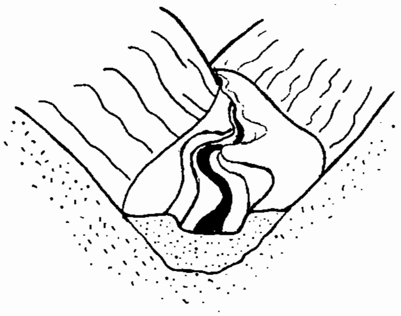
ALC Alluviated Canyon

Valley width = 2-3 x ACW
Slope: Gentle
Sinuosity: Moderate
Channel pattern: Straight, slightly sinuous
W/D: Moderate
Substrate: Gravel-cobble, local boulders
LWD: Common, mostly floated pieces in lateral jams



TBV Terrace-Bound Valley

Valley width = 3-5 x ACW
Slope: Gentle
Sinuosity: Moderate to high
Channel pattern: Sinuous
W/D: Moderate
Substrate: Gravel, fines
LWD: Common



APPENDIX B. Reach Summaries of Undercut Characteristics.

REACH	# of under-cuts	Total length undercut (m)	Reach length undercut (%)	Total area undercut (m^2)	Reach area undercut (%)	Total volume undercut (m^3)	Total low-flow volume undercut (m^3)	Total low-flow volume undercut (%)	Maximum horizontal depth undercut (m)
MILL 1	3	13.4	4.4	7.9	1.0	2.8	0.4	12	1.5
MILL 2	1	2.6	0.9	0.6	0.1	0.2	0.0	0	0.3
MILL 3	0	0.0	0.0	0.0	0.0	0.0	0.0	-	0.0
MILL 4	1	2.0	0.6	0.5	0.1	0.1	0.0	3	0.4
DEER 1	4	7.2	2.4	2.8	0.5	0.4	0.1	29	0.9
DEER 2	0	0.0	0.0	0.0	0.0	0.0	0.0	-	0.0
DEER 3	12	71.9	23.6	30.7	4.5	6.2	1.1	18	2.4
DEER 4	10	68.8	22.6	25.2	4.4	4.1	1.2	30	2.3
DEER 5	12	63.6	20.9	30.8	4.5	5.5	1.1	19	1.7
DEER 6	6	33.4	11.0	13.4	2.2	1.8	1.0	57	1.7
FLYNN 1	3	11.1	3.7	2.8	1.0	0.4	0.0	0	0.5
FLYNN 2	6	18.8	6.2	9.6	2.3	1.9	0.5	24	3.6
FLYNN 3	5	13.4	4.4	5.4	1.0	1.4	0.1	8	0.9
FLYNN 4	6	20.6	6.8	7.9	1.1	1.9	0.5	26	1.0
TROUT 1	1	2.0	0.7	0.6	0.0	0.1	0.0	0	0.4
TROUT 2	2	9.8	3.2	7.2	0.7	3.4	0.0	0	1.7
TROUT 3	1	3.0	1.0	1.0	0.1	0.2	0.1	47	0.5
TROUT 4	0	0.0	0.0	0.0	0.0	0.0	0.0	-	0.0
TROUT 5	2	4.3	1.4	1.4	0.1	0.4	0.1	25	0.8
TROUT 6	4	16.5	5.4	7.3	0.8	1.7	0.7	44	1.2
TROUT 7	4	12.7	4.2	4.1	0.8	1.1	0.1	5	1.3
BOULDER 1	3	14.6	4.8	6.2	0.7	1.4	0.0	1	0.9
BOULDER 2	0	0.0	0.0	0.0	0.0	0.0	0.0	-	0.0
BOULDER 3	4	15.2	5.0	8.7	0.7	2.6	0.0	1	2.4
BOULDER 4	1	2.1	0.7	0.9	0.1	0.4	0.0	0	0.6
BOULDER 5	8	35.8	11.8	19.5	1.5	7.1	0.7	10	1.9
S.FORK 1	2	4.0	1.3	1.1	0.1	0.2	0.0	2	0.6
S.FORK 2	2	10.5	3.4	13.0	1.4	5.8	0.0	0	2.7
S.FORK 3	1	1.5	0.5	0.3	0.1	0.0	0.0	0	0.4
S.FORK 4	1	4.9	1.6	1.7	0.3	0.4	0.0	0	0.6
CUMMINS 1	6	24.3	8.0	8.5	0.9	2.2	0.1	4	0.9
CUMMINS 2	6	39.0	12.8	41.8	3.3	9.2	1.6	18	4.6
CUMMINS 3	7	39.2	12.9	22.0	2.0	7.6	1.2	16	1.5
CUMMINS 4	7	44.7	14.7	33.0	2.9	9.2	2.6	28	2.9
CUMMINS 5	4	29.0	9.5	11.0	0.7	2.9	0.2	8	1.2
CUMMINS 6	6	46.3	15.2	25.7	1.8	8.5	3.3	39	2.7
CUMMINS 7	5	38.7	12.7	24.7	1.6	9.7	1.0	10	2.6
CUMMINS 8	8	36.3	11.9	21.5	1.4	7.0	1.4	19	1.7
ROCK 1	7	27.2	8.9	10.9	0.9	2.2	0.3	15	1.2
ROCK 2	0	0.0	0.0	0.0	0.0	0.0	0.0	-	0.0
ROCK 3	3	30.3	10.0	26.3	2.1	10.0	0.9	9	2.5
ROCK 4	6	34.3	11.3	12.9	1.2	3.5	0.6	16	0.8
ROCK 5	0	0.0	0.0	0.0	0.0	0.0	0.0	-	0.0
ROCK 6	3	12.3	4.0	3.4	0.4	0.5	0.2	33	0.7
ROCK 7	2	5.5	1.8	1.8	0.2	0.3	0.1	41	0.7
ROCK 8	0	0.0	0.0	0.0	0.0	0.0	0.0	-	0.0

APPENDIX C. At-a-Site Undercut Characteristics.

Reach		Length of undercut (m)	Area of undercut (m^2)	Volume of undercut (m^3)	Low-flow Volume of undercut (m^3)	Low-flow Volume of undercut (%)	Maximum horizontal depth (m)
MILL	1	8.5	6.18	2.39	0.32	13.2	1.46
MILL	1	2.8	0.99	0.19	0.04	18.9	0.58
MILL	1	2.0	0.70	0.24	0.00	0.0	0.61
MILL	2	2.6	0.59	0.15	0.00	0.0	0.34
MILL	4	2.0	0.48	0.06	0.00	3.1	0.37
DEER	1	1.6	0.37	0.06	0.02	29.6	0.43
DEER	1	1.7	0.78	0.08	0.03	36.7	0.85
DEER	1	2.3	1.06	0.11	0.06	50.0	0.70
DEER	1	1.7	0.63	0.12	0.01	5.6	0.52
DEER	3	6.7	2.40	0.60	0.04	6.2	0.73
DEER	3	6.4	3.07	0.76	0.31	40.8	2.44
DEER	3	1.5	0.65	0.05	0.02	37.5	0.67
DEER	3	11.9	7.34	1.85	0.31	16.5	1.83
DEER	3	5.5	1.96	0.38	0.08	22.2	0.61
DEER	3	6.1	3.11	0.52	0.16	32.0	1.01
DEER	3	3.7	0.81	0.11	0.11	100.0	0.58
DEER	3	4.0	1.00	0.17	0.00	0.0	0.49
DEER	3	4.3	2.08	0.59	0.08	14.2	0.91
DEER	3	10.8	4.37	0.50	0.02	3.1	0.91
DEER	3	5.7	1.91	0.31	0.00	0.0	0.64
DEER	3	5.3	1.97	0.32	0.01	3.1	0.76
DEER	4	2.6	0.43	0.04	0.04	100.0	0.27
DEER	4	9.4	2.59	0.41	0.13	32.0	0.58
DEER	4	6.4	3.85	0.67	0.15	21.9	1.31
DEER	4	4.3	1.63	0.32	0.13	40.8	0.58
DEER	4	13.4	4.09	0.53	0.53	100.0	0.70
DEER	4	2.1	0.73	0.14	0.05	34.7	0.76
DEER	4	11.6	3.88	0.53	0.00	0.0	0.91
DEER	4	7.6	4.24	0.94	0.00	0.0	2.26
DEER	4	2.3	0.79	0.20	0.06	30.2	0.55
DEER	4	9.1	2.93	0.30	0.15	50.0	0.76
DEER	5	3.0	2.00	0.32	0.15	46.3	1.52
DEER	5	6.1	3.30	0.56	0.18	32.0	0.88
DEER	5	8.7	5.53	1.46	0.19	13.3	1.22
DEER	5	7.8	3.91	0.57	0.00	0.0	1.22
DEER	5	4.4	1.44	0.15	0.07	44.4	0.61
DEER	5	3.8	0.64	0.09	0.04	50.0	0.27
DEER	5	5.2	2.68	0.48	0.24	49.0	1.04
DEER	5	8.8	2.56	0.46	0.00	0.0	0.98
DEER	5	2.4	0.93	0.26	0.01	4.1	0.55
DEER	5	3.0	2.93	0.28	0.00	0.0	1.68
DEER	5	4.4	1.95	0.51	0.03	6.6	0.91
DEER	5	5.8	2.96	0.36	0.14	37.5	1.22
DEER	6	4.5	2.77	0.49	0.49	100.0	1.22
DEER	6	4.6	1.85	0.29	0.05	18.0	0.58
DEER	6	4.4	2.39	0.25	0.25	100.0	0.91
DEER	6	5.2	0.99	0.06	0.02	32.0	0.46
DEER	6	4.7	3.35	0.45	0.22	50.0	1.68
DEER	6	10.1	2.07	0.27	0.00	1.4	0.30

APPENDIX C - continued

Reach		Length of undercut (m)	Area of undercut (m^2)	Volume of undercut (m^3)	Low-flow Volume of undercut (m^3)	Low-flow Volume of undercut (%)	Maximum horizontal depth (m)
FLYNN	1	7.3	1.90	0.25	0.00	0.0	0.52
FLYNN	1	1.5	0.37	0.08	0.00	0.0	0.37
FLYNN	1	2.3	0.49	0.09	0.00	1.4	0.34
FLYNN	2	3.4	5.88	1.32	0.40	30.2	3.60
FLYNN	2	3.7	0.43	0.03	0.01	32.0	0.21
FLYNN	2	2.1	0.68	0.08	0.00	0.0	0.58
FLYNN	2	4.1	1.22	0.21	0.00	0.0	0.58
FLYNN	2	3.0	0.88	0.22	0.04	20.2	0.40
FLYNN	2	2.4	0.50	0.06	0.00	0.0	0.34
FLYNN	3	3.4	1.65	0.56	0.11	20.2	0.88
FLYNN	3	1.8	0.65	0.14	0.00	0.0	0.55
FLYNN	3	2.3	1.05	0.29	0.00	0.0	0.85
FLYNN	3	3.2	1.18	0.19	0.00	0.0	0.79
FLYNN	3	2.7	0.90	0.17	0.00	0.0	0.46
FLYNN	4	1.8	1.25	0.37	0.16	44.4	1.01
FLYNN	4	3.7	1.48	0.29	0.10	34.6	0.79
FLYNN	4	5.2	1.66	0.24	0.00	0.0	0.61
FLYNN	4	2.7	0.88	0.16	0.04	27.8	0.61
FLYNN	4	4.9	1.78	0.58	0.19	32.0	0.52
FLYNN	4	2.3	0.82	0.24	0.00	0.5	0.49
TROUT	1	2.0	0.56	0.11	0.00	0.0	0.40
TROUT	2	2.7	1.73	0.85	0.00	0.0	1.07
TROUT	2	7.0	5.45	2.58	0.00	0.0	1.71
TROUT	3	3.0	1.02	0.23	0.11	46.9	0.46
TROUT	5	2.7	0.90	0.35	0.10	28.8	0.46
TROUT	5	1.6	0.46	0.05	0.00	0.0	0.76
TROUT	6	1.5	0.34	0.07	0.01	10.7	0.37
TROUT	6	5.0	2.87	0.65	0.65	100.0	1.22
TROUT	6	7.8	3.14	0.68	0.07	10.7	1.04
TROUT	6	2.1	0.98	0.31	0.02	6.0	1.07
TROUT	7	2.3	0.57	0.10	0.00	4.7	0.49
TROUT	7	1.5	0.29	0.04	0.01	32.0	0.43
TROUT	7	4.9	2.08	0.69	0.00	0.6	1.28
TROUT	7	4.1	1.14	0.23	0.04	15.4	0.49
BOULDER	1	2.3	1.06	0.18	0.01	4.7	0.82
BOULDER	1	9.4	4.18	0.99	0.00	0.0	0.91
BOULDER	1	2.8	0.95	0.21	0.01	2.5	0.70
BOULDER	3	2.7	0.92	0.28	0.00	0.0	0.52
BOULDER	3	5.9	3.62	0.99	0.00	0.0	1.43
BOULDER	3	2.9	0.73	0.12	0.00	0.0	0.49
BOULDER	3	3.6	3.43	1.23	0.04	2.9	2.44
BOULDER	4	2.1	0.94	0.41	0.00	0.0	0.64
BOULDER	5	1.2	0.48	0.08	0.00	0.0	0.67
BOULDER	5	3.4	2.43	0.91	0.00	0.0	1.37
BOULDER	5	4.4	2.69	1.30	0.02	1.3	0.82
BOULDER	5	11.3	5.16	1.09	0.46	42.0	0.98
BOULDER	5	4.3	0.81	0.09	0.00	0.0	0.37
BOULDER	5	4.6	1.12	0.20	0.20	100.0	0.52
BOULDER	5	1.8	1.13	0.36	0.00	0.0	1.07
BOULDER	5	4.9	5.72	3.04	0.00	0.0	1.89
S.FORK	1	1.8	0.46	0.08	0.00	0.0	0.43
S.FORK	1	2.1	0.62	0.12	0.00	3.1	0.61
S.FORK	2	1.6	0.84	0.16	0.00	0.0	0.85
S.FORK	2	8.8	12.12	5.67	0.00	0.0	2.74
S.FORK	3	1.5	0.34	0.04	0.00	0.0	0.37
S.FORK	4	4.9	1.75	0.36	0.00	0.0	0.64

APPENDIX C - continued

Reach	Length of undercut (m)	Area of undercut (m^2)	Volume of undercut (m^3)	Low-flow Volume of undercut (m^3)	Low-flow Volume of undercut (%)	Maximum horizontal depth (m)
CUMMINS 1	7.2	1.47	0.18	0.00	0.0	0.34
CUMMINS 1	2.3	1.24	0.32	0.04	11.1	0.82
CUMMINS 1	1.5	0.34	0.05	0.00	0.0	0.34
CUMMINS 1	4.5	2.36	0.84	0.05	6.0	0.85
CUMMINS 1	3.4	1.20	0.20	0.00	0.0	0.73
CUMMINS 1	5.4	1.94	0.64	0.01	1.7	0.58
CUMMINS 2	2.9	0.90	0.12	0.12	100.0	0.43
CUMMINS 2	9.4	4.75	0.78	0.22	27.8	1.04
CUMMINS 2	4.1	1.51	0.30	0.09	30.5	0.82
CUMMINS 2	12.5	27.71	6.43	0.00	0.0	4.57
CUMMINS 2	4.9	2.53	0.38	0.00	0.0	1.22
CUMMINS 2	5.2	4.38	1.21	1.21	100.0	1.55
CUMMINS 3	15.2	11.96	4.92	0.68	13.9	1.46
CUMMINS 3	4.3	1.04	0.11	0.03	27.8	0.40
CUMMINS 3	2.3	0.91	0.13	0.06	49.6	0.82
CUMMINS 3	7.1	3.25	0.54	0.00	0.0	0.91
CUMMINS 3	5.9	2.94	0.71	0.07	10.5	0.76
CUMMINS 3	2.4	1.08	0.64	0.32	49.8	0.61
CUMMINS 3	1.8	0.86	0.52	0.04	8.4	0.76
CUMMINS 4	6.7	5.06	1.85	0.54	29.0	1.46
CUMMINS 4	7.3	5.35	1.54	1.54	100.0	2.01
CUMMINS 4	6.7	2.20	0.44	0.10	22.2	0.61
CUMMINS 4	10.4	12.95	3.60	0.04	1.0	2.90
CUMMINS 4	5.2	3.44	0.97	0.02	2.5	1.28
CUMMINS 4	2.7	1.17	0.14	0.06	40.8	0.70
CUMMINS 4	5.6	2.84	0.66	0.30	44.9	1.07
CUMMINS 5	5.8	1.85	0.39	0.00	0.0	0.67
CUMMINS 5	3.0	1.37	0.64	0.01	2.1	0.91
CUMMINS 5	8.5	4.10	0.68	0.22	32.0	1.19
CUMMINS 5	11.6	3.71	1.23	0.00	0.0	0.61
CUMMINS 6	10.4	6.08	2.48	0.99	40.2	2.74
CUMMINS 6	2.1	0.73	0.22	0.00	0.0	0.58
CUMMINS 6	1.8	0.71	0.22	0.00	0.0	0.73
CUMMINS 6	13.4	6.95	2.35	0.69	29.6	1.16
CUMMINS 6	11.9	4.26	1.03	0.51	50.0	1.13
CUMMINS 6	6.7	6.95	2.19	1.09	49.9	2.71
CUMMINS 7	4.9	3.01	1.47	0.04	2.8	0.85
CUMMINS 7	7.6	13.59	5.80	0.95	16.3	2.59
CUMMINS 7	12.2	5.02	1.60	0.00	0.0	0.98
CUMMINS 7	12.5	2.76	0.80	0.01	1.5	0.43
CUMMINS 7	1.5	0.31	0.04	0.00	0.0	0.34
CUMMINS 8	5.8	3.53	1.05	0.53	49.9	1.22
CUMMINS 8	5.2	1.90	0.79	0.00	0.0	0.52
CUMMINS 8	2.7	1.48	0.44	0.04	8.9	1.07
CUMMINS 8	1.2	0.27	0.03	0.01	16.3	0.37
CUMMINS 8	4.6	2.02	0.46	0.00	0.0	0.70
CUMMINS 8	8.2	6.52	2.20	0.67	30.5	1.71
CUMMINS 8	4.9	3.16	0.85	0.11	12.5	1.19
CUMMINS 8	3.7	2.65	1.17	0.00	0.2	1.22

APPENDIX C - continued

Reach		Length of undercut (m)	Area of undercut (m^2)	Volume of undercut (m^3)	Low-flow Volume of undercut (m^3)	Low-flow Volume of undercut (%)	Maximum horizontal depth (m)
ROCK	1	1.8	0.46	0.06	0.00	0.0	0.46
ROCK	1	3.1	0.81	0.08	0.00	0.0	0.43
ROCK	1	3.8	1.49	0.43	0.00	0.0	0.70
ROCK	1	2.3	1.05	0.43	0.06	13.9	0.79
ROCK	1	3.4	2.32	0.47	0.08	16.3	1.19
ROCK	1	10.1	3.91	0.57	0.18	32.0	0.70
ROCK	1	2.7	0.90	0.14	0.00	0.0	0.49
ROCK	3	12.0	9.45	3.25	0.08	2.5	1.68
ROCK	3	6.1	2.18	0.49	0.22	44.9	0.82
ROCK	3	12.2	14.68	6.23	0.62	9.9	2.50
ROCK	4	1.8	0.53	0.09	0.04	48.6	0.55
ROCK	4	5.2	2.41	0.88	0.09	10.7	0.79
ROCK	4	9.1	3.21	0.59	0.22	36.7	0.70
ROCK	4	11.6	4.77	1.56	0.04	2.5	0.70
ROCK	4	3.0	0.86	0.11	0.04	32.0	0.64
ROCK	4	3.5	1.10	0.26	0.13	48.6	0.55
ROCK	6	3.9	1.68	0.26	0.06	22.2	0.67
ROCK	6	2.5	0.48	0.04	0.01	16.3	0.30
ROCK	6	5.9	1.27	0.21	0.10	50.0	0.37
ROCK	7	3.0	1.07	0.23	0.09	37.5	0.73
ROCK	7	2.5	0.78	0.12	0.06	48.0	0.52