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Title: Mass Erosion Occurrence and Debris Torrent Impacts on Some Streams in the Willamette National Forest

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This study focused on extensive soil mass movement occurrence in the Willamette National Forest of western Oregon and on intensive measurements of some physical and biological changes in streams following debris torrents. Debris torrents are a rapid movement of water-charged debris confined to steep headwater channels.

The frequency (events/ha/yr) of mass failures identified from aerial photos increased in the presence of clearcuts and roads relative to forest conditions. Approximately 71% of hillslope mass failures entered the stream channel, and an estimated 43% of hillslope mass failures resulted in debris torrents.

Standing crop of large organic debris and annual input to streams affected by debris torrents were highly variable. Silvicultural conditions of upslope vegetation and morphological

features of debris torrent tracks influenced woody loading and input. Old-growth streams and depositional stream sites contained higher amounts of large organic debris and received higher inputs of large organic debris than streams in clearcuts and erosional stream sites.

Depositional sites along debris torrent tracks have higher pool area and depth relative to erosional stream sites. Stream channel gradient and channel cross-sectional form influence the character of erosional or depositional sites sluiced by a debris torrent. Higher total pool ratings in depositional stream sites indicate spatial complexity of channel form that is related to the availability, transport, and stability of particulate bed materials.

Herbs produced the majority of foliar biomass (> 50% of total) in one-fifth of all stream sites. Shrubs produced the majority of foliar biomass in one-third of all stream sites. Stream sites where estimated foliar biomass of post-torrent plant strata exceeded estimated foliar biomass of residual plant strata were more numerous. Successional changes in clearcut riparian zones included a shift to intolerant deciduous overstory species and more numerous shrub species than in old-growth riparian zones. The diameter growth of tolerant late successional overstory species in these riparian zones was inconsistent, whereas diameter growth of early successional species was rapid.

Case studies of two streams permitted analysis of riparian recovery relative to that of an undisturbed stream site upstream of the debris torrent track. Warfield Creek is a stream where a high energy debris torrent remarkably altered stream conditions. Simmonds Creek is a stream where a low energy debris torrent imperceptibly changed stream conditions.

Channel slope, channel cross-sectional form, severity of debris torrent, position of stream segment within the drainage, and presence of channel obstructions all affect stream response to debris torrents, as do riparian vegetation and litterfall inputs to the stream.

Riparian recovery remains difficult to quantify because of physical and biological structures of stream ecosystems that vary in space and time.

Mass Erosion Occurrence and Debris Torrent Impacts on Some Streams in the Willamette National Forest

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I. INTRODUCTION

Mass erosion processes are generally the most dominant natural mechanisms of sediment transport from mountain slopes to stream channels. Erosion rates in forested mountain watersheds are highly variable, controlled by a combination of geologic, hydrologic, and vegetative factors. Slope disturbance caused by disruptive influences, natural or management-induced, disturbs the quasi-equilibrium between soil formation and soil loss.

Both oversteepened slopes and saturated soil conditions are implicated in the literature as principal contributors to soil instability and landslide hazard over a wide range of geologic conditions. Timber harvest and roadbuilding activity in particular are major initiators and accelerators of soil mass movement. Accelerated erosion due to forest management activities may result in reduced productivity of forest soils, damage to engineering works, and adverse impacts on the stream environment.

Two types of mass erosion may be classified on the bases of depth and rate of movement, mechanics, fluidity, and character of the mantle material. The first and most widespread type is mass movements of debris caused by initial failure in shallow soils overlying an impermeable surface. Examples are debris slides, avalanches, and flows on hillslopes, and debris torrents in channels. The second type, characteristically slow-moving, includes deep-seated soil creep, and slump-earthflows.

Debris torrents consist of the rapid movement of water-charged soil, rock, and organic material down steep stream channels. Debris torrents typically scour steep intermittent and first- and second-order channels. Torrents are frequently triggered by hillslope mass wasting and mobilization of in-channel debris in response to freshets. The slurry of material moving downstream commonly entrains soil, alluvium, and vegetation scoured from channel banks. These events pose a threat to engineering works downstream. Deposition of material forms debris jams which can impede anadromous and resident fish passage.

In forested watersheds, small streams are strongly influenced by the terrestrial ecosystem, and the physical and biological character of channels respond quickly to forest practices. Organisms in small forested streams depend on input of needle and leaf litter, twigs, branches, and large organic debris from the terrestrial ecosystem as a food resource. Nearstream vegetation provides a major portion of the annual energy input for running waters. Riparian vegetation, at the interface between terrestrial and aquatic environments, provides shade, channel bank stability through interlacing root networks, litter, nutrients, large organic debris, and a filtering mechanism for hillslope sediment and debris. Upslope vegetation affects stream function by influencing runoff characteristics and the rate of sediment transfer to streams. Hence, forest operations in headwater areas can have a pronounced effect on the aquatic environment (Gibbons and

Salo 1973; Moring and Lantz 1975; Burns 1972; Erman et al. 1977).

Debris in channels can greatly influence stream biology and sediment transport of small and intermediate size streams. First- and second-order streams in the Pacific Northwest usually contain large concentrations of debris, much of which may reside in the channel for decades. The kinetic energy of water and sediment routing is influenced by woody debris which tends to create a stepped longitudinal profile. The pool-riffle sequences formed by organic stepping create habitats and retention structures for food materials important to aquatic organisms.

The quantity and spatial distribution of large organic debris affect sediment storage and energy dissipation in steep headwater channels. Large debris is capable of deflecting or locally reducing streamflow velocities, altering the rate of energy dissipation by a stream and its movement of sediment.

This study is primarily concerned with the effects of debris torrents on certain channel characteristics of headwater streams in the Willamette National Forest. Scoured streams within the Willamette National Forest were located by aerial photo identification followed by ground verification of mass erosion events. This study will provide local forest resource managers with a comprehensive inventory of hillslope and channel events forest wide. This extensive view of mass erosion in the Willamette National Forest will be complemented by site specific, intensive study of in-channel mass erosion impacts.

Study Objectives

This research has two main objectives:

1. Determine the effects of roads and clearcuts and the occurrence of debris torrents in portions of the Willamette National Forest.
2. Determine rates of riparian vegetation recovery, measure physical habitat alteration, and quantify large organic debris loading in channels that have been subjected to debris torrents.

II. LITERATURE REVIEW

Soil Mass Erosion

Mass erosion, a slope sculpturing process, is generally the dominant natural mechanism of sediment transport from hillslope to stream channel in steep lands. Substantial literature addresses the occurrence and mechanisms of soil mass movement (Croft and Adams 1950; Bishop and Stevens 1964; Fredriksen 1956, 1970; Dyrness 1967; Gray and Brenner 1970; Swanston 1970; O'Loughlin 1972; Fiksdal 1974; Swanson and Swanston 1976, 1977; Pierson 1977; Swanson and Swanson 1977; Ketcheson and Froehlich 1977; Schuster and Krizek 1978; Gresswell, Heller, and Swanston 1979; Fredriksen and Harr 1979).

Slope stability is controlled by geomorphic, edaphic, biotic, and hydrologic factors interacting over the landscape to produce an equilibrium between force and resistance (Carson and Kirkby 1972). Mass erosion results from forces which overcome the resistance of soil mantle material to movement. Often they result from some triggering action that sets in motion an earth mass already on the verge of failure (Sowers and Sowers 1970).

Timber harvesting, road construction, and wildfire have a major impact on soil erosion processes (Dyrness 1967; Fredriksen 1970; Rice et al. 1971; Swanston 1971; Megahan 1972; Stone 1973; Fredriksen et al. 1975; Swanston and Swanson 1976; Swanson et al. 1979). The amount of soil lost due to management activities depends largely on the type of harvesting procedures employed in relation to susceptibility of the terrain to mass erosion. A particular forest practice may produce very different impacts on soil stability under differing geologic, vegetative, and climatic settings (Cromack, Swanson, Grier 1979). Though small watersheds are unique in space and time and exhibit a wide range of response to timber harvest, measurements of road and clearcut impacts indicate an increased amount of soil loss relative to undisturbed forest conditions (Dyrness 1967; Fredriksen 1970; Megahan and Kidd 1972; Swanston and Swanson, 1976; Swanson and Swanston 1976).

Mass Movement Processes

Mass movement processes can be classified into two types according to their principal movement mechanism, as described by Swanston and Swanson (1976). These types overlap geologic and physiographic boundaries and are controlled primarily by slope gradient, soil depth, soil water content, and specific soil physical characteristics. The first and most widespread type is mass movement of debris produced by an initial failure in shallow soils overlying an impermeable surface. This type includes, with increasing water content in the failure mass, debris slides, avalanches, flows, and torrents. Movement velocities are usually high with variable displacement volumes. The second type includes deep-seated and pervasive soil creep, and slump-earthflow.

Movement results from quasi-viscous flow and progressive failure of weathered mantle material. Movement rates vary from almost imperceptible creep (0 - 15mm/yr) to high-velocity flows; volumes are also highly variable.

The Role of Water in Initiation of Mass Erosion

Landslide occurrence and rainfall have been shown to be correlated (Hack and Goodlett 1960; Swanston 1967; Gonsior and Gardner 1971; Rice and Foggin 1971; Williams and Guy 1971; O'Loughlin 1972; Rapp and Stromquist 1976; Pierson 1977). In his study of Oregon Coast Range soils, Pierson (1977) found that infiltrating rainwater and antecedent moisture conditions are critical to the development of pore-water pressures that trigger soil mass movement. The buoyant force of pore water in the soil reduces the shear strength of a soil mass, creating conditions conducive to soil slippage.

Forests regulate hydrology through a combination of interception, evapotranspiration, and influence on snow accumulation patterns and snowmelt rate (Rothacher 1963, 1971, 1973; Anderson 1969; Harr 1976, 1981; Harr et al. 1979). Hydrologic influences afforded by an extensive cover of *Pseudotsuga menziesii*, *Tsuga heterophylla*, and other species are believed to enhance slope stability (Gray 1970; Swanston and Swanson 1976). Forest vegetation exercises some control over the amount and timing of water and snow. Trees are the principal source of soil water use. Their removal results in a higher stored water content in the soil at the end of the dry season. It is commonly believed, but this phenomenon is not well-documented, that with wetter soils, saturation and active pore-water pressure develop more rapidly during fall storms, increasing the risk for soil slippage (Swanston 1971). Froehlich (1979) reasons that the soil moisture status of shallow soils is essentially the same in soil mantles of harvested and forested hill-slopes at the time of greatest mass wasting, given the small amount of soil water present. Making site specific analyses involves uncertainty. Swanston and Swanson (1976) concluded that possible harvesting-related increases in peak discharge of surface and subsurface water were not known to influence deep-seated movement.

Rooting Influences

Plant roots stabilize soil mantles in the presence of clear-cutting and wildfire (Bishop and Stevens 1964; Endo and Tsuruta 1969; Swanston 1969; Gray 1970; Nakano 1971; Swanson and Dyrness 1975; Burroughs and Thomas 1977; Ziemer and Swanston 1977). The rooting networks of forest vegetation play a crucial role in stability of steep, shallow soils by adding mechanical strength to the soil mantle. Roots also distribute stress within the soil mass by transferring excess loads to the substratum (O'Loughlin 1972).

The decay of anchoring roots in shallow soils and root binders in all soils may greatly reduce the mechanical stability provided by roots (Swanston 1971; Burroughs and Thomas 1977). Bishop and Stevens (1964) and Swanston (1967, 1969) demonstrated the probable effect of roots on slope stability in southeast Alaska and correlated increased landslide activity with time after logging. A maximum loss of root strength occurs three to five years after cutting western conifers (Swanston 1970; O'Loughlin 1972, 1974; Burroughs and Thomas 1977). Ziemer (1981) reported that soil shear strength increases in proportion to root biomass in the soil. Burroughs and Thomas (1977) showed that small roots (< 1 cm) comprise the bulk of the total root system and deteriorate most rapidly in tensile strength compared with other size classes. Ziemer (1981) observed that shrub and hardwood species that commonly invade clearcut sites had stronger roots than conifer species. These shrub and hardwood species included elderberry, ceanothus, and golden chinkapin. The tensile strength of certain size roots of huckleberry invading clearcuts in southeast Alaska was similar to that of young western hemlock and sitka spruce (Ziemer and Swanston 1977). Rooting density decreases with increasing soil depth, so roots cannot stabilize soil if the potential failure surface is below the root system. The stabilizing effect of root networks may be negligible where failure planes exist below the effective rooting depth.

Roading Influences on Mass Wasting

Timber access roads far overshadow logging or fire as a cause of accelerated erosion (Dyrness 1967; Rothacher and Glazebrook

1968; Fredriksen 1970; O'Loughlin 1972; Cederholm and Lestelle 1974; Swanston and Swanson 1976; Swanson and Swanson 1977). Roads increase potential slope instability through all the factors created by deforestation. In addition, they disrupt the basic equilibrium of steepland forest soils by interrupting surface drainage (Dyrness 1967), altering subsurface water movement due to redistribution of soil and rock (Parizek 1971; Megahan 1972), and changing the distribution of mass on a slope by loading and undercutting.

Jensen and Cole (1967) reported about 90% of mass wasting which occurred along the South Fork of Idaho's Salmon River during a storm in April, 1965, was road-associated. The greatest number of these events were caused by road fill failures; next were failures due to road drainage construction. Road right-of-way area is small on managed forest land, less than 6% generally, but the incidence of mass failure related to roads is much higher than clearcut-related wasting (O'Loughlin 1972; Fiksdal 1974; Morrison 1975; Swanson and Dyrness 1975). However, a much smaller roading erosional impact relative to clearcutting was reported in the Mapleton district of the Siuslaw National Forest. Gresswell et al. (1979) believed that special efforts by district personnel to improve road design and maintain drainage structures substantially helped reduce road-generated soil failures.

Debris Torrents

Debris torrents are high-velocity mass wasting events in steep headwater channels. The debris, a slurry of water-charged soil, rock and organic material, may originate from an in-channel mobilization of debris or from a hillslope mass failure. Debris torrents commonly strip or scour large quantities of additional inorganic and organic material from the stream bed and banks. When a torrent loses momentum, the debris is deposited, usually as a tangled mass of woody debris in a matrix of sediment and fine organic matter. The main factors influencing the occurrence of debris torrents are the quantity and stability of debris in channels, steepness of channel, stability of adjacent hillslopes, and channel morphometry (Swanston and Swanson 1976). Debris torrents have been studied by only a few investigators in the Pacific Northwest (Fredriksen 1963, 1965; Morrison 1975; Swanson and Lienkaemper 1978; Ketcheson and Froehlich 1977; Swanson et al. 1977). In the western Cascade Range, their occurrence has been documented in only two small areas (Morrison 1975; Swanson, unpublished data) despite their significance in affecting biological and physical components of the stream ecosystem. Data from Swanson et al. (1976) indicate that debris torrents are commonly caused by material from road failures entering the stream channel.

Large Organic Debris

Though the residence times of large organic debris in stream channels in some instances may approach centuries (Keller and Tally 1979), the role of organic debris dams in the fluvial system has only recently received attention (Zimmerman et al. 1967; Heede

1972, 1975, 1976; Swanson et al. 1976; Bilby 1979; Keller and Swanson 1979). The streams of western Oregon and Washington are commonly loaded with a jumble of debris (tree tops, limbs, root wads, and entire trees) which greatly influences stream hydrology, biology, and sediment transport. Froehlich (1971, 1973) and others (Lammel 1972; Froehlich et al. 1972; Swanson and Lienkaemper 1978; Keller and Tally 1979; Keller and Swanson 1979) have quantified debris loading in streams. Froehlich (1972) observed a maximum accumulation of debris of 84.6 kg/m^2 in the channel. A recently sluiced out channel contained about 3.3 kg/m^2 of debris. Swanson (Franklin et al. 1981) observed a maximum accumulation of 43.5 kg/m^2 in a first-order stream in western Oregon.

Generally, stream size and debris loading are inversely related. Headwater streams tend to have narrow valleys and channels, steep hillslopes, high mass movement occurrence, and small drainage area, all contributing to an increase in debris loading (Keller and Tally 1979). Keller and Swanson (1979) measured a debris concentration in a first-order tributary 48 times higher than in the sixth-order mainstem river.

Total debris loading reflects a balance between input and export. Large organic debris is randomly located in first- and second-order streams where it initially fell. Channel morphology and hydrology generally permits debris redistribution in third- through fifth-order channels, forming definite in-channel accumulations (Swanson et al. 1976; Swanson and Lienkaemper 1978).

Larger rivers generally have scattered debris on islands, banks, or floodplains. Large organic debris minimally influences river functioning.

Large organic debris enters the stream channel through several processes, often acting in concert. Principal mechanisms include blowdown, hillslope mass failure, undercutting of channel banks, and timber harvest operations. Debris torrents and flotation redistribute in-channel woody debris, occasionally forming channel-wide jams.

Large Organic Debris and Physical Processes

Large organic debris markedly affects channel morphology and fluvial processes in headwater and intermediate-sized streams (Heede 1972, 1975, 1976, 1977; Keller and Tally 1979; Keller and Swanson 1979). The presence of logs effectively regulates the development of the stream's long profile (Heede 1972, 1975, 1976, 1977; Bilby 1979; Keller and Tally 1979) and provides a diversity of channel morphologies and sediment storage sites (Zimmerman et al. 1967; Swanson et al. 1976; Swanson and Lienkaemper 1978). Typically, a stepped bed profile results where there is a sequence of short, steep debris created cascades and long, low gradient sections along the streambed. Hence, a large portion of the stream's potential energy is lost in plunge pools, and less erosive work is performed on sensitive banks and bed. Keller and Tally (1979) found that 60% of the channel's drop in elevation in a second-order stream was debris related. Heede (1972), studying high elevation streams in Colorado, reported cumulative height of log steps to exceed 75% of the total fall of the channel bed.

Large organic debris has other effects on the physical and biological components of the stream ecosystem, including diversity of aquatic habitat (Sheridan 1969; Hall and Baker 1975; Meehan et al. 1977), areal sorting of bedload (Helmers 1966; Lotspeich 1978), and erosion-deposition patterns (Swanson et al. 1976; Heede 1977; Swanson and Lienkaemper 1978; Beschta 1979; Bryant 1980). A stepped profile creates a variety of channel depths. Large logs can cause differential scour resulting in a variety of channel depths (Beschta 1979). Variable channel depth and width are important in offering diverse habitats for aquatic biota (Swanson and Lienkaemper 1978). Large volumes of sediment are temporarily detained behind debris dams. Megahan and Nowlin (1976) reported that the annual sediment yield from an undisturbed watershed in Idaho averaged 10% of that stored behind obstructions. Organic debris comprised about 83% of these retention structures. Swanson and Lienkaemper (1978) report a similar degree of sediment retention within the H. J. Andrews Experimental Forest, with additional storage present within the channel system. Keller and Tally (1979) studied the coastal Redwood environment of northern California and found at least 50% of their storage sites were debris-related. These storage sites occupied 40% of the channel area.

Sedimentation

Disturbance resulting from timber harvesting practices which alter the stream environment through increased sedimentation can directly affect the biological components of the stream system as well as downstream water quality and beneficial uses (Cordone and Kelley 1961; Bjornn et al. 1974; Brusven and Prather 1974; Fredriksen et al. 1975; Siegfried and Knight 1977; Bjornn et al. 1977). Sediment yields related to logging activities have been considered by a number of a researchers in recent years (Packer 1967; Dyrness 1967; Sheridan and McNeil 1968; Megahan and Kidd 1972; Fredriksen et al. 1975; Megahan 1975; Dyrness 1975). Road construction is implicated as the most serious cause of erosion and sedimentation (Rice and Wallis 1962; Fredriksen 1965, 1970; Anderson 1970; Brown and Krygier 1971; Megahan 1975; Fredriksen et al. 1975; Swanston and Swanson 1976; Beschta 1978). Patterns of increases in annual sediment yield for recently roaded watersheds are highly site specific; investigators have found initial increases ranging from 2.2 (Fredriksen 1970; Brown and Krygier 1971) to 45.2 (Megahan and Kidd 1972) times greater than the sediment yield from undisturbed watersheds. Sediment yields generally decrease with time after logging and roading.

The excess storage capacity afforded by large organic debris ameliorates sedimentation impacts downstream (Fredriksen et al. 1975; Swanson and Lienkaemper 1978; Keller and Tally 1979). Debris is significant in the routing of sediment through the fluvial system by providing an upstream buffer when pulses of sediment enter the stream. Hence, the impacts of natural and management-related mass failures on the stream ecosystem may be lessened. The stepped profile tends to rout sediment through the stream ecosystem in a slow trickle. Stream reaches scoured to bedrock by debris torrents are subject to rapid transfer of bedload.

Large Organic Debris and Biological Processes

Within limits, large organic debris is necessary for a healthy stream environment (Hall and Baker 1975). The presence of large organic debris allows a complex pattern of flow velocities and depths to develop, thus permitting areal sorting of bedload material (Swanson and Lienkaemper 1978; Keller and Tally 1979). Sprules (1947) reported that diversity of benthic fauna found on any particular type of bottom in Ontario was related to the variety of utilizable microhabitats associated with the substrate character. He also reported that the disruptive effect of a freshet was minimized in areas where the bottom was composed of large particles which provided shelter. Smith and Moyle (1944) and others found that insect production is higher in rubble and decreases as the substrate becomes composed of finer materials. The importance of benthic fauna in the stream ecosystem includes abundant evidence to support the view that deposition of inorganic sediment will damage and reduce bottom fauna, and in many cases, will thus adversely affect salmonid populations (Cordone and Kelley 1961). Numerous authors have made similar conclusions (Hollis et al. 1964; Gebhardt 1970; Koski 1972; Gibbons and Salo 1973; Reiser and Bjornn 1979).

Large organic debris plays a key role in retaining fine organic debris in streams for subsequent biological processing. Triska and Sedell (1975) estimate that 60-70% of the annual organic inputs to small streams in the Pacific Northwest are retained long enough to be utilized by stream organisms. Organic debris in streams increases diversity of aquatic habitat by forming pools and protected backwaters, serves as a source of nutrients and substrate for biological activity, and affects sediment movement and storage by dissipating energy of flowing water and trapping sediment (Triska and Sedell 1976; Swanson et al. 1976; Triska and Sedell 1977; Anderson et al. 1978).

Stream Ecology

The stream ecosystem, from headwaters to rivers, is a continuum of process zones characterized by qualitative differences in organic inputs along the system (Vannote et al. 1980). A basic feature of the conceptual scheme is the decreasing influence of streamside vegetation and increasing importance of inputs from upstream tributary systems progressively from headwaters to mouth (Cummins 1975). Wood-consuming organisms ("shredders"), the major representative functional group in first- to third-order streams (Cummins 1975), depend heavily on inputs of terrestrial detritus. Larger streams (fourth to sixth order) are inhabited by grazers, collectors, and predator organisms, which feed on periphyton, suspended fine particulates, and live prey, respectively (Cummins and Klug 1979). Fish populations grade from consumers of insects, to fish and benthic insects, to benthic insects and plankton, progressing from headwaters to rivers (Cummins 1975).

Small headwater streams are of tremendous importance in the production of salmon and anadromous trout in the Pacific Northwest. Hall and Baker (1975) reported that Needle Branch, in the Alsea Watershed study, supported a population of resident and anadromous cutthroat trout and spawning populations of up to 80 adult coho salmon, although the stream's summer flow was almost negligible (0.01 - .02 cfs). They believe that any stream of suitable gradient, regardless of size, should be considered important as potential fish habitat.

The role of large organic debris in streams with respect to fish populations, is not well-documented. Many researchers studying the carrying capacity of trout streams have alluded to the importance of cover in a stream (Tarzwell 1937; Boussu 1954; Giger 1973; Reiser and Bjornn 1979). Hartman (1965) observed that coho and steelhead tended to reside in areas of log jam cover. Bustard and Narver (1975) in studying the behavior of juvenile coho and steelhead in British Columbia, noted a high level of utilization of natural debris as winter cover. Toews and Moore (1982) observed the effects of streamside logging on the stability, quantity, and distribution of in-stream debris in British Columbia. Recently logged streams contained less in-stream mobile debris than in steams that were not logged. Long-term (nine years) population surveys indicated increased fry utilization in summer immediately after logging and a decrease in coho fry density with the redistribution of debris by winter storm flows. Bishop and Shapley (undated), in their study of log jams in southeast Alaska on debris-sediment relationships, cited a significant reduction in the percentage of fines (less than 1.65 mm) in the gravel downstream of log jams and an increase in the intragravel dissolved oxygen level. Bisson and Sedell (1982) observed shifts in the species and age group composition of steelhead, coho, and cutthroat trout that resulted from habitat changes accompanying timber harvest and debris removal. Loss of pool volume caused a decline of coho and older cutthroat but underlying steelhead increased. The removal of large organic debris in a Coast Range stream in Oregon was shown to accelerate the downcutting of previously stored sediments (Beschta 1979), resulting in increased levels of turbidity and suspended sediment during several storms after debris removal. Increased bedload movement after debris torrents or log jam removal can cause shifts in community structure of aquatic life. The smothering effect and instability of sediment reduce invertebrate diversity and populations (Tebo 1955, 1957; Burns 1972; Brode 1973), reduce available living space for fish (Hollis et al. 1964; Phillips 1971), and reduce early survival of fish (Wickett 1958; McNeil and Ahnell 1964; Hall and Lantz 1969). Reiser and Bjornn (1979) review the habitat requirements of anadromous salmonids in more detail.

Riparian Vegetation

Riparian vegetation has historically been defined as vegetation rooted at the water's edge (Franklin and Campbell 1979), but functionally, riparian vegetation includes all floodplain and hillslope vegetation which provides shade and detritus to the stream (Meehan et al. 1977). Riparian zones can be viewed from temporal and spatial perspectives.

From a temporal perspective, the effectiveness of riparian zones in regulating inputs of light, dissolved nutrients, and detritus is reflected in streamside vegetation patterns shaped by topography, stream gradient, substrate type, and incidence of slope and channel disturbances such as wildfire, recent floods, and mass wasting. Riparian succession at maturity is characterized by a conifer overstory, deciduous shrub layer, and herbaceous ground cover in the Pacific Northwest. Permanent immaturity may be a prime characteristics of an active riparian zone (Franklin and Campbell 1979), but increasing maturity of the adjacent forest does affect riparian vegetation through shading and competition.

From a spatial perspective, the effect and character of streamside vegetation changes with stream order. Headwater streams are maximally influenced by shading and detrital inputs from near-stream vegetation. Riparian zone change in the downstream direction reflects the increasing importance of deciduous floodplain vegetation relative to the coniferous hillslope vegetation. As the floodplain generally widens with increasing stream order, communities of deciduous trees become more widespread as larger canopy openings favor their development. Wider streams have less riparian influence.

Community composition along headwater streams varies widely from one stream to another, no one stream reach supporting all communities. Franklin and Campbell (1979) believe that community composition in low order reaches is essentially random, depending upon seed sources, particle size of the seed bed, light availability, elevation, and sediment movement.

In the western Cascades, all pioneer species have special requirements for establishment not met in the understory of a mature stand. Red alder and willow, pioneers with vigorous juvenile growth, characteristically establish themselves in disturbed segments of the riparian zone. Red alder is an important pioneering hardwood in riparian zones in the Pacific Northwest and southeast Alaska (Trappe et al 1968; DeBell et al. 1978). Early senescence of alder (50 - 80 years) leads to succession in coniferous stands, wherein an overstory of western hemlock and small quantities of western red cedar and Douglas-fir remain

(Newton et al. 1968). The relative richness of vegetation under stands of alder (pure and mixed) has been noted (Sharpe 1956; Franklin and Pechanec 1968). Franklin and Pechanec (1968) noted a higher coverage of shrub and herb layers in stands in the Cascade Head Experimental Forest in Oregon.

Little documentation exists as to the role and importance of herb and shrub litter in the trophic relations of aquatic insects (Hynes 1970; Cummins et al. 1973). Generalizations of aquatic insect food habits are usually based on incomplete studies (Cummins 1973). Riparian zones composed of three distinctive strata (overstory, shrub, herb layer) in mature stages of riparian succession permit a sequencing of utilization of inputs (Mahan 1980). This results in rich and diverse populations of aquatic invertebrates which perceive the timing and varied quality of the detrital input (Meehan et al. 1977). Food quality for biota and overall production of species have important implications for stream functioning as fish food production areas (Chapman 1966; Reiser and Bjornn 1979). A diverse riparian community structure providing diverse habitats may also play an important role in producing food for salmonids, as terrestrial insects are also important food items (Sekulich and Bjornn 1977; Reiser and Bjornn 1979).

The riparian zone provides organic debris to the channel, creating pools and protective cover for salmonids. Streamside vegetation regulates stream heating through shading, sediment input through filtering, and provides bank stabilization and overhanging cover by interlacing root networks (Meehan et al. 1977).

III. STUDY AREA DESCRIPTION

Climate

The climate of the Willamette National Forest is moderated by the Pacific Ocean 150 kilometers to the west. Moist maritime air masses moving east deliver precipitation to the western slope of the Cascade Range, usually during long duration (18 - 72 hr.) frontal storms of low intensity (less than 12 mm/hr.) (Harr 1981). Locally, precipitation caused by the position and intensity of high and low pressure systems over the ocean is augmented by orographically controlled precipitation.

Precipitation is lowest on the major valley floors and increases with elevation. In normal years, approximately 80% of the total annual precipitation falls between October 1 and April 1. Precipitation varies from 120 cm on valley floors to 300 cm on the higher ridges. Temperature variations range from a recorded winter low of -26°C at Santiam Pass to a recorded high of 43°C at Oakridge Ranger Station. See Table 1 in the Appendix for a climatic summary.

During fall and winter, low pressure systems form in the Pacific Ocean and frontal storms with southwesterly flow are common. In some years, areas below 800 meters are snow-free year-round. Above 1100 meters, from between one-third to over three-fourths of annual precipitation may fall as snow. In this elevational zone, snowpacks persist from early December to late April.

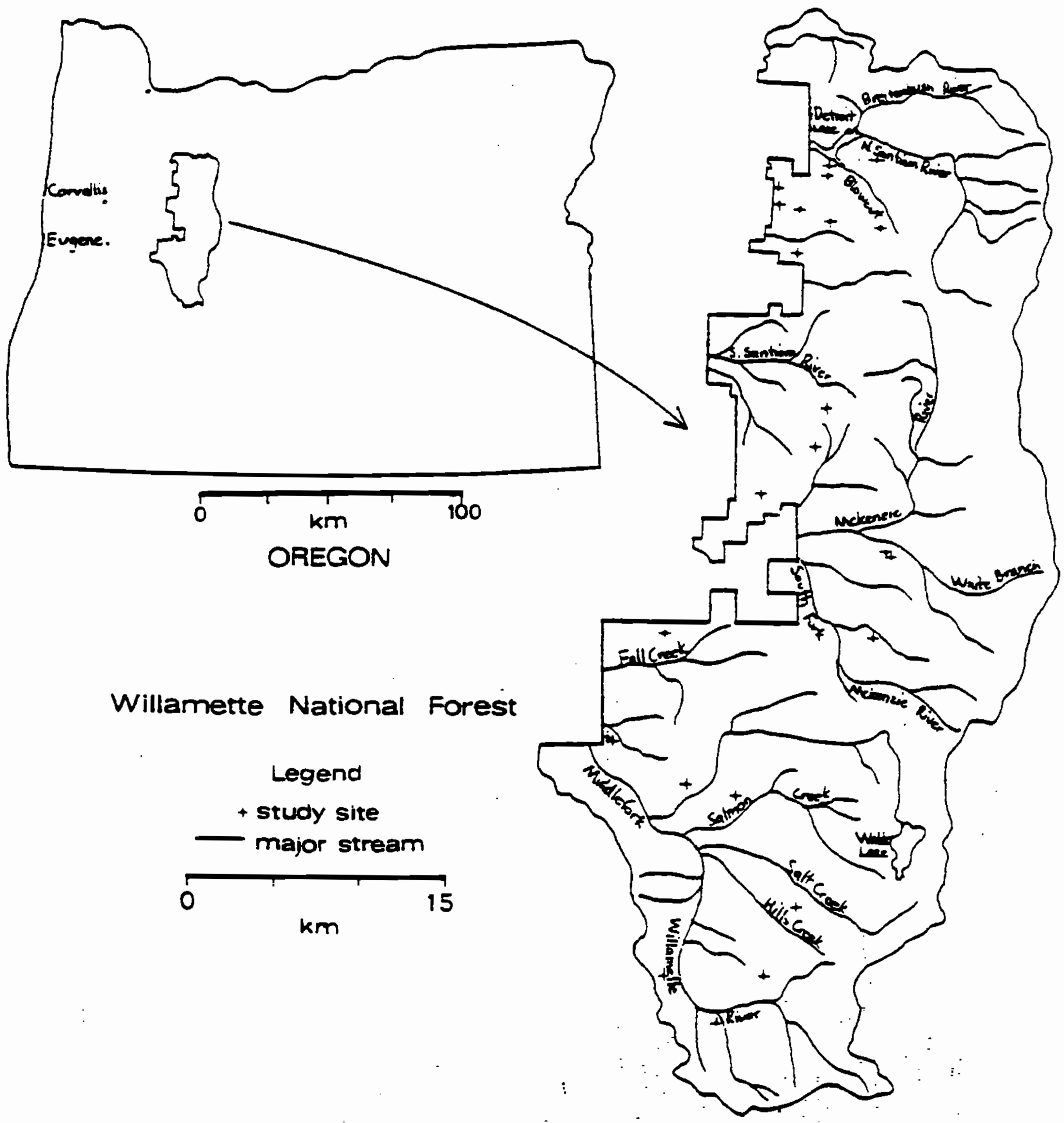

Figure 1. Location of study sites within the Willamette National Forest.

Average total snowfall ranges from 100 to 220 cm.

In the H. J. Andrews Experimental Forest, Blue River drainage, annual peak stream discharge occurs in the period between November and January, typical also of other basins within the Willamette National Forest. Rain-on-snow conditions have produced some of the highest peak flows on record (Harr 1981).

During mid- to late spring, high pressure systems become more common, resulting in prevailing northwesterly air flow. These circulation patterns bring dry and warm conditions which persist through the summer. A summer drought period is common, creating a situation conducive to forest fires.

Geology

Mass erosion activity investigated in this study occurs within the Western Cascades physiographic region, as defined by Baldwin (1959) and Franklin and Dyrness (1973). The Western Cascades, which form most of the west slope of the Cascades, are characterized by a dendritic drainage pattern on Tertiary volcanic rocks. Peck and others (1964) have mapped two major stratigraphic units within the Willamette National Forest: the Little Butte Volcanic Series and the Sardine Formation.

The Little Butte Volcanic Series is predominately composed of tuffs and breccias, with small amounts of andesite and basalt. The rock materials of this series, when exposed to weathering, tend to spall and break down easily. Deep colluvial and residual soils from this series can develop on moderate slopes and give rise to a condition of natural instability. The soils are characteristically high in clay content, cohesive, poorly drained, with rotational and translational failures common in both the soil and underlying bedrock.

The Sardine Formation is composed of andesitic and basaltic flow rock, tuffs, and breccias. In general, the bedrock materials in this formation are less altered and more stable than those found in the Little Butte Volcanic Series. Soils forming from these lava flow materials are generally more stony, coarser in texture, and better drained than soils derived from volcaniclastic bedrock.

The characteristics of parent material have a major effect on the relative strength of the soil mantle in this area. The fine-grained, extensively altered volcaniclastic rocks characteristic of the Little Butte Volcanic Series tend to form sloping terrain subject to creep and slump-earthflow types of mass failure (Swanston and Swanson 1976). Conversely, residual soils developed from lava flows and basaltic intrusion, characteristic of the Sardine Formation, are more subject to shallow mantle failures of the debris avalanche-debris torrent type. Both shallow and deep-seated failures are major agents of soil material transport to streams in the area.

Vegetation

The Willamette National Forest is part of the Tsuga heterophylla Zone (Franklin and Dyrness 1973). Large portions of the forest are dominated by Pseudotsuga menziesii (Douglas-fir). Other major forest tree species include Tsuga heterophylla (western hemlock) and Thuja plicata (western red cedar). Pinus ponderosa (ponderoda pine) occurs sporadically in the drier, southern portions of the study area, and Abies amabilis (Pacific silver fir) and Abies procera (noble fir) occupy the upper elevations. Hardwoods are uncommon, except on recently disturbed sites or along riparian corridors. These subordinate species include Alnus sp. (red alder and Sitka alder), Acer macrophyllum (bigleaf maple), Populus trichocarpa (black cottonwood), and Salix sp. (willow).

Common shrubs and herbs which occupy the understory include, along a gradient from hot, dry sites to cool, moist sites: Holodiscus discolor (creambush oceanspary), Castanopsis chrysophylla (golden chinkapin), Rhododendron macrophyllum (Pacific rhododendron)/Gaultheria shallon (salal), Berberis nervosa (Oregon Grape), and Polystichum munitum (sword fern). Additional discussion of shrub and herbaceous species is found in work by Campbell and Franklin (1979).

The forests of this area represent optimal development of the temperate coniferous forest. Evergreen conifers dominate deciduous hardwoods. Kuchler (1946) estimated the ratio of hardwoods to conifers at 1:1000. Hardwoods are most common on stressful sites as pioneer species. In old-growth forest, the dominant conifers are long-lived and achieve large sizes. Biomass accumulation of old-growth ecosystems here are among the highest of any plant communities in temperate zones (Franklin 1979).

Secondary succession following disruption or destruction of a forest stand by wildfire or timber harvest follows a generalized sequence, though dependent upon site conditions and disturbance severity. The sequence begins with a weed state that lasts from 4 to 5 years. Invading annual and perennial herbs prevail, and residual herbs may constitute significant cover. A shrub-dominated period gradually develops; common species are *Acer circinatum* (vine maple), *Rhododendron macrophyllum* (Pacific rhododendron), *Rubus* sp. (blackberry), and *Salix* sp. (willow). This stage continues until tree samplings overtop the shrubs, after about 10 to 25 years (Isaac 1940; Dyrness 1973).

The young forest stands are highly variable with respect to composition and density. Development of dense, almost pure, even-aged stands of Douglas-fir is common. Western hemlock or red alder are two other species which may dominate suitable sites.

Ecologists have observed some variation in late successional trends. On most sites, western hemlock is the sole climax species. On very dry sites, western hemlock is absent, and

Douglas-fir attains a climax role. On very wet sites, western red cedar will play a significant role in the climax stand. Western hemlock can reproduce itself under a forest canopy whereas Douglas-fir cannot. In the absence of disturbance, western hemlock will eventually replace Douglas-fir.

IV. THE EXTENSIVE STUDY

Methods of Soil Mass Erosion Detection

Preliminary site selection began with air photo identification of mass erosion occurrence in the Willamette National Forest (Fig. 1). Aerial photo survey of these mass erosion events was confined to those slides displacing more than approximately 75 cubic meters of material. A series of photos taken in the years 1949, 1959, 1967, 1972, providing complete coverage of the WNF, were studied closely. The 1979 airphotos, which covered 60% of the forest, were also studied. Individual mass erosion occurrences were described on an aerial photo identification worksheet (Fig. 1, Appendix), listing geomorphic characteristics, and cause of features.

For purposes of this study, soil mass wasting includes several types of shallow, translational slides (debris slides, debris avalanches, debris flows) and one type of deep-seated, rotational slide (slump). Difficulty in detecting occurrence of earthflow and soil creep in aerial photos prevented their inclusion into this study.

Air photo identification of mass erosion in forested areas is difficult because of canopy closure, so it is unlikely that all events were located. No ground search was conducted in the forested areas to determine the probable underestimation of slide frequency. Identification of clearcut and road-related mass erosion is relatively certain because they are highly visible on the landscape. Enumeration of mass erosion related to clearcuts and roads is conservative because small (< 75 m^3), multiple failures in close proximity (< 100 m) were tallied as one event, rather than separately. The result may be an underestimation of mass erosion frequency for the three land uses.

Mass erosion inventory by aerial photos provides a reasonable approximation of slide activity. Numerous small slides were probably missed. It is likely that large slides that transport the greatest volume of material were accounted for in this inventory.

A debris torrent is defined in this study as: (1) movement of a mass of debris down a channel for at least 50 meters; and (2) channel scour resulting from one discrete mass failure (initiated either by mobilization of debris in the channel or by a mass movement from the hillslope). Streams studied were third-order or smaller, and had been subjected to a torrent within the past 50 years.

Results and Discussion of Aerial Photo Survey

A total of 232 mass erosion events, spanning approximately 50 years, were identified from airphotos of 6700 Km^2 of the Willamette National Forest. Data collected on each mass failure included geographic location, map information, geomorphic characteristics, and failure origin.

Dates of mass erosion events were identified by the earliest airphoto series in which the slide occurred. The accuracy of dating mass erosion events was judged to be within four years of actual occurrence. Over half of the mass failures were identified from the 1967 airphoto series, probably reflecting the slide-producing storms of December 1964 - January 1965, the most severe of the entire period of airphoto record (Harr 1981).

To locate debris torrent sites for the intensive study of riparian recovery, 38% of the total mass failures identified from airphotos were visited (Table 1). The failure sites were checked to verify their point of origin and whether the hillslope failure mass entered a stream channel.

Over the period of record, the percentage of hillslope mass erosion events that entered the stream channel remained relatively constant, approximately 71% (Fig. 2). The fate of some of these failure masses in the channel was investigated further in the intensive study on riparian recovery from debris torrents.

Road and clearcut mass erosion frequency is higher than forest mass erosion frequency (Table 2). In comparison to forested areas, road mass erosion frequency ranged from 11 to 705 times greater over the 49-year study period. Clearcut mass erosion frequency, compared to road mass erosion frequency, was far lower, ranging from 4 to 22 times greater than the mass erosion frequency in the forest. The highest frequency of mass erosion for all three land use classes was observed in the 1967 airphoto series.

Table 1. Aerial photo identified soil mass movements that were field checked.

air photo series	forest	land use clearcut	road
1949	5	0	0
1959	7	0	1
1967	18	11	33
1972	1	1	7
1979	0	1	5
total	31	12	46

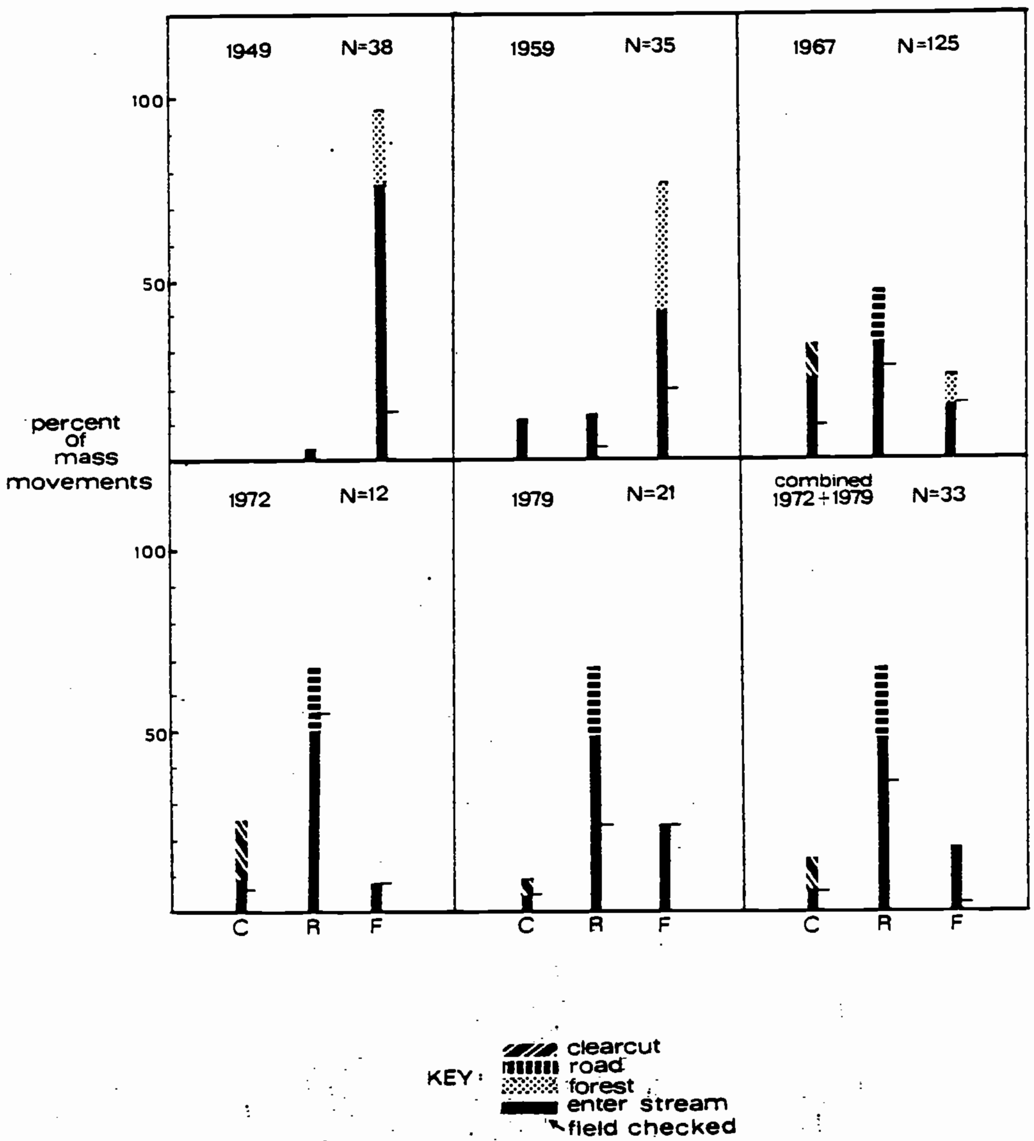

Figure 2. Land use effects on the occurrence of airphoto identified mass erosion features in the Willamette National Forest.

Table 2. Frequency of soil mass movement in the Willamette National Forest for three land uses over time.

airphoto year	total number events	# cc	Clearcut ev/km^2/yr	# rd	Road ev/km^2/yr	# for	Forest ev/km^2/yr	t	land use area* km^2 for	cc	rd	mass failure frequency (xforest) rd	cc
1949	38	0	0	1	4.1×10^{-3}	37	3.7×10^{-4}	19	5241	42	13	11.1	--
1959	35	4	2.0×10^{-3}	4	1.8×10^{-2}	27	5.4×10^{-4}	10	5041	199	22	33.3	3.7
1967	125	40	9.9×10^{-3}	57	1.6×10^{-1}	29	7.7×10^{-4}	8	4689	507	44	207.8	12.9
1972	12	3	9.6×10^{-4}	8	3.1×10^{-2}	1	4.4×10^{-5}	5	4562	627	51	704.5	21.8
1979	21	3	6.1×10^{-4}	14	3.3×10^{-2}	4	1.3×10^{-4}	7	4480	700	60	253.9	4.7

*combined area of the three land uses decreases over time due to water impoundments

The frequency of clearcut and road-related mass erosion related to mass erosion frequency in forest is similar to that found in other studies in the region (Swanston and Swanson 1976; Swanson and Swanson 1977; Marion 1981). Evidence indicates that roading continues to contribute to highest mass erosion frequency.

The overall frequency of mass erosion for each of three land uses in this study is much lower than reported elsewhere in selected drainages of the Willamette National Forest (Morrison 1975; Swanson and Dyrness 1975; Marion 1981). The underestimation of mass erosion frequency in this study is due to the use of an airphoto-based inventory of slide activity. An airphoto inventory of mass erosion occurrence is not as accurate as ground-based detection.

Soil transfer rates provide a means of assessing the changes in sediment delivery to fluvial systems as a result of hillslope mass wasting. Since volume determinations of soil mass movements inventories by aerial photos were not made, this study does not address soil transfer rates.

V. THE INTENSIVE STUDY

Methods of Stream Selection

The entire length of a torrent track was walked to establish stream sites for measuring large organic debris, physical habitat alteration, and riparian zone alteration. A few streams lent themselves to an upstream non-scoured vs. downstream scoured comparison. For all but two streams, the torrent track included only two 50-meter sites, one erosional and the other depositional. Two streams (Warfield and Simmonds) had an upstream control site unaffected by debris torrent passage, in addition to erosional and depositional reaches.

Erosional and depositional sites were selected to be representative with respect to large organic debris loading (quantity, position, input class), channel physical features, and vegetation structure and biomass. Though a certain degree of subjectivity could not be avoided in site selection due to the heterogeneous nature of small watersheds, efforts were made to select purely erosional and depositional sites based on physical features which affected debris torrent routing, such as changes in channel and hillslope gradients, bends and constrictions in the channel, width of floodplain, distribution of logs and boulders, and presence or absence of scarred tree boles, indicative of the passage of a debris torrent, all of which affect torrent movement.

Stream site selection was also based on interpretation of large organic debris loading characteristics and riparian zone structure. Clues such as the position of individual logs, fire-scarred exteriors, degree of wood deterioration, presence or absence of pioneering vegetation such as alder and willow aided in the interpretation of torrent tracks.

Methods of Measurements

The riparian zone, for the purposes of this study, is a 50-meter zone along the stream and extending one bankfull channel width up from the water's edge onto both banks. Measurements of large organic debris, channel physical structure, and riparian vegetation were confined to this zone (Fig. 2, Appendix).

Large Organic Debris

Woody debris greater than 10 cm diameter, not appreciably rotted and heavily colonized by mosses and saphrophytic fungi, was defined as large organic debris (LOD). "Appreciably rotted" debris would shatter if subjected to the force of a peak flow. Position of large organic debris was noted as either "channel," "bank," or "potential." Classification of pieces as either "channel" or "bank" was arbitrarily set at more than two-thirds the length of the piece occupying either channel or bank, respectively. "Potential" LOD pieces were defined as being positioned a minimum of one meter above the level of annual high flow of the stream, and which could eventually enter the channel. LOD was classified as either "torrent moved," "post-torrent input," or "of ambiguous origin." Length and diameter, maximum and minimum, were recorded to the nearest centimeter with loggers tape and calipers. Mass of LOD within study sites was calculated as metric tons per 50 meters, using Smalian's rule (Dilworth 1973) and assuming 0.50 g/cm^3 as the density for wood.

Physical Habitat

Morphometric features important in creating channel physical habitat were measured. Channel width, depth, and bankfull channel width were measured at each ten-meter interval. Along the channel axis, pools were measured for length, width, depth, and cover; qualitative measurements included predominant size of bottom material, embeddedness, and pool-forming feature (log, boulder, cobble, bedrock). Boulders were defined as being > 25 cm in diameter, cobbles, 8 - 25 cm diameter. Channel and hillslope gradient (percent), and aspect (degrees), were measured with an inclinometer and compass.

Riparian Vegetation

Three distinctive riparian vegetation strata were measured. The overstory component was measured throughout the 50-meter stream segment. Herbaceous and shrub communities were sampled at three transects laid perpendicular to the stream center (Fig. 3, Appendix). Stand density of deciduous and coniferous overstory vegetation by stem diameter classes was determined. Foliar biomass of ground cover, shrubs, and trees was computed using equations of Gholz et al. (1979) (Table 3, Appendix). The equations provide an estimate of foliar biomass. The information provided from this portion of the study can be used to index the condition of streamside vegetation-groundcover, understory, and overstory.

Results and Discussion

Large Organic Debris Accumulations

Standing crop of large organic debris (LOD) for streams subject to debris torrents ranged from 0 to 35.2 kg/m^2 for erosional reaches and from 0 to 36.9 kg/m^2 for depositional reaches (Table 3, Appendix). These patterns are consistent with values obtained in other western Oregon streams flowing through forested, mountainous terrain (Froehlich 1973; Swanson, in Franklin et al. 1981). The means of LOD standing crops were not analyzed because of high standard deviations about the means. Patterns of LOD loading reveal a high number of depositional sites containing over 10 kg/m^2 LOD and a high number of erosional sites containing less than 5 kg/m^2 LOD. Four times as many depositional sites had total LOD in excess of 10 kg/m^2 compared to erosional sites (Fig. 3). Almost twice as many erosional sites had less than 5 kg/m^2 compared to depositional sites. There were similar numbers of

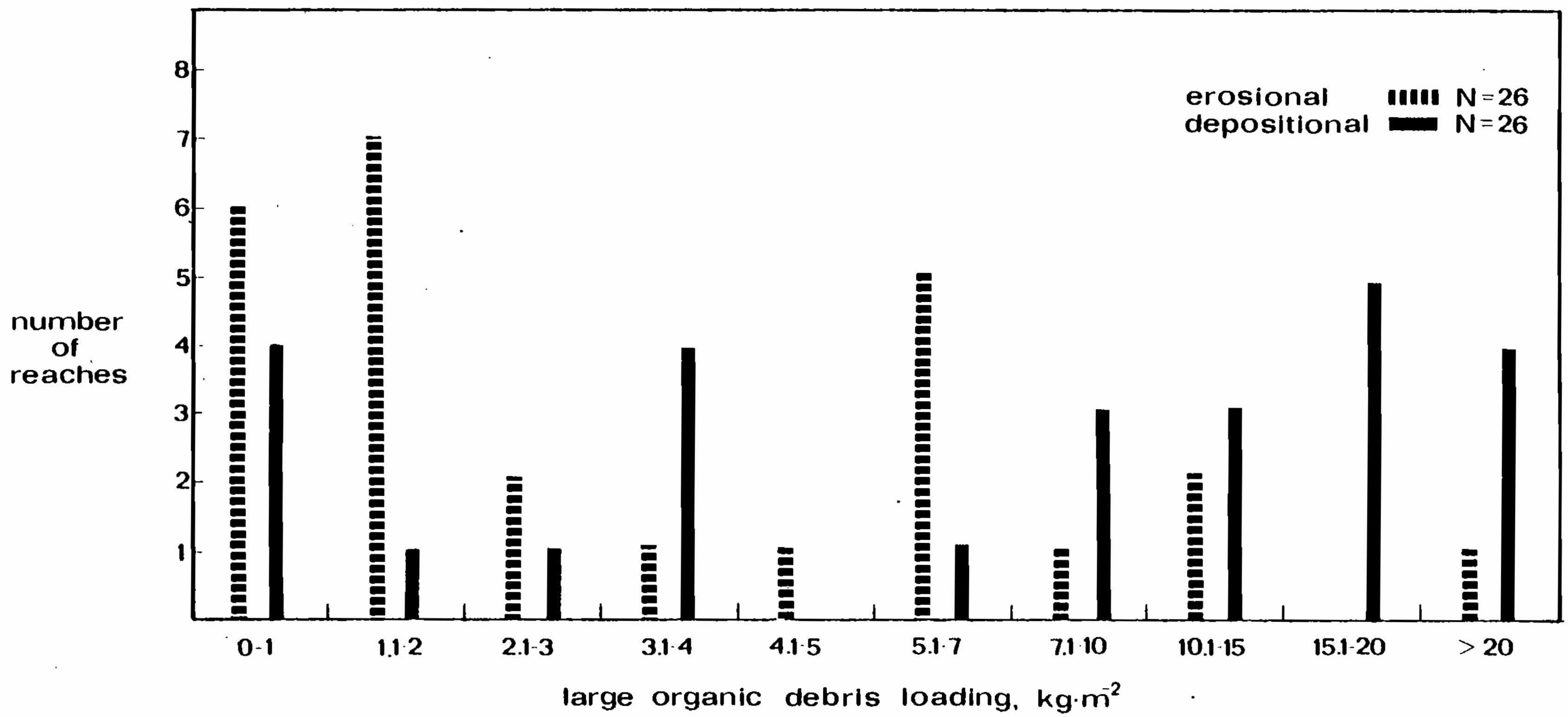

Figure 3. Large organic debris accumulations in erosional and depositional reaches subject to debris torrents.

erosional and depositional sites with LOD between 5 and 10 kg/m^2.

Comparison of total LOD in clearcut (N = 19) and old-growth (N = 33) streams shows patterns similar to erosional and depositional sites: a high number of sites had LOD accumulations that were greater than 10 kg/m^2 and less than 2 kg/m^2 (Fig. 4). One-half and one-third of clearcut (N = 19) and old-growth (N = 33) sites contained less than 2 kg/m^2 LOD. One-third of old-growth sites had LOD exceeding 10 kg/m^2; 40 percent of clearcut sites had LOD exceeding 5 kg/m^2.

LOD Annual Input

Annual LOD input to old growth and clearcut streams after a debris torrent was highest in old-growth streams (Fig. 5). The rank order of increasing LOD input to streams is depositional-clearcut (N = 8), erosional-clearcut (N = 11), erosional-old growth (N = 15), and depositional-old growth (N = 18). LOD input to clearcut streams is similar for erosional and depositional stream sites. The erosional and depositional-old growth stream sites had wide differences in LOD input. The higher input to old-growth compared to clearcut sites is due to the greater availability of woody debris in the riparian zone.

Without consideration of silvicultural condition, LOD input to depositional (N = 26) sites was much greater than input to erosional (N = 26) sites (Fig. 5).

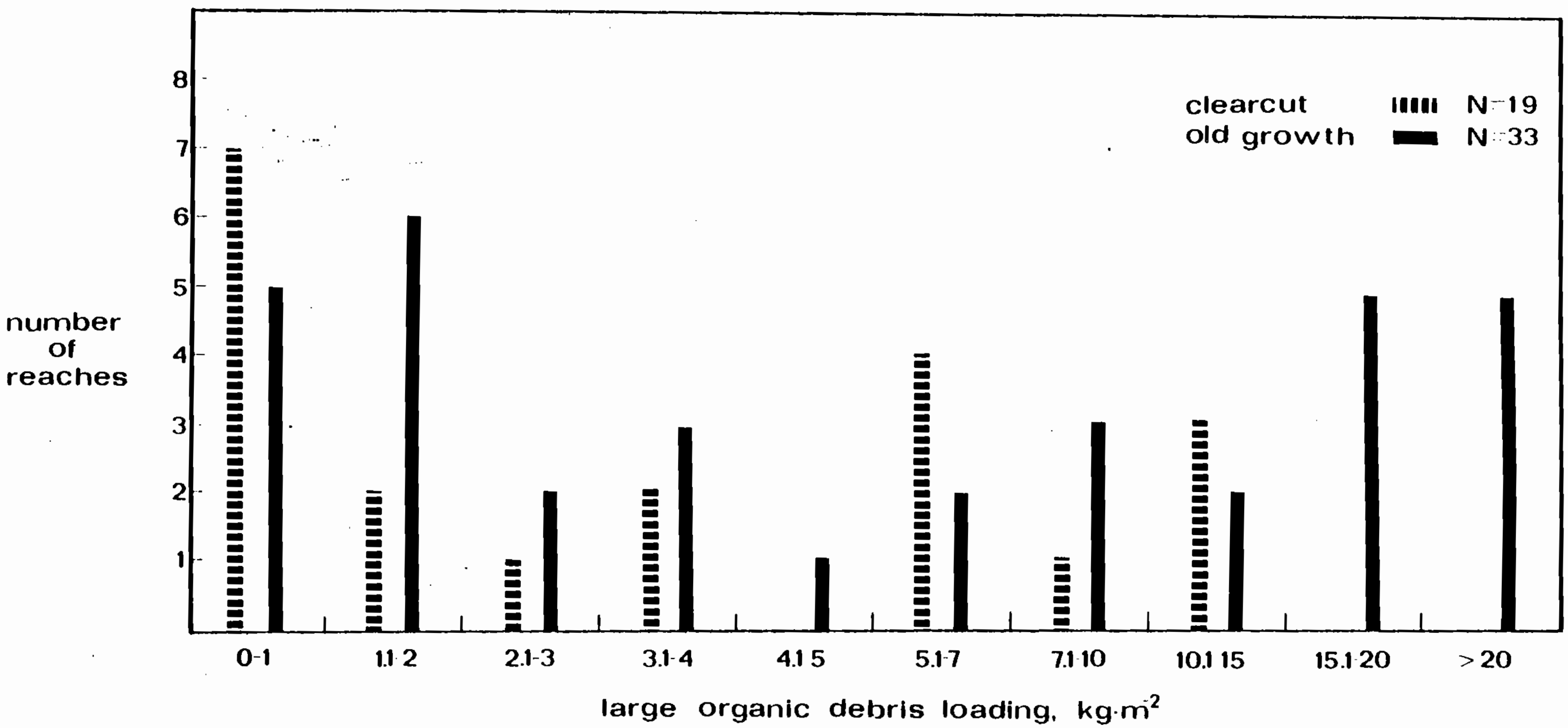

Figure 4. Large organis debris accumulations in clearcut and old growth streams subject to debris torrents.

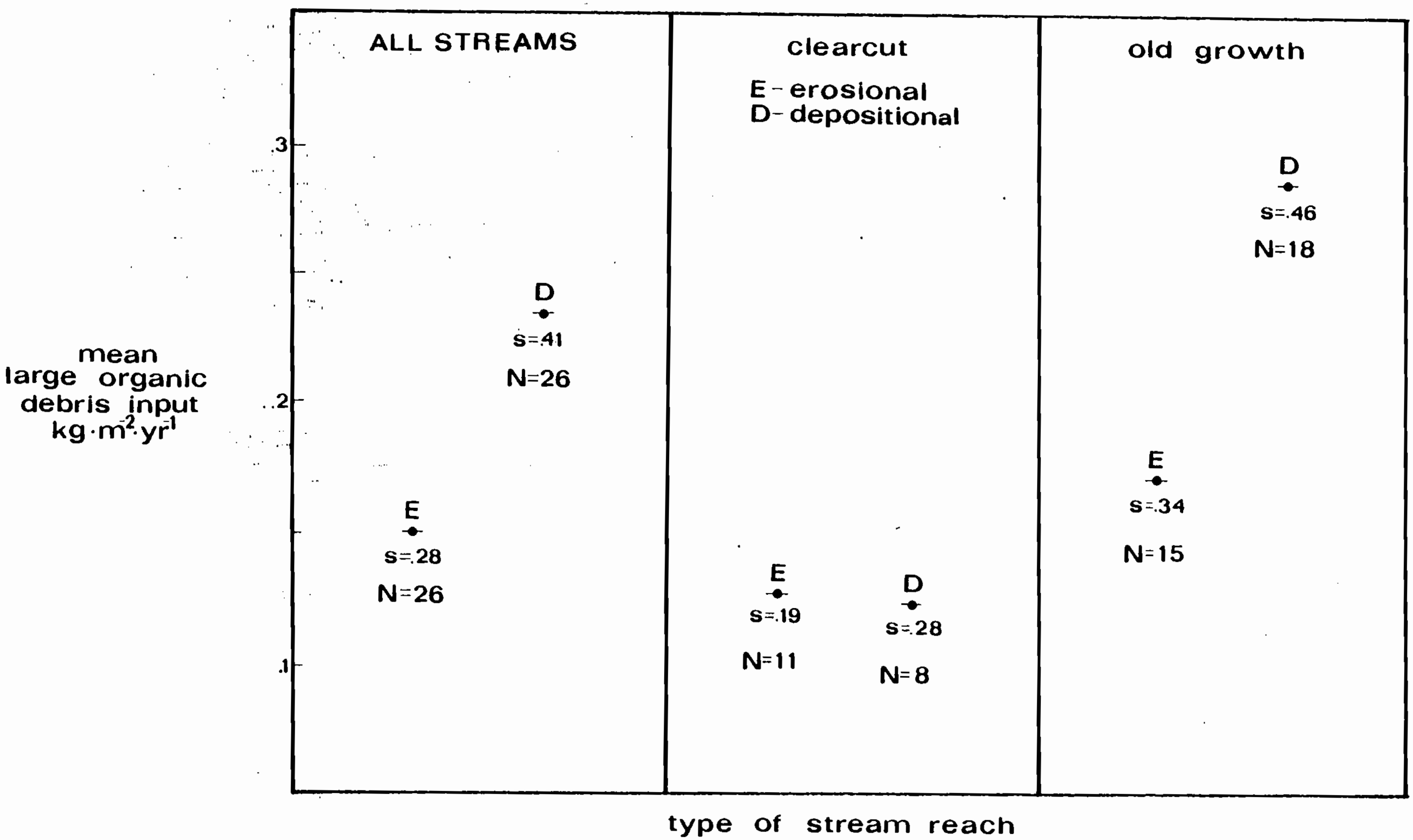

Figure 5. Annual large organic debris input to streams subject to debris torrents.

Mechanisms for Entry and Disposition of LOD

The quantity of LOD in streams is a balance between processes of accumulation and loss by physical export or decomposition. LOD randomly enters streams through windthrow, mass movement, bank undercutting, and as logging slash from timber harvest operations. The episodic occurrence of hillslope mass erosion such as earthflow and debris avalanche also affects LOD loading. Debris torrents and freshets can redistribute LOD located on banks and in the streambed.

Chronosequence of LOD Input

There was no pattern for increased LOD loading with time since debris torrent occurrence. A large number of sites (N = 17) subject to debris torrents in 1965 provided a good opportunity in this study to assess LOD standing crop and LOD input. Both standing crop and annual input of LOD for streams sluiced in 1965 were highly variable.

In headwater streams, annual LOD input appears to be random in space and time. The chronosequence of LOD input to streams may be better assessed from a decades- to century-long perspective.

Channel Morphology

Pool Formation and Frequency

Boulders (> 25 cm diameter) formed about one-half of the 339 pools measured in this study (Table 3). Logs formed about one-fourth

Table 3. Pool size class distribution by channel bed material for streams subject to debris torrents.

Pool Size Class Distribution for All Streams

	$<1.4m^2$		$1.4-4.7m^2$		$>4.7m^2$	
	#	%	#	%	#	%
boulder	90	47	64	56	20	55
log	45	24	22	20	9	25
cobble	35	18	13	12	1	3
bedrock	21	11	13	12	6	17
Σ	191		112		36	

and bedrock and cobbles (8 - 25 cm diameter) each formed less than one-fifth of all pools.

Log-formed pools were ten times more numerous in depositional sites compared to erosional sites. Old-growth sites had almost twice as many log-formed pools as clearcut sites (Table 4). Boulder-formed pools were slightly more numerous in depositional sites compared to erosional sites. Cobble-formed pools were almost twice as numerous in old-growth sites compared to clearcut sites. Bedrock-formed pools were three times more numerous in erosional sites compared to depositional sites. Total numbers of pools per 100 m were similar for old-growth and clearcut sites. Depositional sites had almost twice as many pools per 100 m as erosional sites, especially larger pools.

Erosional-Depositional Comparisons

Boulders formed one-half of all pools in erosional and depositional sites (Table 5). Logs contributed to the formation of one-quarter to one-half of pools in depositional sites. In erosional sites, bedrock depressions, and to a lesser extent cobbles, comprised the next major pool forming component of channel material.

Total pool numbers per 100 m stream length were 1.5 to 2 times more numerous in depositional sites for boulder, log, and cobble-formed pools (Fig. 6). Three times as many pools were formed by bedrock in erosional sites than those formed in depositional sites.

In depositional sites, boulder-formed pools less than 1.4 m^2

Table 4. Pool frequency by channel bed material type for streams subject to debris torrents.

Number of pools / 100m

	E	D	D/E	OG	CC	OG/CC
boulder	5.1	7.8	1.5	6.8	6.0	1.1
log	0.5	5.3	10.6	3.5	1.9	1.8
cobble	1.8	2.5	1.8	2.1	1.5	1.4
bedrock	2.2	0.7	0.3	1.4	2.0	0.7
Σ	9.2	16.7		13.4	11.0	

Table 5. Pool size class distribution for various channel bed materials in erosional and depositional stream reaches subject to debris torrents.

Erosional
Pool Size Classes

	<1.4m²			1.4-4.7m²			>4.7m²		
	#	%	#/100m	#	%	#/100m	#	%	#/100m
boulder	31	48	2.4	21	64	1.6	15	54	1.2
log	6	9	0.5	1	3	0.1	1	3	0.1
cobble	9	15	0.7	3	9	0.2	8	29	0.6
bedrock	18	28	1.4	8	24	0.6	4	14	0.3
Σ	64		5.0	33		2.5	28		1.0

Depositional
Pool Size Classes

	<1.4m²			1.4-4.7m²			>4.7m²		
	#	%	#/100m	#	%	#/100m	#	%	#/100m
boulder	50	44	3.9	45	56	3.5	7	33	0.5
log	37	32	2.9	21	26	1.6	11	52	0.9
cobble	25	22	1.9	8	10	0.6	1	5	0.1
bedrock	2	2	0.2	7	8	0.5	2	10	0.2
Σ	114		8.9	81		6.2	21		1.7

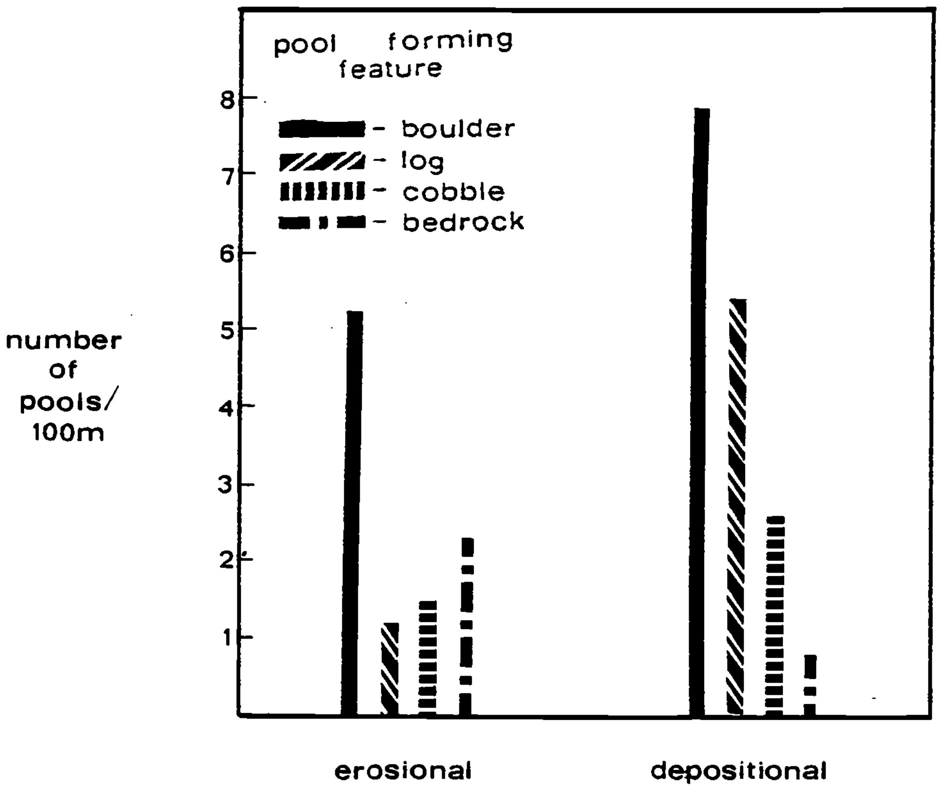

Figure 6. Frequency of pools formed by channel bed materials in erosional and depositional stream reaches subject to debris torrents.

and log pools 1.4 - 4.7 m^2 in area were very numerous (Fig. 7). Numbers of log-formed pools were very low in erosional sites for all pool-size classes. Large pools (> 4.7 m^2) were nearly 1.5 times more numerous in erosional sites. Pools < 4.7 m^2 were more numerous in depositional sites.

Old-Growth/Clearcut Comparisons

For old-growth and clearcut streams, the highest percentages of pools for any pool-size class were formed by boulders (Table 6). Log-formed pools were more prevalent in old growth. Boulders formed an increasing percentage of pools in clearcuts with increasing pool-size class. Numbers of cobble- and bedrock-formed pools were highest in pools < 1.4 m^2 for clearcuts. The percentage of bedrock-formed pools increased as pool size increased in old-growth sites; the reverse trend was observed in clearcuts. The percentage of cobble-formed pools decreased with increasing pool-size class for old growth and clearcuts.

Total pool numbers per 100 m stream length were 1.5 times more numerous in old growth relative to clearcut stream segments (Fig. 8). Boulder and log pools were twice as numerous in old growth relative to clearcuts. Cobble and bedrock pool numbers were similar for both conditions.

Pool numbers per 100 m stream length by pool-size class indicated twice as many pools greater than 4.7 m^2 in area for clearcuts relative to old growth, and twice as many pools 1.4 - 4.7 m^2 in

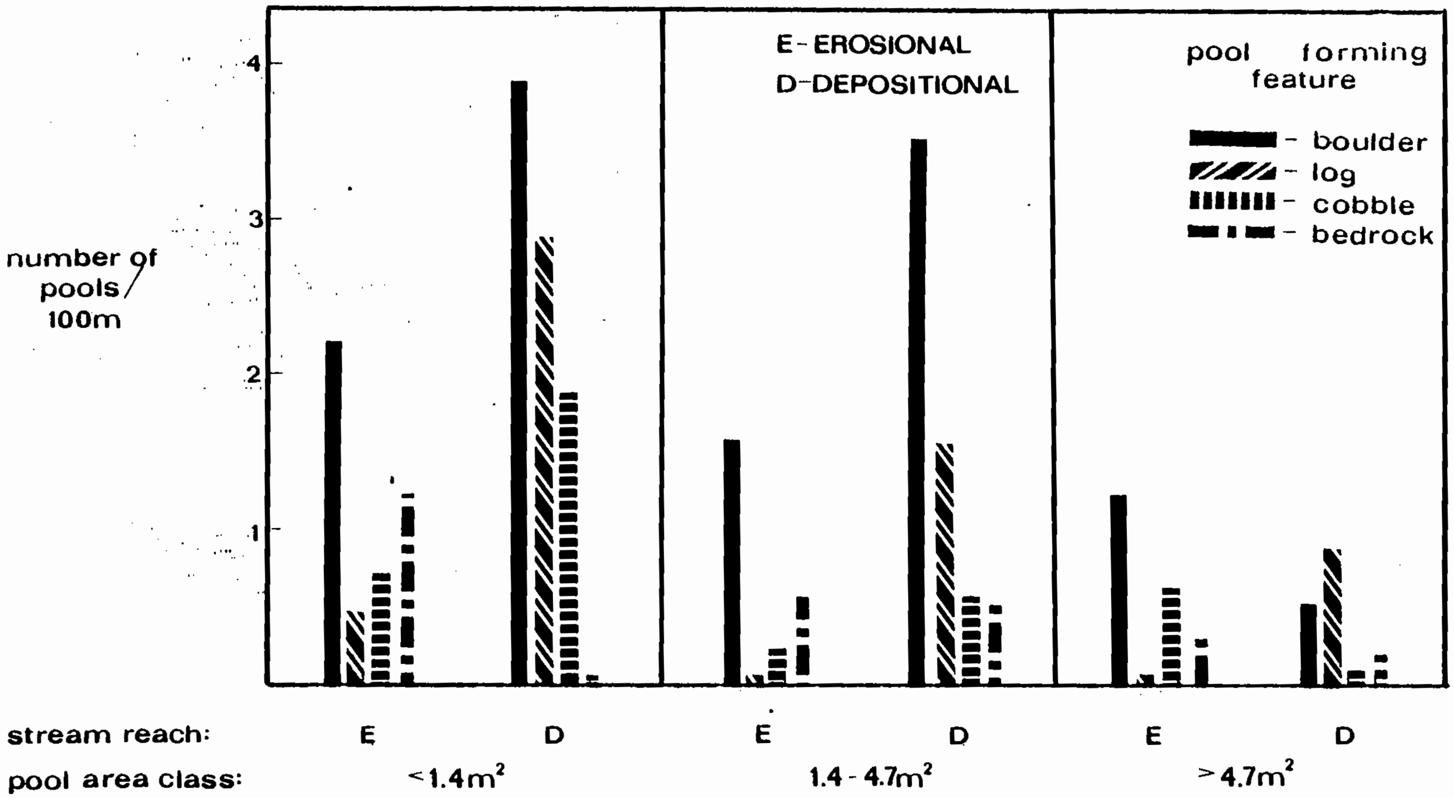

Figure 7. Frequency of pools vs. size classes formed by various channel bed materials in erosional and depositional stream reaches subject to debris torrents.

Table 6. Pool size class distribution for various channel bed materials in old growth and clearcut stream reaches subject to debris torrents.

Old Growth
Pool Size Classes

	<1.4m²			1.4-4.7m²			>4.7m²		
	#	%	#/100m	#	%	#/100m	#	%	#/100m
boulder	53	46	3.2	51	59	3.1	6	35	0.4
log	33	29	2.0	18	20	1.1	6	35	0.4
cobble	23	19	1.4	10	11	0.6	0	0	0
bedrock	7	6	0.4	9	10	0.6	5	30	0.3
Σ	116		7.4	88		5.4	17		1.1

Clearcut
Pool Size Classes

	<1.4m²			1.4-4.7m²			>4.7m²		
	#	%	#/100m	#	%	#/100m	#	%	#/100m
boulder	28	47	2.9	14	54	1.5	14	74	1.5
log	7	12	0.7	7	27	0.7	3	16	0.3
cobble	11	19	1.2	1	4	0.1	1	5	0.1
bedrock	13	22	0.4	4	15	0.4	1	5	0.1
Σ	59		5.2	26		2.7	19		2.0

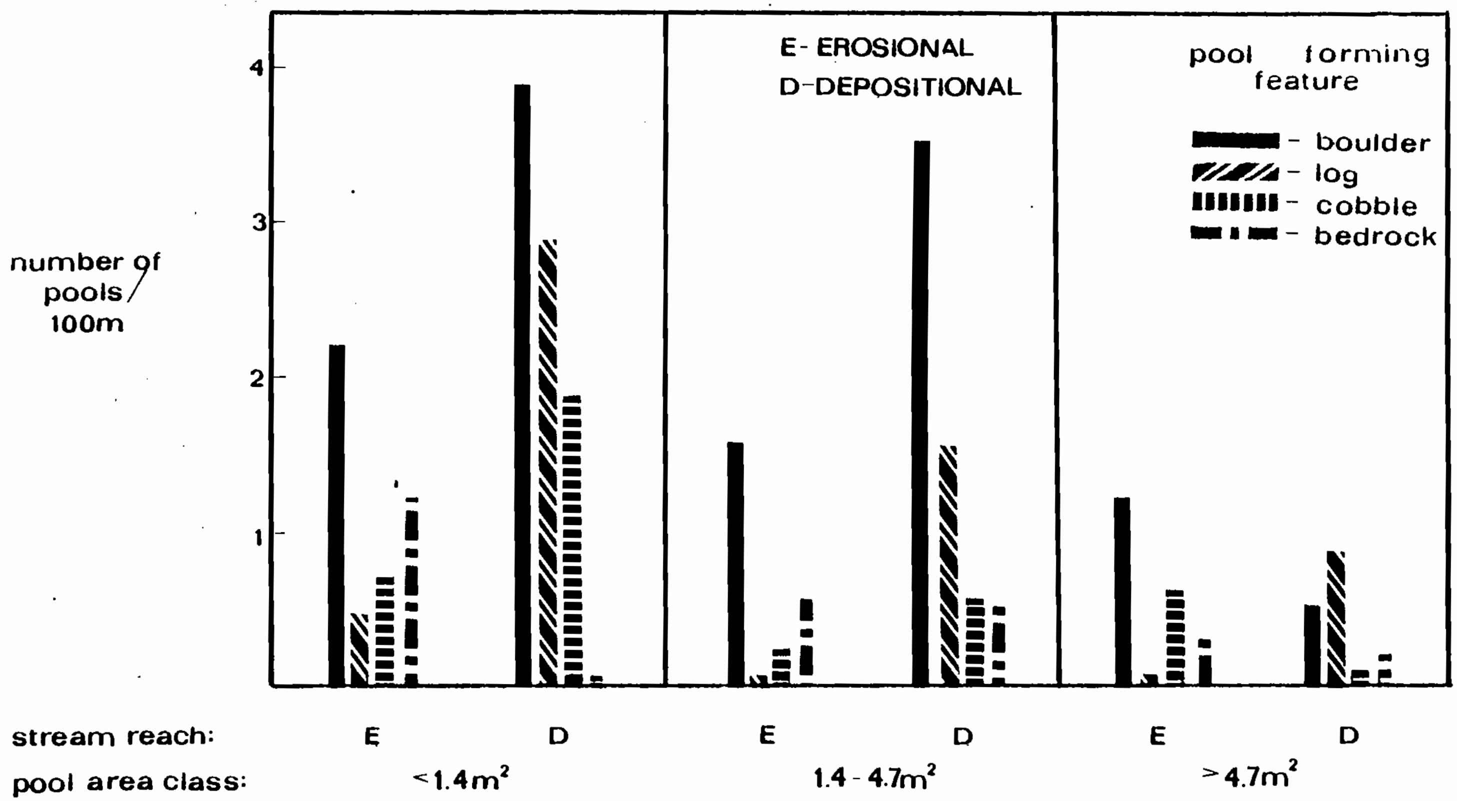

Figure 7. Frequency of pools vs. size classes formed by various channel bed mater in erosional and depositional stream reaches subject to debris torrents

area in old growth relative to clearcuts (Fig. 9). Numbers of pools less than 1.4 m^2 were similar for old growth and clearcuts. It appears that lower channel gradients in clearcut streams favor the presence of large (> 4.7 m^2) pools. In higher gradient, old-growth streams, there appears to be a shift to smaller pools (< 4.7 m^2). As in the comparison of pool numbers vs. pool-size classes for erosional and depositional sites, there was a lower number of pools as pool area increased.

Clearcut streams had higher pool area than old-growth streams (Table 7). This may be due to lower channel gradient in clearcut streams relative to old-growth streams. Pool area in depositional sites was higher than erosional sites in both clearcut and old-growth sites.

Pool Ratings

The total pool rating (Table 8, Appendix) developed in this study is an index of channel storage and habitat. The pool rating concept (based on cumulative pool area and depth, number of pools, and average channel width and depth) should give average values for storage and habitat if channel measurements were made during a period of average annual streamflow. The fluctuating height of water surface with discharge changes the basic relation between scour and fill of bed material for pools and riffles. Stream quality ratings are attempts to describe a dynamic system at one point in space and time, and these inherent limitations should be realized.

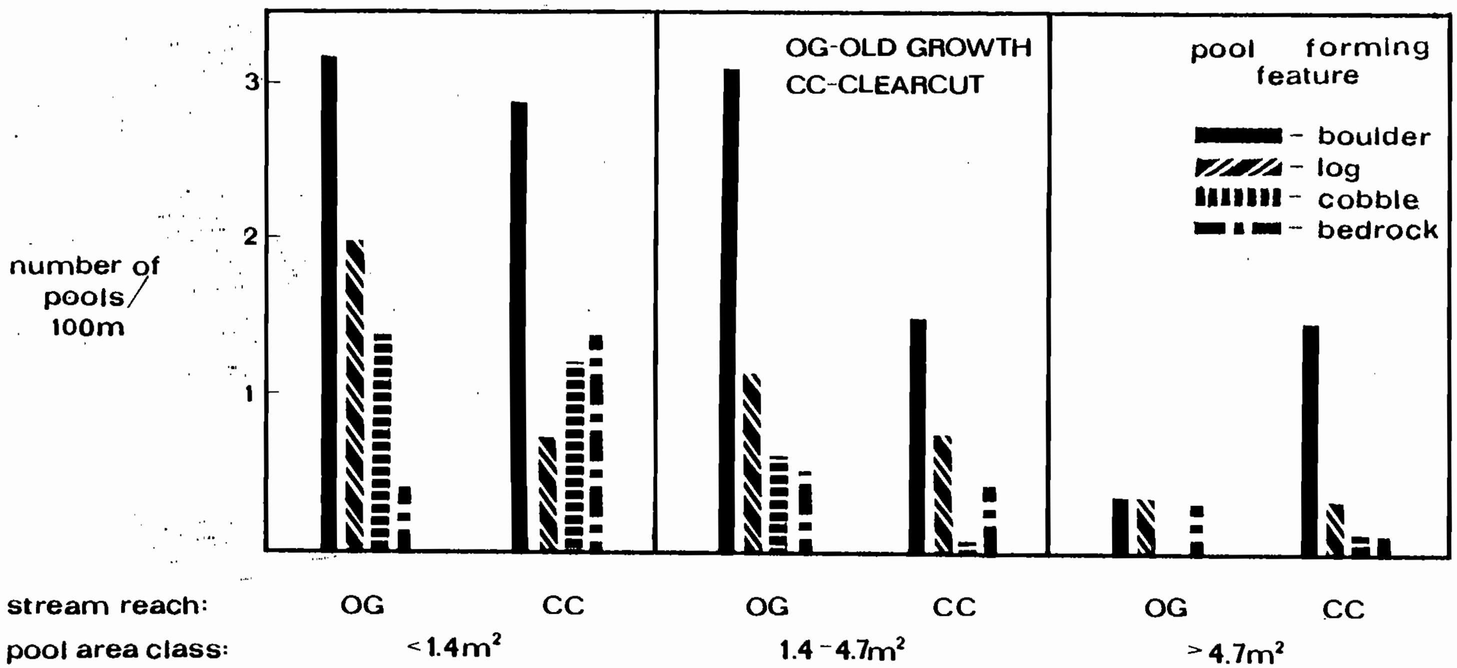

Figure 9. Frequency of pools vs. size classes formed by various channel bed materials in old growth and clearcut stream reaches subject to debris torrents.

Table 7. Comparison of pool area and depth of Old Growth and Clearcut streams subject to debris torrents.

Type of Stream Reach	Number of Reaches	Pool Area, Σm^2	Pool Depth, Σm^2	Channel Slope, %,(se)	Pool Areal %*
Erosional,Old Growth	15	77.6	12.6	22,(8.4)	4.4
Depositional,Old Growth	18	313.0	58.2	13,(6.4)	10.4
Erosional,Clearcut	11	181.4	22.6	16,(11.2)	10.8
Depositional,Clearcut	8	200.6	16.8	8,(3.8)	15.8

*expressed as a percentage of total channel area

Total pool ratings for depositional stream sites were almost twice as high as for erosional sites (Tables 8 and 9). Stream action that reworks the veneer of bed material laid down by debris torrents in depositional sites promotes complex channel bed contours. The spatial complexity created by pool-riffle sequences creates storage sites for sediment and organic matter and creates numerous surfaces and interstitial spaces for aquatic habitat.

Riparian Vegatation

Overstory

Post-torrent changes in stand density for overstory species in clearcuts show a pattern of increase in stand density (Fig. 10). This trend sharply increased for depositional sites in clearcuts in the period 10-15 years after debris torrent occurrence. Erosional sites in clearcuts exhibited lower stem densities that showed no change over time. Both erosional and depositional sites of clearcuts supported stands with nearly 90% composed of broadleaf species.

The old-growth chronosequence of stand development for overstory species shows a rapid decrease in stem density through time (Fig. 11). Deciduous species comprised about 30% of the stand; this condition reflects the strong control exerted by residual conifers over secondary succession in the stream corridor. The peculiar patterns for stem density is explained by a dense carpet of conifer seedlings inhabiting channel banks and bars of streams

Table 8. Parameters describing channel physical structure for erosional and depositional stream reaches subject to debris torrents, mean, (s.e.).

	Erosional N=26		Depositional N=26	
	Channel Morphology			
channel slope,%	19.9	(9.8)	10.9	(6.0)
channel width,m	2.6	(1.3)	3.3	(1.9)
channel depth,cm	8.3	(7.1)	9.5	(4.9)
cumulative pool area,m^2	9.9	(18.2)	19.0	(19.5)
cumulative pool depth,m	1.4	(1.8)	2.9	(2.5)
pool number/100m				
total pool rating	18.6	(19.0)	33.8	(20.3)
	Percent of Pool Area or Depth Formed by Material Type			
area: boulder	25.7	(36.8)	33.9	(34.2)
area: log	4.9	(14.2)	30.2	(34.3)
area: cobble	10.0	(22.6)	17.5	(26.8)
area: bedrock	28.9	(41.1)	10.7	(25.6)
depth: boulder	26.8	(35.0)	37.3	(36.5)
depth: log	2.3	(5.8)	31.0	(35.1)
depth: cobble	12.4	(25.3)	15.8	(25.8)
depth: bedrock	27.7	(38.7)	8.3	(19.9)
	Large Organic Debris			
channel,kg/m^2	1.4	(1.8)	4.1	(6.6)
bank,kg/m^2	2.1	(2.7)	5.7	(4.9)
total,kg/m^2: bank, channel,potential	4.7	(7.0)	10.8	(9.8)

Table 9. Parameters describing channel physical structure for old growth and clearcut stream reaches subject to debris torrents, mean, (s.e.).

	Old Growth N=13 Erosional	Old Growth N=13 Depositional	Clearcut N=6 Erosional	Clearcut N=6 Depositional
	Channel Morphology			
channel slope,%	23.3 (8.3)	12.9 (7.1)	14.5 (11.8)	6.5 (2.3)
channel width,m	2.4 (1.3)	2.7 (1.2)	3.2 (1.2)	3.6 (2.5)
channel depth,cm	7.0 (4.8)	9.5 (4.1)	13.2 (12.3)	10.8 (9.1)
cumulative pool area,m^2	5.5 (6.6)	13.9 (11.6)	19.6 (29.4)	26.2 (22.6)
cumulative pool depth,m	0.9 (0.8)	2.7 (1.8)	1.9 (1.8)	2.4 (1.9)
pool number/100m	0.4 (0.4)	1.3 (0.8)	1.6 (1.1)	2.2 (1.5)
total pool rating	15.7 (16.8)	35.4 (18.8)	18.3 (15.9)	29.0 (19.6)
	Percent of Pool Area or Depth Formed by Material Type			
area: boulder	16.8 (27.5)	40.9 (39.9)	42.7 (47.4)	23.0 (21.7)
area: log	4.5 (12.4)	36.6 (41.0)	7.2 (17.6)	24.2 (31.9)
area: cobble	13.9 (27.8)	13.4 (20.1)	9.3 (22.9)	16.7 (27.9)
area: bedrock	34.9 (44.2)	7.6 (25.2)	31.5 (48.9)	19.5 (31.8)
depth: boulder	19.2 (24.0)	39.5 (38.4)	42.0 (46.5)	39.0 (35.7)
depth: log	2.4 (6.1)	35.2 (41.2)	0 (0)	23.8 (27.5)
depth: cobble	16.2 (29.9)	11.1 (20.7)	11.8 (28.9)	6.5 (11.7)
depth: bedrock	31.5 (39.4)	7.6 (22.9)	29.5 (46.3)	14.0 (22.3)
	Large Organic Debris			
channel,kg/m^2	1.8 (2.2)	4.1 (7.8)	0.6 (0.7)	1.9 (2.6)
bank,kg/m^2	2.4 (3.3)	5.3 (5.2)	2.1 (2.3)	2.8 (3.4)
total,kg/m^2: bank, channel,potential	6.1 (9.3)	11.1 (11.8)	2.7 (2.7)	5.0 (5.0)

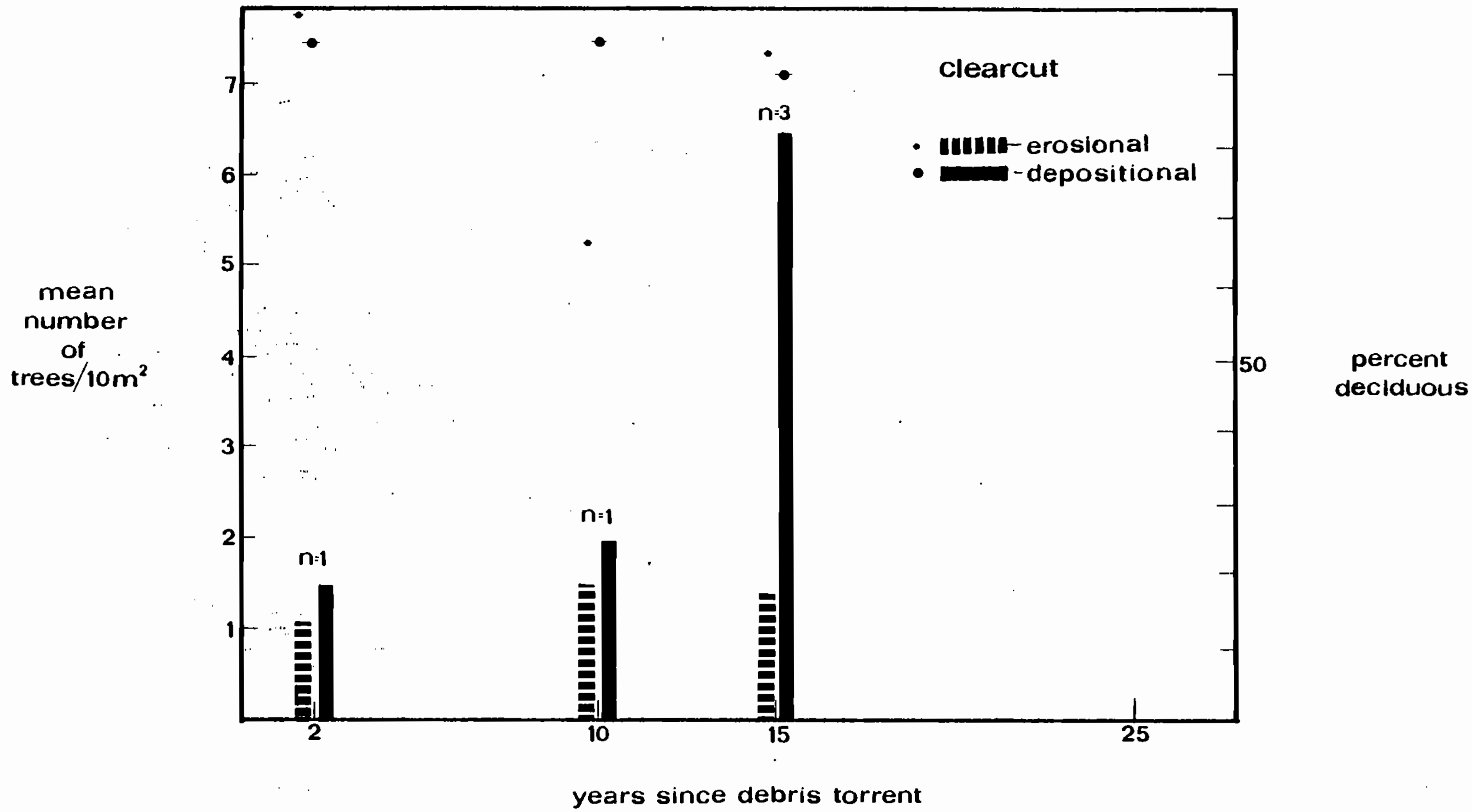

Figure 10. Changes in stand density and deciduous component in overstory successional species through time in adjacent erosional and depositional reaches in clearcut streams subject to debris to-rents.

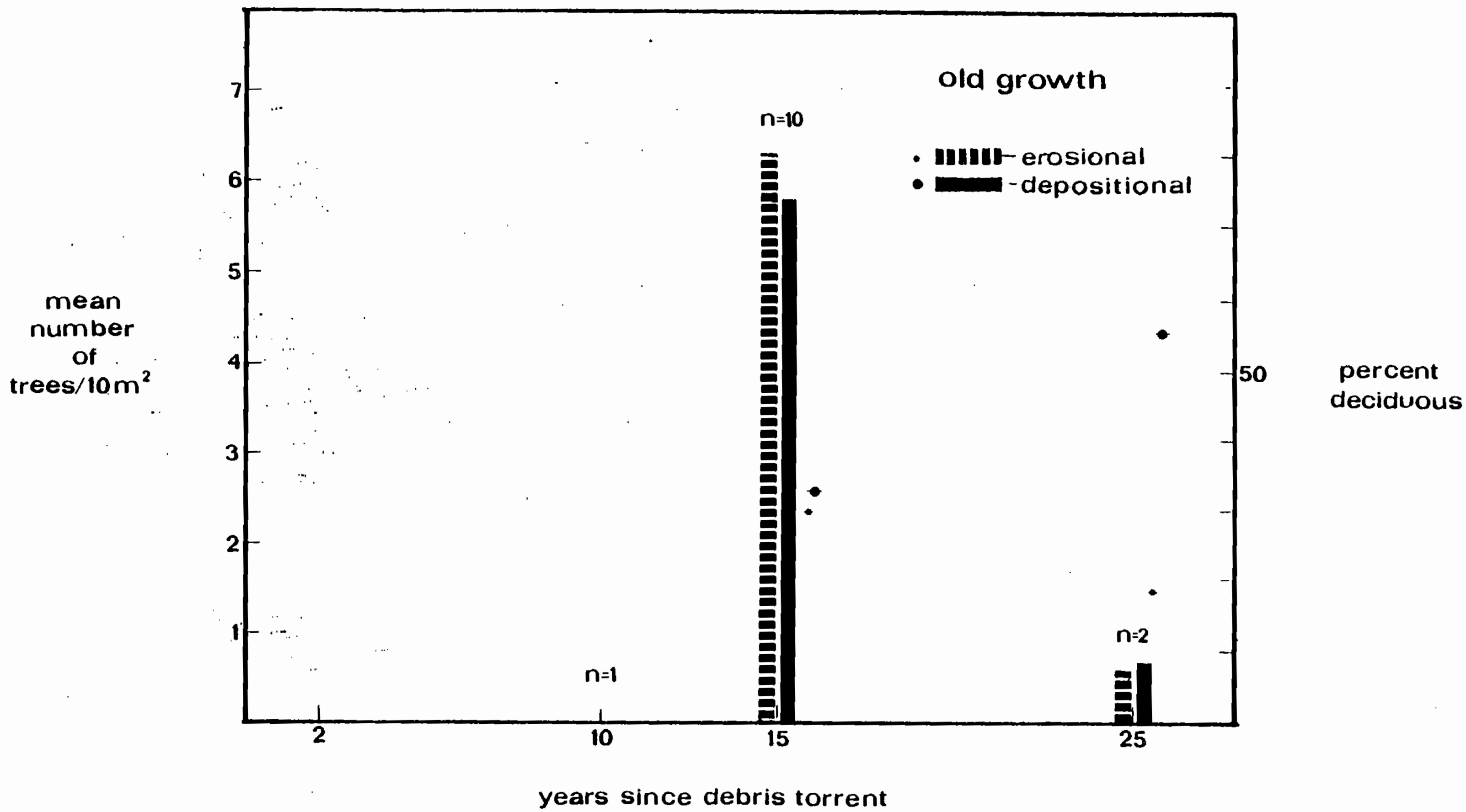

Figure 11. Changes in stand density and deciduous component in overstory successional species through time in adjacent erosional and depositional reaches in old growth streams subject to debris torrents.

sluiced in 1965. Extreme channel bank instability for Lower Box Canyon Creek prevented the rooting of plants on stable soil masses. At Avenue One and Avenue Two Creeks, severe scouring offered few sites for plant rooting; another site did not support seedling development due to competition from other post-torrent communities for light and rooting sites. Many old-growth sites were not sufficiently widened by debris torrent action to affect light availability. Channel aspect also affects light availability.

Trends for diameter growth in old-growth post-torrent overstory species show a rapid increase for alder, bigleaf maple, and western red cedar, especially in depositional sites (Fig. 12). The increase in stem diameter for western hemlock was pronounced; Douglas-fir diameter growth was low. Erosional sites supported slightly larger diameter trees for many species. Diameter growth of alder was high.

Trends for diameter growth for clearcut riparian species indicate rapid growth for alder and western red cedar, especially in erosional sites (Fig. 13). Bigleaf maple, western hemlock, and Douglas-fir growth exhibited no apparent change relative to alder.

Middlestory

Post-torrent patterns in the high shrub community (willow, vine maple) of the riparian middlestory show the influence of canopy closure. Shrubs were virtually absent from old-growth sites (Fig. 14). Depositional sites in clearcuts supported higher

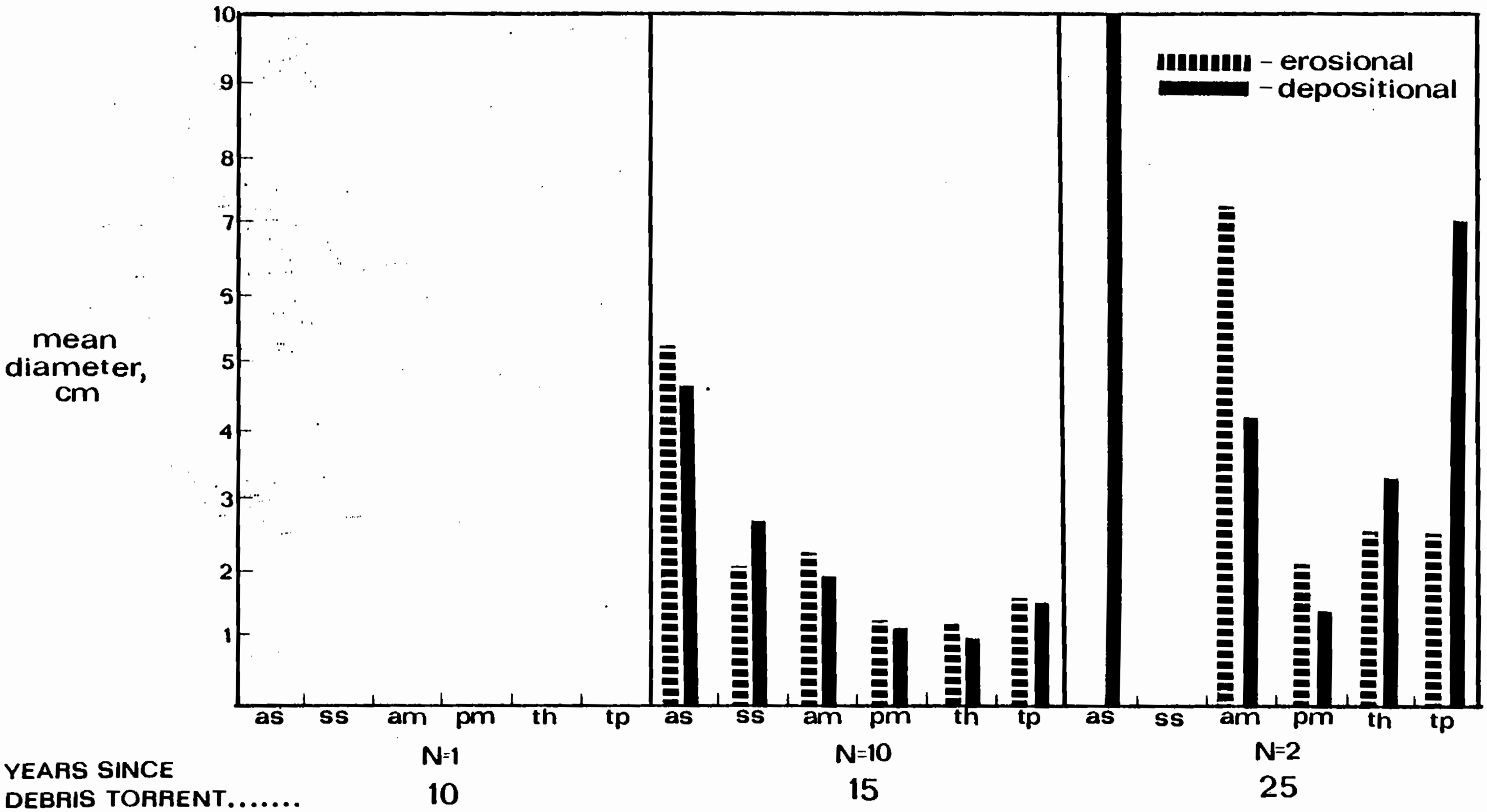

Figure 12. Diameter growth of successional species in adjacent pairs of old growth sites: Alnus species (as), Salix species (ss), Acer macrophyllum (am), Pseudotsuga menziesii (pm), Tsuga heterophylla (th), and Thuja plicata (tp).

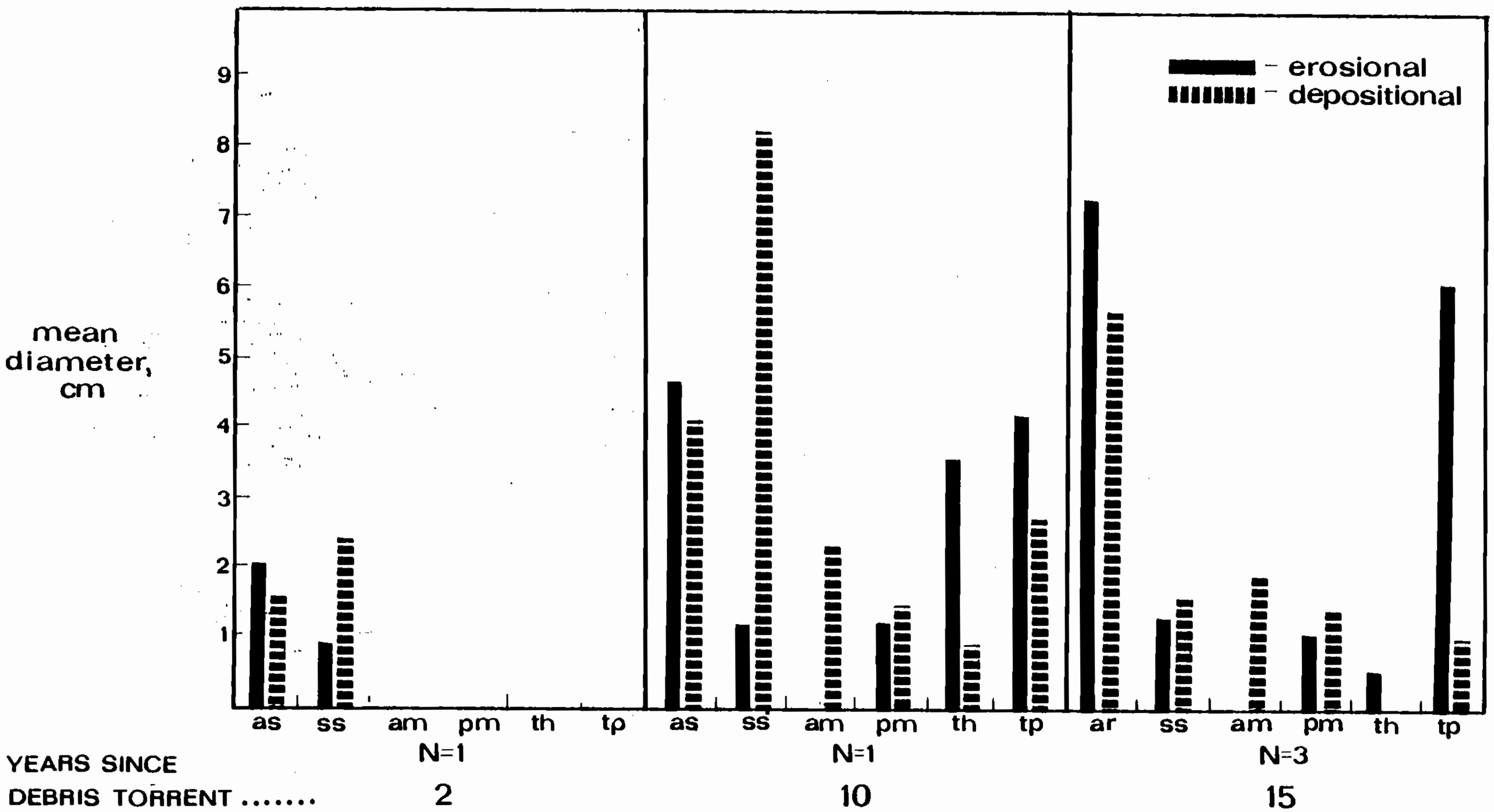

Figure 13. Diameter growth of successional species in adjacent pairs of clearcut sites: Alnus species (as), Salix species (ss), Acer macrophyllum (am), Pseudotsuga menziesii (pm), Tsuga heterophylla (th), and Thuja plicata (tp).

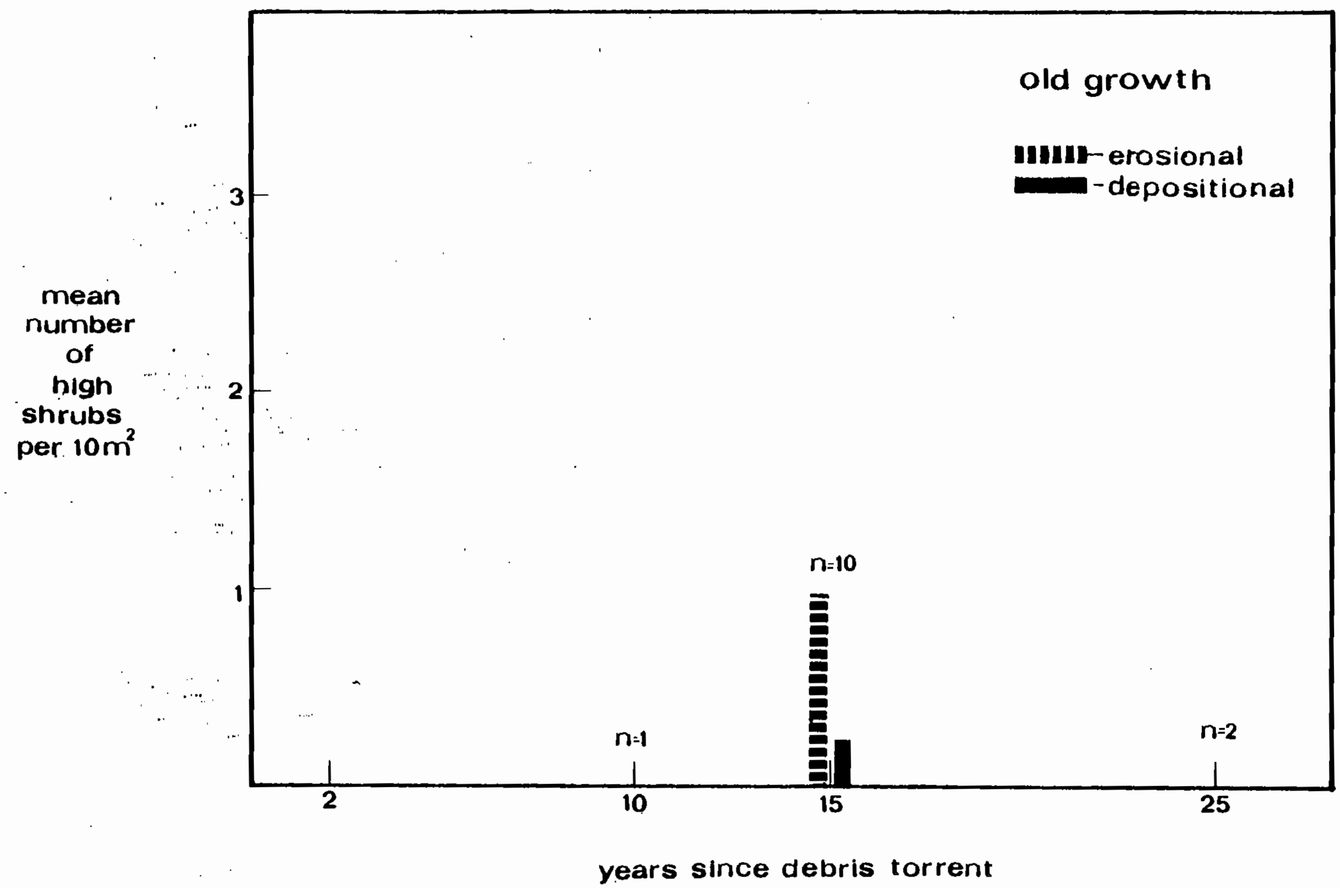

Figure 14. Stem density of successional high shrubs in adjacent erosional-depositional sites in old growth streams subject to debris torrents.

numbers of willow and vine maple through time (Fig. 15). For clearcuts, the rapid increase in numbers of high shrubs is synchronized with a similarly high rate of increase in numbers of overstory species. The combined clearcut overstory and middlestory response indicates rapid site occupancy. Comparisons to these riparian components in old growth cannot be made due to lack of data.

The post-torrent trends for overstory vegetation of clearcuts to be primarily deciduous, and evergreen for old growth, are due to differences in light regimen and seed source. The residual overstory stand in old growth, encroaching upon the channel, provides an aerial source of seed. Canopy closure restricts availability of direct sunlight and favors the growth of late successional species, i.e., western hemlock and western red cedar. In clearcut riparian zones, removal of overstory canopy favors development of shade intolerant tree and shrub species, such as alder and willow. Their rapid juvenile growth in full sunlight provides a superior competitive edge in colonizing these sites.

The favorable influence of depositional microsites in supporting higher stem densities than erosional sites is evident. In clearcuts, and to a lesser extent in old growth, alluvium more often rapidly supported advanced regeneration of late successional species, Douglas-fir, western hemlock, and western red cedar.

Foliar Biomass

Foliar biomass for post-torrent species increased through time, with the exception of old growth-depositional sites (Fig. 16).

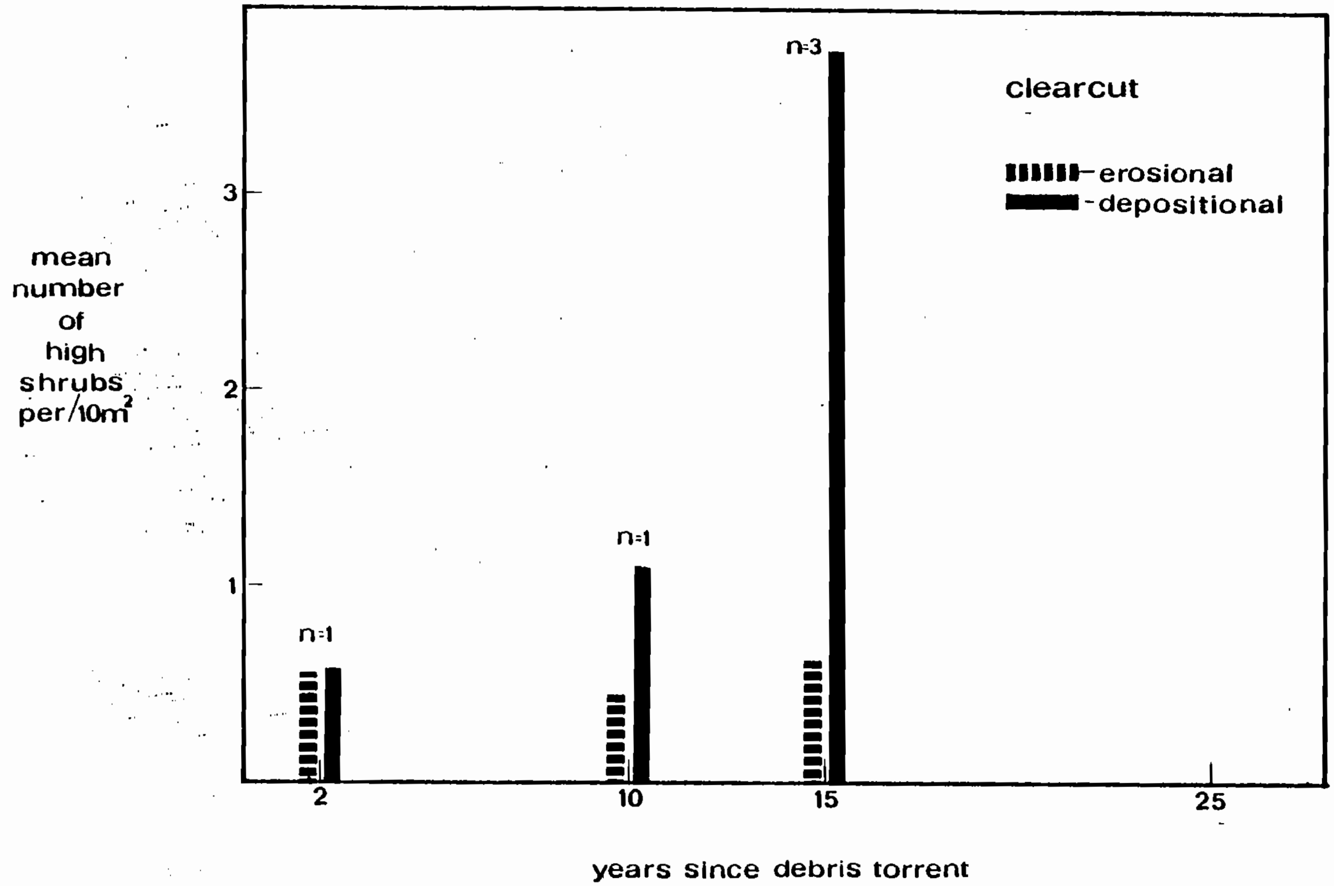

Figure 15. Stem density of successional high shrubs in adjacent erosional-depositional sites in clearcut streams subject to debris torrents.

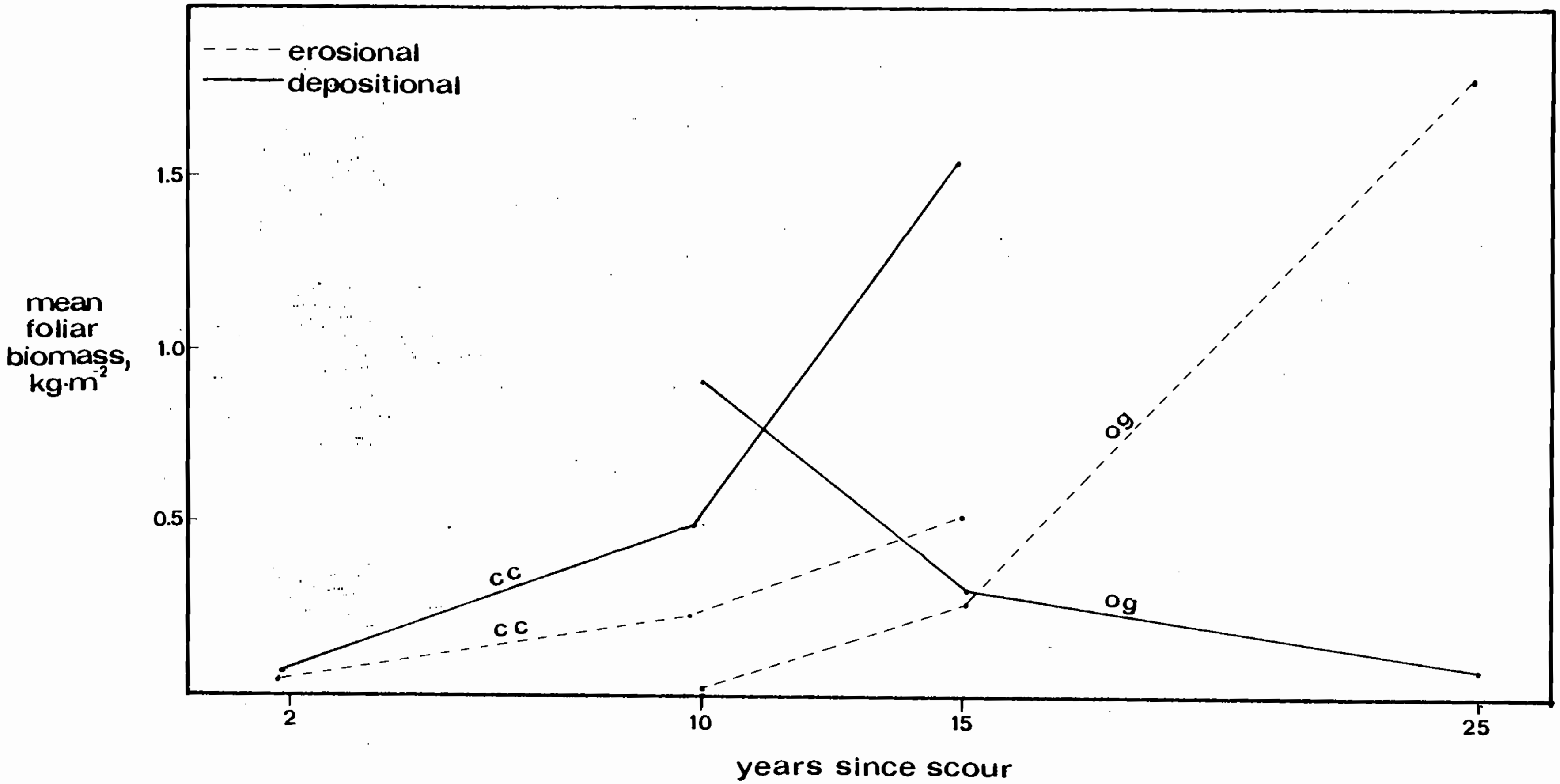

Figure 16. Estimated foliar biomass production for all successional plant strata in adjacent erosional-depositional sites of old growth and clearcut riparian zones subject to debris torrents.

Foliar biomass estimates for clearcut-depositional and old growth-erosional sites were similar over fifteen-year periods. The foliar biomass response was more rapid in clearcuts than in old growth. Clearcut-depositional sites produced more foliage than erosional sites over time. Foliar biomass in old growth-erosional sites increased at a rate similar to that in clearcut-depositional sites; a decrease in foliar biomass accumulation was observed for old growth-depositional sites.

Overstory communities produced large amounts of leaf litter in stream reaches under vigorous stands of alder. This occurred along two 15-year-old sluiced clearcut streams and along an old-growth stream. These sites supported trees whose diameter exceeded 10 cm. Alder significantly contributed to foliar biomass production in recently (< 10 years) scoured streams in clearcuts.

Shrub communities produced more than two-thirds of the total foliar biomass in one-third of all sites (N = 52) (Table 10). Shrub communities in 24 of 52 sites produced over one-half of total post-torrent foliar litterfall. In 16 of 52 sites, shrubs produced over three-fourths of the litterfall as estimated by foliar biomass equations (Gholz et al. 1979).

Post-torrent communities produced all foliar litterfall (residual and post-torrent combined) in 29 of 52 stream sites (Table 10). Only in ten sites was post-torrent foliar biomass less than one-half of the total foliar biomass. These ten sites were located in old growth where residual conifers, unaffected by

Table 10. Annual leaffall estimates of riparian zones sluiced by debris torrents.

			post-torrent			residual and post-torrent	
				% of total[1] by stratum			
stream	event year	forest type	total[1] kg/m²/yr	S	H&S	total[2] kg/m²/yr	total[1] as % of total[2]
1.	1965E	cc	.3	73	81	.33	100
	D	cc	7.3	96	97	7.3	100
2.	1965E	og	.2	89	97	.2	100
	D	og	.4	95	97	.4	100
3.	1965E	cc	.1	98	99	.1	100
	D	og	.1	51	100	.4	27
4.	1970E	og	0	0	0	.1	0
	D	cc	.1	30	53	.1	100
5.	1965E	cc	.6	99	99	.6	100
	D	og	.1	73	100	.1	71
6.	1965E	og	0	0	0	0	0
	D	cc	.1	14	31	.1	71
7.	1965E	og	.1	21	25	.02	100
	D	og	.2	85	94	.2	100
8.	1955E	og	3.6	99	99	3.6	100
	D	og	.1	26	78	.1	100
9.	1955E	og	.003	0	0	.003	100
	D	og	.006	0	84	.006	100
10.	1965E	og	.4	83	99	.8	48
	D	og	.2	78	97	.5	40
11.	1965E	og	.006	0	100	3.1	2
	D	og	1.8	19	100	6.4	28
12.	1965E	og	.4	99	99	.8	50
	D	og	.2	57	97	.4	50
13.	1965E	cc	.7	43	47	.7	100
	D	cc	.1	0	37	.1	100
14.	1970E	cc	.2	8	58	.3	67
	D	cc	.9	89	92	.9	100
15.	1978E	cc	.05	36	75	.05	100
	D	cc	.06	0	64	.06	100
16.	1965E	cc	.02	1	84	.02	100
	D	og	.05	20	21	.1	38
17.	1970E	cc	.1	1	12	.1	100
	D	og	.04	4	87	.3	12
18.	1965E	og	.6	97	99	.6	100
	D	og	.4	77	83	.5	80
19.	1965E	cc	.7	0	0	1.4	50
	D	cc	.4	1	32	.4	100
20.	1965E	og	.2	5	54	.2	100
	D	og	.2	59	84	.3	67
21.	1965E	og	.1	62	92	.1	100
	D	og	.6	97	99	.6	100
22.	1965E	og	.2	0	66	.2	100
	D	og	.3	0	44	.3	100
23.	1965E	cc	1.8	96	99	1.8	100
	D	og	.2	18	44	2.9	69
24.	1965E	og	1.1	92	97	1.1	100
	D	og	.04	0	5	1.4	29
	C	og	.5	-	-	1.0	52
25.	1978E	cc	0	0	0	2.7	0
	D	cc	0	0	0	.6	0
	C	cc	0	-	-	.2	0
26.	1965E	og	.1	0	92	.2	33
	D	og	.3	5	9	.4	81

[1] total= post-torrent tree, shrub, and herb
[2] total= post-torrent and residual all strata
E=erosional, D=depositional, S=shrub, H=herb

debris torrent passage, continued to produce foliar litter that drifted into the riparian zone.

Foliar biomass production by overstory remnants not destroyed by debris torrent passage was almost entirely an old-growth phenomenon (Table 10). Residual foliar litterfall was a major component of total foliar litterfall in 12 of 19 old-growth sites where there was residual detrital input from nearstream vegetation. Conditions limiting development of post-torrent communities along these 12 sites included extreme channel bank instability, severe degradation-aggradation, and canopy closure. Litterfall yielded by the stand remaining after debris torrent passage in the clearcuts of Tom Creek and Blowout Creek was produced by a few trees high on channel banks that were not within the clearcut boundary.

Alder and Willow in the Riparian Zone

Alder and willow were common post-torrent overstory and middlestory components of stream sites affected by debris torrents (Table 4, Appendix). Alder was present in 27 of 52 sites, willow, 28 of 52 sites. Riparian sites which supported dense stands of alder usually lacked willow, and vice versa; such mutual exclusion was seen in 19 of 28 stream sites. Both species grow rapidly and canopy closure can restrict development of understory competitors.

Comparatively low percentages (21% and 26%) of clearcut sites (N = 19) lacked alder and willow. High percentages (64% and 58%) of old-growth sites (N = 33) lacked alder and willow. Light availability appeared to regulate site occupancy.

Fifteen reaches, ten in clearcuts, supported pure alder stands with stem diameters at breast height exceeding 10 cm. These well-developed stands were all rooted in gravel bars and recent alluvium, optimum sites for rapid growth. It is likely that alder found along streams sluiced in 1965 developed in response to debris torrent perturbation. Alder can attain height growth of 8-10 m in 10 years on good sites, and diameter growth of 8-12 cm (Robert Tarrant, personal communication). Elevation, light availability, and soil conditions are site factors that influence alder growth habit.

Though both alder and willow produce large quantities of foliar litter, alder can remedy unfavorable soil conditions and improve soil productivity by increasing available soil nitrogen and soil organic matter content (Tarrant and Trappe 1971; Zavitkovski and Newton 1971). Alder improves soils by stimulating microbial activity, reducing bulk density, increasing soil porosity, and conserving nutrients (Tarrant and Trappe 1971). These changes can profoundly influence the concurrent and succeeding development of plant communities during various successional stages (Tarrant et al. 1969).

VI. SYNTHESIS

Introduction

Debris torrents are perturbations of headwater stream ecosystems that shape the structure and composition of nearstream vegetation. They also alter the fluvial processes that regulate the patterns of loading, transport, utilization, and storage of organic particulates and sediment. Instream large organic debris produced by the streamside forest stand creates obstructions to flow that decelerate the routing of litterfall. In the absence of instream woody debris, physical habitat is shaped by predominantly boulder formed pool-riffle sequences.

Physical Structure of Stream Channels

The principal structural and functional components that regulate channel storage in headwater streams are large organic debris and boulders. Large organic debris and boulders comprise the major obstructions to flow in channels characterized by a stepped profile of pool-riffle sequences. In stream segments subject to the scouring action of debris torrents, where the veneer of bed material is entirely removed, the initial changes in bed morphology are likely to persist. The bedrock streambeds of the erosional reaches of Avenue Creeks One and Two remain in a condition essentially unchanged since debris torrent occurrence in 1955.

Several erosional sites of streams subjected to intense scouring action in 1965 remain scoured to bedrock. The persistence of this bedrock condition is controlled by a number of mechanisms: (1) lack of supply of bed material; (2) transport of material into a channel segment; and (3) establishment of particulate bed material stability.

Supply and transport limitations for erosional sites occur under conditions of bed material stability upstream of the site and/or bank stability adjacent to the site. These conditions impose severe restrictions on downstream movement and lateral transport of bed material for flow deceleration or diversion. Recovery to a condition of diverse bed morphology may take several decades or more to achieve.

In depositional sites where debris torrents have deposited loads, reworking of channel debris by stream action is rapid. Depositional sites of streams subject to debris torrents in 1978 (N = 2) reveal total pool ratings similar to depositional sites of streams affected by torrents in 1965 (N = 19). In these stream segments, recovery to diverse bedforms occurred primarily due to conditions of abundant supply of bed material, where transport and subsequent bed material stability were not limiting factors.

The erosional or depositional character of a stream segment appears to be more critical in controlling channel adjustment to debris torrent perturbation than the silvicultural condition of the riparian stand. Overstory removal by clearcut timber harvest initially reduces annual LOD input to the stream and total accumulations of woody debris. The reduction of LOD in clearcut sites (N = 19) did not affect total number of pools per 100 m stream length, and total pool ratings were found to be similar to old-growth streams. Similar total pool numbers per unit stream length and total pool ratings indicate a similar storage capacity, but the longevity of these features, and their efficiency in retaining bed material and processing organic influxes are unknown. The residence time of instream woody debris can exceed 100 years in certain environments (Keller and Tally 1979). The longevity of LOD is affected by high flows that cause flotation, breakage, and redistribution, and by structural weakening due to physical abrasion, invertebrate and microbial feeding, and the frequency of debris torrents.

Boulders are important in controlling pool formation in streams. For streams lacking woody debris as flow obstructions, the function of logs in sediment and detritus retention and the formation of diverse habitat is served by boulders. Boulders often accumulate pieces of instream woody debris smaller than average channel width, especially in narrow, V-notched first- and second-order channels. Hence, boulders can stabilize logs that create partial or total flow deflection. In contrast to logs, boulders are ubiquitous, durable, and a more stable channel bed feature at high flows. Though boulders do not perform the dual role of detrital resource and flow obstruction, boulder surface area may exceed that of instream woody debris and offer more habitat opportunities for grazer and collector components of invertebrate functional groups.

Riparian Vegetation

The riparian zone links terrestrial and aquatic ecosystems by decelerating sediment input from hillslopes, stabilizing channel banks, and producing coarse particulate organic matter and woody debris for streams. Debris torrents are perturbations that reset succession of riparian vegetation, and modify the production, timing, and quality of organic matter influxes to the stream. Silvicultural activities also exert control over the structure and function of riparian vegetation through successional patterns following clearcut timber harvest.

Changes in site occupancy are dramatic 15 years after debris torrent occurrence. The highest recorded stem densities of overstory species for erosional and depositional-old growth sites and depositional-clearcut sites occurred in streams sluiced in 1965. As overstory succession continues beyond 15 years since torrent occurrence, it is likely that basal area will increase at a faster rate than stem density due to competition. Foliar biomass is likely to increase also. The few streams in this study that were sluiced prior to 1960 precluded a decades-long perspective on riparian stand development in response to debris torrents.

The site occupancy of 15-year-old stands best exemplifies the strong control that silvicultural activities exert on stand composition. Clearcut sites supported a high proportion of shade intolerant, broadleaf overstory species, whereas old-growth sites supported a much lower proportion of this riparian component. This condition has implications for the timing and quality of the detrital resource for aquatic biota.

Successional dynamics of shrub communities along debris torrent tracks are strongly controlled by overstory canopy cover. The presence of old-growth forest over the channel suppresses shrub communities through lack of seed source and insufficient light. Overstory removal by timber harvest stimulates site occupancy by shrubs. In clearcut erosional-depositional sites that are adjacent, the similar changes in stem density over time for high shrubs and overstory (willow and red alder), were due to an exclusion phenomenon, where one species rapidly dominated the other. Examples of this are found in the depositional site of Cedar Creek which supported among the highest numbers of willow with no alder competition. Tom and Detroit Reservoir Creeks supported high numbers of alder with no willow competition.

Foliar Litter Production

Leaves and needles from the surrounding terrestrial environment are the most prevalent form of terrestrial coarse particulate organic matter influxes to headwater streams (Cummins 1974; Hynes 1975). Riparian zone structure and composition in first- to third-order streams are complex, varying spatially and with time since disturbance. Both terrestrial and aquatic ecosystems are generally characterized by a high degree of species richness. Any current differences between perturbed and unperturbed streams can be ascribed to change in patterns of the quantity, quality, and timing of detrital inputs (Patten and Webster 1979). Detrital input integrates terrestrial and aquatic environments: riparian vegetation provides the necessary detrital resource base for processing and utilization by microorganisms and benthic invertebrates.

Annual foliar litterfall of riparian communities established by debris torrent disturbance indicates rapid increases in production. This trend is consistent with increased production rates of several above-ground biomass components in other studies (Likens and Bormann 1979; Cline, in preparation).

The production of foliar litter is strongly controlled by the functional interactions of fluvial processes and riparian vegetation dynamics. The silvicultural condition of the adjacent hillslopes and the physical conditions of the stream bed control the influx and efflux of organic matter to channel banks and running waters.

The maximum foliar biomass production of post-torrent riparian communities in response to debris torrents occurs in clearcuts about ten years earlier than in old growth. This shift in foliar production levels is due to a fundamental change in succession following clearcutting. This more rapid production of foliar litter in clearcuts contributes to detrital resource stability and stream recovery from disturbance by replacing debris torrent removed biomass.

Herbs are important sources of foliar litter in debris torrent disturbed riparian zones (Franklin and Campbell 1979; Mahan 1980). Their most important role may lie not in detrital input, but rather in ameliorating surface erosion on severely scoured channel banks and improving the status of soil fertility by conserving nutrients and producing soil organic matter. Lateral transfer of herbage inputs from upslope sites, rather than direct infall, probably occurs to a greater extent on the characteristically steep channel banks in the study area than occurs elsewhere (Mahan 1980).

Foliage Quality and Processing

Compositional changes in riparian zones due to debris torrents change the nature of leaf inputs to streams. The observed shift to broadleaf dominated early successional species in clearcuts results in a high quality, readily processed leaf litter. Senescence of deciduous species and the heavy influx of leaves and herbage coincide with the onset of fall and winter storms. In old growth, there is a change in the type of litterfall inputs relative to clearcut streams. Old-growth riparian corridors which remain intact after debris torrent passage will continue to produce needlefall that is low in nutritional quality from the residual stand, without a pronounced autumnal peak.

Quantities of leaffall in this study compare to other work on leaffall and coarse particulate organic matter (CPOM) influxes to streams in western Oregon and the United States (Table 5, Appendix). The range of tree and herb foliar litterfall values are very similar to that of Cline who studied riparian regrowth after clearcutting in western Oregon (Cline, in preparation). The high shrub values for foliar litterfall in this study of 7.0 kg/m^2/yr occurred in Cedar Creek in a depositional-clearcut site which was totally encompassed by a dense stand of willow. The high light and moisture availability at this alluvial deposit provided optimum growth conditions. The absence of tree, shrub, or herb foliar litter in thirteen streams indicates the highly variable nature of successional response along headwater streams.

Transport and retention of foliar litter or sediment entering running waters depends on the distribution of channel bed forms. Flow obstructions (bed material such as logs, boulders, cobbles, bedrock) create complex channel bed forms formed by differential scour and fill at high flows. Relic pools and riffles store organic and inorganic loads, and regulate habitat and food availability.

Sediment and organic matter budgets for headwater streams provide balance sheets for the input, processing, change in storage, and export of particulate detritus. Large organic debris traps large volumes of sediment in stream channels and removal of LOD can result in rapid downcutting and sediment export (Megahan and Nowlin 1976; Beschta 1977). LOD dams regulate storage of coarse particulate organic matter in headwater streams and allow processing into finer size fractions (Bilby and Likens 1981). Drift distances of leaves entering running waters have been reported to vary between 100 m and 2500 m (Fisher and Likens 1973; Young et al. 1978; Cummins, personal communication). Retention of leaves and CPOM is enhanced by the presence of in-stream LOD, decreasing the travel distance of leaves (Bilby and Likens 1981; Gregory, unpublished data).

Debris torrents disturb the influx, storage, processing, and export of organic matter. Foliar litter entering stream sites with low retention capacity is exported downstream, and processing is displaced to sites where entrainment occurs. Erosional sites probably are more likely to export detritus and sediment because of lower total pool ratings, cumulative pool depths, and cumulative pool area relative to depositional sites. For depositional sites, morphologic features increase and probability of local retention and processing of detrital input.

Case Study: Warfield and Simmonds Creeks

Simmonds Creek and Warfield Creek exemplify sites at the extremes of a response spectrum to debris torrents (see Table 7, Appendix). Simmonds Creek revealed little evidence of debris torrent passage, whereas Warfield Creek revealed the obvious scars of intense disturbance. These were the only streams in this study where data were collected at sites upstream of hillslope debris entry to the channel; these streams permit comparisons of control, erosional, and depositional sites.

Channel gradient and channel cross-sectional form and area determine the effects of debris torrent disturbance. Warfield

Creek, in old growth, had ideal physical conditions for high-intensity impact: consistent 25% channel slope and V-notched (channel width < 4.0 m, hillslopes > 60%) cross section; this debris torrent traveled approximately 3 km. Simmonds Creek, in a 35-year-old clearcut had ideal physical conditions for low-intensity impact: consistent 5% channel slope, a wide U-shaped (channel width 5-8 m, hillslopes 35%) cross section, and large drainage area. This debris torrent traveled approximately 0.8 km. Channel substrate at Simmonds was not appreciably altered; channel substrate in Warfield was completely altered by debris torrent passage.

Position of a stream segment within a drainage can influence stream response to debris torrent perturbation. Stream segment position, related to the source area for runoff yielded from the basin, affects the quantity of streamflow available to rework channel bed material, redistribute large organic debris, and influence nearstream vegetation. The greater streamflow of channel segments located lower in the drainage (e.g., Simmonds Creek site), relative to channel segments located higher in the drainage (e.g., Warfield Creek site), can remove traces of debris torrent occurrence due to the flushing action of water.

Total pool rating values for Warfield Creek, scoured in 1965, varied widely. Warfield Creek had an erosional site completely scoured to bedrock, and channel material reworked in the depositional site to a normal substrate appearance. The extremely high total pool rating for the control site of Warfield Creek, the highest recorded in this study, gives a comparative sense of channel structure prior to debris torrent disturbance. On the basis of total ratings and detrital input, the depositional site of Warfield Creek appears to have achieved a high degree of recovery from intense disturbance compared to undisturbed site of this stream.

Total pool ratings for the three sites at Simmonds Creek were moderate values that were remarkably consistent. Boulder- and cobble-formed pool-riffle sequences gave the appearance of a stream unaffected by disturbance. The lower pool rating for the depositional site was due to aggradation by gravels and fines; the higher pool rating in the erosional site was due to scour around stable large boulders which resulted in large, deep pools. The pool ratings indicate complexity of channel bed topography for a stream subject to low-intensity perturbation only very recently (1978). Pool ratings and detrital input for erosional and depositional sites are similar to that in the undisturbed site and indicate comparative recovery of erosional and depositional sites.

The annual input of large organic debris was low for both streams, though leaf litter input from residual and post-torrent nearstream vegetation for both streams in this study was moderate to high.

The discussion of response to debris torrent disturbance for Warfield and Simmonds Creeks is incomplete without assessing particulate retention of the stream and community structure of benthic invertebrates. No adequate methodologies exist for assessing retention at present and invertebrate sampling was not an objective of this study. Inferences about stream recovery to debris torrent impact should be made recognizing these limitations.

VII. CONCLUSIONS

The objectives of this study have been twofold: an extensive study of mass erosion occurrence in the Willamette National Forest and an intensive study of changes induced by mass erosion to streams. Attempts have been made to describe riparian recovery from debris torrent disturbance.

The extensive study of mass erosion occurrence throughout the Willamette National Forest was based on aerial photo identification of 232 soil mass movements over a period of 50 years. Soil mass movement frequency related to logging and roading was observed to increase relative to that under undisturbed forest conditions. Logging increased mass erosion frequency 4-20 times compared to forest mass erosion frequency. Roading increased mass erosion frequency 11-700 times compared to forest mass erosion frequency. These findings substantiated other studies in the region as to frequency of occurrence of management-related failures relative to forest failures.

Volumes of individual failures were not estimated in this study, so inferences cannot be made regarding soil transfer rates (m^3/ha/yr). Inference can be drawn, however, as to the effects of hillslope mass failures on stream systems. Seventy-one percent of 232 air photo identified hillslope mass failures entered stream channels; approximately 43% of hillslope mass failures spawned debris torrents.

The intensive portion of this study focused on the effects of debris torrents on changes in large organic debris accumulations, channel morphology, and riparian vegetation. Quantities of large organic debris ranged from 0 to 37 kg/m^2. These values, lower than those reported by Swanson (Franklin et al. 1981) and Froehlich (1973) in western Oregon, indicate that debris torrents disperse woody debris upon channel banks and along the channel. Large organic debris loading and annual LOD input was highly variable. Depositional sites in old-growth streams contained the highest standing crop of LOD and received the highest annual woody input. Random processes that affect the entry and fate of LOD in streams make quantification of LOD difficult. There was no evidence for consistent change (increase or decrease) in LOD standing crop. The lack of a clear chronosequence scenario for LOD may be due to the short-term (< 30 yrs) perspective of this study.

Boulders were important in forming pools in streams where logs were removed by debris torrent passage. Log-formed pools were ten times more numerous in depositional sites than erosional sites. Total pool numbers per unit stream length were twice as high in depositional sites relative to erosional sites. This indicates that the availability of channel bed material is crucial to the recovery of complex bed contours that are similar to natural stream conditions. This study indicates that the condition of a channel bed scoured to bedrock in erosional sites can persist for 25 years or more.

The total pool rating developed in this study can provide an index of the physical structure of the channel as it relates to habitat for macroinvertebrates and retention of organic and inorganic particulates. Total pool ratings were generally higher in depositional sites, regardless of the silvicultural condition of the surrounding terrain. The inherent limitations of a pool rating scheme should be recognized. The pool rating value is sensitive to changes in flow, and varies in time.

Quantities of foliar litter produced by nearstream vegetation were highly variable. Foliar litter production by post-torrent vegetation in clearcuts occurred more rapidly than in old growth. This observed phenomenon was probably due to compositional changes inherent in clearcut sites that favored rapidly growing high shrub and tree species such as willow and alder. Shrubs and herbs belonging to post-torrent communities were important in producing leaf litter, a detrital resource for bank and channel flora and fauna. Post-torrent litterfall was the major component of detrital input to streams. Residual litterfall, produced by riparian plant strata not affected by debris torrent passage, was an important detrital influx for old-growth streams.

Estimates of leaf fall for various riparian plant strata were made through equations that predict foliar biomass based on species-specific growth architecture. Though the values for litter obtained in this study were similar to other studies (Mahan 1980; Sedell et al. 1974; Cline, in press), seasonal and year-to-year fluctuations were not accounted for, nor was spatial variability of nearstream plant communities. These factors influencing foliar litter production should be born in mind.

Stream response to debris torrent disturbance in this study was highly variable, as exemplified by the case studies of Warfield and Simmonds Creeks. Each of these streams provided an opportunity to assess the physical and biological structure of treatment (debris torrent affected) vs. control (upstream of debris torrent) stream sites. The difficulty in assessing stream response depends on the developmental processes and environmental conditions that influence persistance of ecosystem attributes and/or recovery to undisturbed conditions.

Despite the need of resource managers and researchers to determine the ability of stream systems to withstand and recover from periodic or cataclysmic disturbance, it remains difficult to quantify because the responses of streams to disturbance are due to physical and biological differences that vary in space and time.

Further research needs to be directed towards assessing the retention capacity of channel beds as a function of bed material type. The trapping efficiencies of boulders and logs varies as a function of discharge, and size and placement of bed material; this relationship needs to be better understood. Long-term (> 30 yrs) study of large organic debris entry and disposition could better provide an understanding of its role in shaping the structure and function of streams. Detrital input studies would also benefit from this longer time perspective. Macroinvertebrate processing and assimilation of organic detritus should also be assessed in light of the interrelationships that exist between detrital input, bed material stability, retention capacity, and processing.

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APPENDICES

APPENDIX I

Table 1.

CLIMATIC DATA [1/]
WILLAMETTE NATIONAL FOREST AND ADJACENT AREAS
AVERAGE MEAN MONTHLY AND ANNUAL TEMPERATURE AND PRECIPITATION

STATION	ELEVATION	PERIOD	JANUARY (1)	JANUARY (2)	FEBRUARY (1)	FEBRUARY (2)	MARCH (1)	MARCH (2)	APRIL (1)	APRIL (2)	MAY (1)	MAY (2)	JUNE (1)	JUNE (2)	JULY (1)	JULY (2)	AUGUST (1)	AUGUST (2)	SEPTEMBER (1)	SEPTEMBER (2)	OCTOBER (1)	OCTOBER (2)	NOVEMBER (1)	NOVEMBER (2)	DECEMBER (1)	DECEMBER (2)	ANNUAL MEAN AVERAGE (1)	ANNUAL MEAN AVERAGE (2)
Belknap Springs Sec. [illegible]	2152'	1961-73	32.4	11.73	37.0	8.57	38.9	8.51	41.0	6.01	51.4	3.41	59.1	3.56	64.6	0.51	64.0	1.01	58.1	2.01	48.2	6.53	40.5	11.67	33.3	11.51	47.0	76.05
Cascadia State Park Sec. [illegible]	850'	1931-73	37.0	6.88	41.0	6.86	43.5	7.06	48.1	5.98	53.5	3.85	59.6	3.91	64.2	0.56	65.5	0.91	59.3	2.11	54.5	5.67	41.6	8.34	38.5	9.58	50.3	61.40
Cougar Dam Sec. [illegible]	1161'	1960-73	-	15.09	-	11.05	-	9.78	-	6.70	-	4.35	-	3.08	-	0.45	-	1.38	-	2.93	-	4.09	-	11.79	-	11.64	-	85.07
Detroit Dam Sec. [illegible]	1300'	1956-73	37.5	15.16	41.7	9.50	43.0	9.91	46.5	6.77	53.7	4.47	60.5	3.09	66.1	0.63	66.8	1.40	61.0	3.56	51.6	7.53	44.1	11.65	38.5	14.19	50.9	87.86
Detroit, Oregon Sec. [illegible]	1586'	1931-71	33.7	11.26	37.7	9.11	40.6	8.78	46.6	5.38	53.0	3.72	58.3	1.63	65.0	0.56	63.3	1.04	58.5	2.79	50.3	7.18	41.3	11.56	36.3	13.17	46.6	78.50
Eugene, Oregon	359'	1931-73	40.1	7.11	41.1	5.85	45.8	5.56	50.1	2.57	56.3	2.11	57.0	1.43	66.3	0.17	66.0	0.59	60.9	1.45	53.2	3.03	45.9	5.61	40.9	7.38	53.3	42.05
Foster, Oregon Sec. [illegible]	710'	1963-73	40.5	11.35	43.5	5.60	45.8	6.77	47.7	5.81	55.5	2.81	59.6	1.96	65.3	0.47	65.5	0.35	58.5	3.30	53.5	3.35	45.9	5.10	40.3	9.55	51.7	55.61
Hills Cr. Dam Sec. [illegible]	1175'	1960-73	-	6.94	-	5.13	-	5.51	-	3.30	-	2.80	-	1.81	-	0.19	-	0.51	-	1.57	-	3.41	-	6.51	-	7.11	-	43.86
Leaburg Dam Sec. [illegible]	675'	1933-73	39.8	8.93	43.5	7.11	46.0	6.78	51.0	5.53	56.5	3.45	61.5	1.83	66.9	0.60	66.5	0.86	61.3	2.28	53.8	5.71	45.7	8.71	41.1	9.61	53.9	61.59
Lookout Point Dam Sec. [illegible]	717'	1955-73	40.8	7.55	45.0	4.60	46.6	5.00	49.5	3.35	55.1	3.08	61.5	1.07	66.7	0.36	67.1	0.78	61.0	1.76	55.5	3.68	47.4	6.17	41.9	6.99	51.8	45.78
Lowell 1-E Sec. [illegible]	1010'	1946-55	-	8.50	-	5.36	-	5.80	-	2.87	-	2.53	-	2.57	-	0.38	-	0.70	-	1.15	-	5.16	-	5.67	-	7.11	-	44.01
Lowell 3-N Sec. [illegible]	750'	1951-59	-	7.08	-	3.48	-	5.69	-	2.95	-	3.03	-	2.86	-	0.33	-	0.74	-	1.10	-	4.55	-	4.88	-	8.16	-	46.26
Marion Fk. Fish Hatchery Sec. [illegible]	2415'	1951-73	31.1	12.03	36.8	7.53	37.0	8.16	41.6	4.60	50.7	3.31	57.6	2.04	61.5	0.58	62.0	1.17	55.5	2.41	46.9	5.92	37.8	10.13	32.6	10.71	46.0	68.85
McCredie Springs Sec. [illegible]	2011'	1945-50	33.0	7.05	36.5	6.47	40.8	5.13	48.1	3.40	55.1	3.45	50.5	2.76	61.9	0.95	65.0	0.51	58.4	1.06	48.0	4.37	39.0	7.43	35.7	5.99	48.3	50.17
McKenzie Ranger Station Sec. [illegible]	1375'	1911-73	35.1	11.37	39.8	8.06	41.9	7.99	46.4	4.69	54.6	3.71	60.1	2.79	65.7	0.51	65.5	0.81	59.5	1.46	51.8	6.37	41.8	9.77	36.8	11.61	50.3	70.05
Oakridge Ranger Station Sec. [illegible]	1310'	1931-57	38.1	6.40	41.6	4.91	46.2	4.91	51.1	3.17	57.6	2.41	61.0	1.48	68.0	0.47	68.4	0.45	63.9	1.12	55.3	3.90	45.1	5.88	40.3	6.33	53.1	41.32
Oakridge Salmon Hatchery Sec. [illegible]	1275'	1951-73	37.5	7.07	41.4	4.75	45.4	5.08	49.9	3.08	55.8	3.03	61.8	1.06	67.1	0.31	67.1	0.65	61.1	1.40	53.5	3.67	44.9	6.31	39.1	7.71	51.1	45.77
Quartzville Sec. [illegible]	873'	1951-60	-	16.76	-	10.56	-	11.16	-	6.18	-	5.05	-	3.26	-	0.58	-	1.31	-	[illegible]	-	8.58	-	11.30	-	15.55	-	91.46
Santiam Junction Sec. [illegible]	3990'	1953-65	-	9.71	-	8.46	-	9.10	-	6.00	-	4.31	-	1.50	-	0.62	-	1.36	-	3.46	-	4.77	-	10.69	-	10.84	-	70.97
Santiam Pass Sec. [illegible]	4740'	1961-73	27.4	19.77	30.4	8.63	31.0	9.15	35.5	5.98	43.3	3.49	51.1	3.07	58.4	0.91	58.0	1.47	58.5	3.60	41.8	6.56	34.1	11.05	30.1	16.00	40.6	88.67
Westfir, Oregon Sec. [illegible]	1070'	1940-66	-	6.86	-	5.87	-	5.38	-	3.07	-	3.48	-	1.97	-	0.55	-	0.56	-	1.77	-	4.16	-	6.70	-	3.50	-	46.55

1/ Data compiled from the following sources: Weather Bureau, U.S. Dept. of Commerce, Eugene Water & Electric Board, U.S. Army Corps of Engineers. The above values are summations of various sources of data and may vary slightly from other reported information.

(1) Mean Temperature

(2) Mean Precipitation

APPENDIX II

Figure 1. Sample aerial photo interpretation worksheet.

AIR PHOTO INTERPRETATION WORKSHEET

PAGE ___ OF ___

IMAGERY

DATE FLOWN ______________

SCALE ______________

SOURCE ______________

FILM TYPE ______________

____
BASIN

____
TOPOGRAPHIC QUAD

INTERPRETED BY ______________

DATE ______________

VERIFIED BY ______________

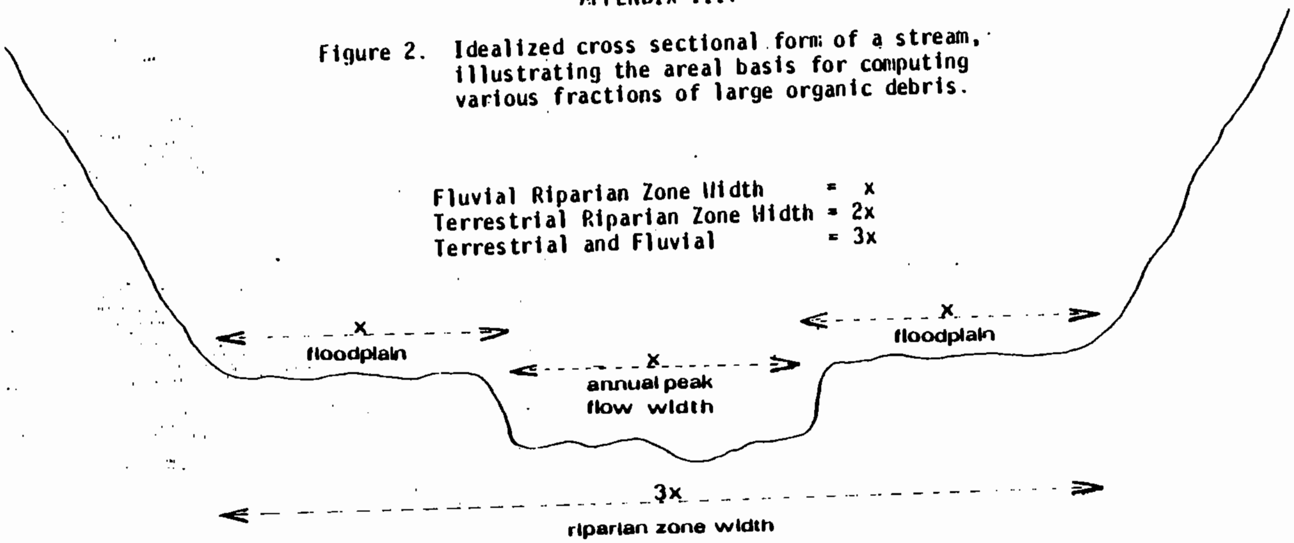
DATE ______________

FEATURE NUMBER	GEOGRAPHIC LOCATION				MAP INFORMATION		GEOMORPHIC CHARACTERISTICS								CAUSE OF FEATURE					[illegible]	[illegible]	COMMENTS AND OBSERVATIONS
	TOWNSHIP/RANGE			IMAGERY NUMBERS			TOPOGRAPHY		[illegible]	[illegible]	APPARENT POINT OF ORIGIN	[illegible]			NATURAL	LAND MANAGEMENT ACTIVITY						
	TOWNSHIP	RANGE	SECTION		FEATURE SYMBOL	TERRAIN UNIT	ELEVATION	SLOPE ASPECT	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]		AGRICULTURAL	FORESTRY	MINING	ROADS			

APPENDIX III.

Figure 2. Idealized cross sectional form of a stream, illustrating the areal basis for computing various fractions of large organic debris.

Fluvial Riparian Zone Width = x
Terrestrial Riparian Zone Width = 2x
Terrestrial and Fluvial = 3x

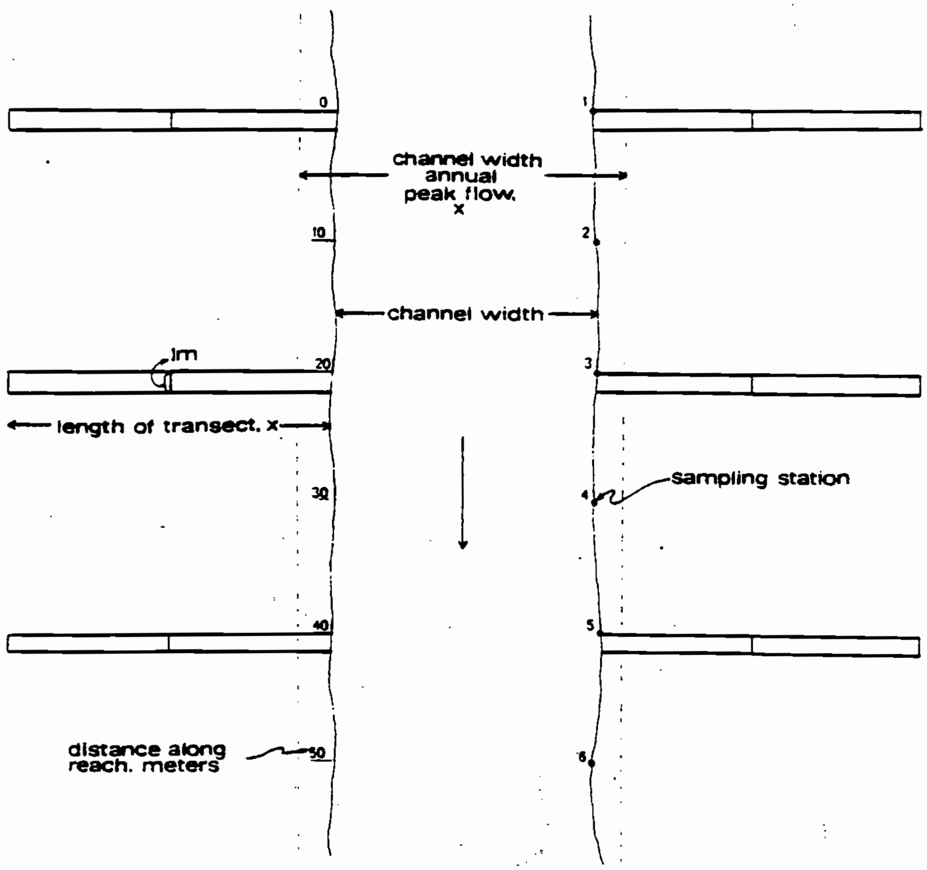


For the purposes of this study, the areal basis for LOD determinations have been defined as follows:

Fluvial Zone (x)	Terrestrial Zone (2x)	Terrestrial and Fluvial (3x)
CH,Pot,CHTM,CHPost,PotTM,PotPost	BK,BKTM,BKPost	TM,Post,?

APPENDIX IV.

Figure 3. Plan view of transect layout for sampling sampling groundcover and low shrubs.



Measurements at stations 1,3,5 included: channel width and depth, annual floodplain width, %groundcover, and low shrub cover, i.e., _Ribes_, _Rubus_, _Rhododendron_ sp.

APPENDIX V.

Table 2. Parameters for equations used to generate foliar biomass estimates of riparian vegetation, from Gholz et al. (1979).

Overstory	parameters,(units)	range	foliar biomass units
Abies amabilis	dbh,(cm)	11.7-90.4	kilograms
Abies procera	dbh,(cm)	18.8-111.0	kilograms
Acer macrophyllum	dbh,(cm)	7.6-35.3	kilograms
Alnus rubra	dbh,(cm);ht,(m)	1.3-40.8	kilograms
Pseudotsuga menziesii	dbh,(cm)	1.8-162.0	kilograms
Thuja plicata	dbh,(cm)	15.5-60.2	kilograms
Tsuga heterophylla	dbh,(cm)	15.3-78.0	kilograms
Shrubs			
Acer circinatum	dba,(cm)		grams
Acer circinatum sprouts	dba,(cm)		grams
Acer macrophyllum sprouts	dba,(cm)		grams
Holodiscus discolor	dba,(cm)		grams
Oplopanax horridum	dba,(cm)		grams
Rhododendron macrophyllum	dba,(cm)		grams
Ribes bracteosum	dba,(cm)		grams
Rubus spectrabilis	dba,(cm)		grams
Salix sitchensis	dba,(cm)		grams
Herbage			
Berberis nervosa	cover,(%)		grams
Blechnum spicant	# fronds·length ave. frond,(cm)		grams
Gaultheria shallon	cover,(%)		grams
Oxalis oregana	cover,(%)		grams
Polystichum munitum	# fronds·length ave. frond,(cm)		grams
Pteridium aquilinum	dba,(cm)		grams

All equations are of the form $\ln Y = a + b \ln X$, except for a few species. "X" is the input parameter, and "Y" is foliar biomass. For *A. rubra*, the equation is $Y = (dbh)^2 \cdot ht/100$.

Leaffall from evergreen conifers of the overstory was estimated as a percentage of foliar biomass. Reiners (1974) estimated leaffall from *Thuja occidentalis* to be 17% of foliar biomass. Gessel and Turner (1976) estimated leaffall for other conifers to be approximately 15% of foliar biomass.

APPENDIX VI.

An Interpretive Guide for Reading Tables in This Study

Overview

Twenty six study sites from twenty four streams subject to debris torrents were measured for various biological and physical structural and functional indicators of ecosystem stability.

Twenty four of twenty six study sites contained erosional and depositional pairs of reaches, not necessarily belonging to the same forest type (old growth or clearcut). Warfield and Simmonds Creeks each had in addition to erosional-depositional pairs of reaches, a "control" reach, located upstream of the erosional-depositional pairs of sites, where measurements were also made in order to evaluate the resistance and resilience characteristics of streams.

Table Reading

Whether reading large organic debris data or channel morphology data, all tables areastructured identically. Data for each stream site (N=26) is presented as erosional reach data first, and depositional data second. This sequence repeats itself for the twenty six study sites except for Warfield and Simmonds Creeks, where data is presented as erosional, depositional, control for each of these two study sites.

APPENDIX VII.

Table 3.

Larne organic debris accumulations of streams sluiced by debris torrents.

STREAM	EVENT YEAR	LAND TYPE	TOTAL (TMAPost) kg/m²	TM	Post	?*	BK	CH	Pot	INPUT g/m²/yr
					Percentage					
1. Cedar	65E	cc	1.2	100	0	0	50	50	0	0
	D	cc	13.3	97	3	0	69	31	0	247
2. South Fork Simpson	65E	og	1.2	100	0	0	26	74	0	0
	0	og	1.2	100	0	0	100	0	0	0
3. Elk Tributary	65E	cc	6.1	32	62	0	32	68	0	2764
	0	og	17.1	100	0	0	96	4	0	0
4. School 2	70E	og	0.7	100	0	0	12	88	0	0
	D	cc	3.6	71	29	0	100	0	0	1058
5. Upper Canal	65E	cc	10.6	12	88	0	0	35	65	6254
	0	og	23.0	40	60	0	25	71	4	9333
6. Blowout	65E	og	5.6	86	13	1	84	16	0	513
	0	cc	13.8	88	12	0	81	16	3	211
7. Rebel	65E	og	1.2	91	9	0	8	92	0	76
	D	og	3.4	71	28	1	31	69	0	655
8. Avenue 1	55E	og	35.2	14	85	1	31	25	44	12102
	0	og	29.9	29	65	6	20	21	59	8276
9. Avenue 2	55E	og	2.7	0	100	0	72	0	28	1066
	D	og	3.5	80	20	0	79	7	13	280
10. Lower Canal	65E	og	6.7	36	64	0	23	16	55	3253
	D	og	18.8	89	11	0	58	42	0	1427
11. Lower Box Canyon	70E	og	11.6	38	49	13	21	44	35	6507
	0	og	36.9	51	43	6	14	78	8	16945
12. Staley Tributary	65E	og	1.8	38	12	0	6	94	0	148
	0	og	2.4	100	0	0	51	49	0	0
13. Detroit Reservoir	65E	cc	0	0	0	0	0	0	0	0
	0	cc	0.2	97	3	0	97	3	0	5
14. School 1	70E	cc	1.6	11	89	0	89	11	0	1403
	0	cc	3.2	91	9	0	100	0	0	303
15. Shitepoke	78E	cc	0.9	44	56	0	90	10	0	2415
	0	cc	5.9	73	27	0	46	30	24	6165
16. Upper Box Canyon	65E	cc	2.9	38	62	0	40	60	0	1235
	0	og	17.3	85	15	0	38	55	7	1705
17. Slipout	70E	cc	0.6	80	20	0	83	17	0	116
	D	og	20.2	70	30	0	40	60	0	6024
18. Bohemia	65E	og	<< 1	100	0	0	60	40	0	0
	0	og	0	0	0	0	0	0	0	0
19. Tom	65E	cc	5.7	98	1	1	64	36	0	61
	0	cc	7.3	99	.5	.5	17	82	1	5
20. Upper Zog	65E	og	7.8	77	18	5	78	22	0	963
	0	og	16.3	96	3	1	89	11	0	338
21. Lower Zog	65E	og	1.3	100	0	0	82	16	0	0
	0	og	8.5	76	24	0	79	13	8	1382
22. Dartmouth	65E	og	3.8	0	100	0	74	26	0	0
	0	og	7.9	50	49	1	68	32	0	2613
23. McQuade	65E	cc	0.6	100	0	0	100	0	0	0
	0	og	11.7	89	11	0	91	9	0	825
24. Warfield	65E	og	1.5	46	54	0	36	15	49	555
	0	og	0.3	76	24	0	78	3	19	46
	C	og	0.2	0	0	100	32	63	5	--
25. Simmonds	70E	cc	6.5	100	0	0	93	7	0	0
	0	cc	<< 1	9	0	91	96	4	0	0
	C	cc	0	0	0	0	0	0	0	--
26. Squaw	65E	og	4.8	61	19	0	67	33	0	507
	0	og	15.3	69	11	0	94	2	4	1140

*Ambiguous Oricin

APPENDIX VIII.

Table 4. Alder and willow stem density in riparian zones sluiced by debris torrents.

	EVENT YEAR	LAND TYPE	ELEVATION meters	STEMS PER HECTARE 0-10cm willow	0-10cm alder	11cm alder
1. Cedar	65E	cc	880	1075	2000	0
	0	cc	880	14792	0	0
2. South Fork Simpson	65E	og	1520	4000	0	0
	0	og	1520	4286	0	0
3. Elk Tributary	65E	cc	730	1941	0	0
	0	og	730	0	0	0
4. School 2	70E	og	490	0	0	0
	0	cc	490	2545	2273	0
5. Upper Canal	65E	cc	1160	2538	615	0
	0	og	1160	36	0	0
6. Blowout	65E	og	1100	269	0	0
	0	og	1100	1133	700	0
7. Rebel	65E	og	980	600	400	0
	0	og	980	0	529	0
8. Avenue 1	55E	og	1100	0	0	0
	0	og	1100	0	83	0
9. Avenue 2	55E	og	1100	0	0	0
	0	og	1100	0	0	0
10. Lower Canal	65E	og	1160	0	0	0
	0	og	1160	0	0	0
11. Lower Box Canyon	70E	og	1100	0	0	0
	0	og	1100	0	0	0
12. Staley Tributary	65E	og	1220	190	0	0
	0	og	1220	0	158	0
13. Detroit Reservoir	65E	cc	460	0	5483	1552
	0	cc	460	0	4958	917
14. School 1	70E	cc	370	947	1263	263
	0	cc	370	5278	2278	222
15. Shitepoke	78E	cc	730	2063	563	0
	0	cc	730	1897	621	0
16. Upper Box Canyon	65E	cc	1160	61	0	0
	0	cc	1160	0	0	0
17. Slipout	70E	cc	730	394	788	273
	0	cc	730	18	0	0
18. Bohemia	65E	og	1100	2211	0	0
	0	og	1100	42	1675	167
19. Tom	65E	cc	580	0	2000	514
	0	cc	580	0	3049	659
20. Upper Zog	65E	og	670	0	1296	185
	0	og	670	95	190	71
21. Lower Zog	65E	og	490	632	0	0
	0	og	490	10417	0	0
22. Dartmouth	65E	og	850	0	1042	0
	0	og	850	0	1912	324
23. McQuade	65E	cc	790	1667	0	0
	0	og	790	100	256	22
24. Harfield	65E	og	1460	2229	0	0
	0	og	1460	759	0	0
	C	og	1460	0	0	0
25. Simmonds	78E	cc	490	0	472	623
	0	cc	490	83	940	786
	C	cc	490	0	1140	362
26. Squaw	65E	og	730	0	92	0
	0	og	730	0	729	0

APPENDIX IX.

Table 5. Estimated litterfall inputs to streams in various environments in the United States.

REFERENCE	TYPE OF INPUT	QUANTITY kg/m²	RIPARIAN COMPONENT	FOREST TYPE
Fisher and Likens, 1973	CPOM*	0.6		New Hampshire, mixed hardwoods
Sedell et al., 1974	CPOM	0.9		Oregon, douglas-fir
Mahan, 1980	CPOM	0.1-0.6		Michigan, mixed hardwoods
Cline (in press)	leaf	0.07-0.82	tree	Oregon, clearcuts
		<<0.01-0.12	high shrub	
		<<0.01-<.01	low shrub	
		0.02-0.13	herb	
This study	leaf	0-0.35	tree	Oregon, clearcuts, old growth
		0-7.0	shrub	
		0-0.14	herb	

*Coarse Particulate Organic Matter

APPENDIX X.

Table 6. Watershed data for twenty six stream sites subject to debris torrents.

	EVENT YEAR	LAND TYPE	WS SIZE ha	STREAM ORDER	ELEV m	CHAN SLOPE %	HILL SLOPE %	CHAN DEPTH cm	CHAN WIDTH m	RIPARIAN ZONE AREA $x10^{-2}$ha
1. Cedar	65E	cc	52	1	880	38	95	5.7	2.4	3.9
	D	cc	52	1	880	10	73	1.9	1.6	3.6
2. South Fork Simpson	65E	og	52	1	1520	30	69	2.9	0.6	1.7
	D	og	52	1	1520	14	23	3.5	0.8	1.7
3. Elk Tributary	65E	cc	65	1	730	16	119	6.2	1.7	4.1
	D	og	65	1	730	8	88	9.8	4.3	6.5
4. School 2	70E	og	70	1	490	10	79	5.7	1.1	3.2
	D	cc	70	1	490	6	70	10.9	1.1	6.3
5. Upper Canal	65E	cc	80	1	1160	37	115	8.7	1.3	2.7
	D	og	80	1	1160	19	113	8.3	2.6	5.7
6. Blowout	65E	og	85	1	1100	22	75	5.2	2.6	5.2
	0	cc	85	1	1100	14	45	7.8	3.0	8.4
7. Rebel	65E	og	91	1	980	20	35	6.9	2.0	3.5
	D	og	91	1	980	11	100	8.3	1.7	5.7
8. Avenue 1	55E	og	119	1	1100	24	100	3.4	1.9	3.9
	D	og	119	1	1100	10	90	8.3	2.4	7.6
9. Avenue 2	55E	og	127	1	1100	23	80	9.8	2.2	4.5
	D	og	127	1	1100	20	65	6.5	4.5	14.3
10. Lower Canal	65E	og	130	2	1160	12	63	6.5	5.9	8.6
	D	og	130	2	1160	8	79	10.4	3.5	8.4
11. Lower Box Canyon	70E	og	148	1	1100	39	113	9.5	1.2	4.2
	D	og	148	1	1100	27	88	7.6	1.7	4.8
12. Staley Tributary	65E	og	166	1	1220	30	113	5.4	2.1	3.3
	D	og	166	1	1220	18	63	5.9	1.9	3.3
13. Detroit Reservoir	65E	cc	171	1	460	13	88	9.2	2.4	19.9
	D	cc	171	1	460	7	73	5.8	2.9	6.9
14. School 1	70E	cc	192	1	370	7	68	4.3	1.9	3.8
	D	cc	192	1	370	4	65	8.1	1.8	8.8
15. Shitepoke	78E	cc	194	1	730	9	73	9.1	3.2	6.9
	D	cc	194	1	730	7	65	10.2	2.9	4.9
16. Upper Box Canyon	65E	cc	199	1	1160	18	88	2.5	3.3	5.4
	D	og	199	1	1160	11	85	10.9	2.7	8.6
17. Slipout	70E	cc	257	1	730	13	60	5.5	3.3	4.6
	0	og	257	1	730	10	60	10.1	5.7	12.6
18. Bohemia	65E	og	272	1	1100	12	70	5.3	1.9	4.3
	D	og	272	1	1100	6	90	6.6	2.4	5.2
19. Tom	65E	cc	383	1	580	13	80	13.2	3.7	5.1
	D	cc	383	1	580	7	65	10.6	4.1	9.1
20. Upper Zog	65E	og	435	2	670	11	65	6.2	2.7	6.0
	D	og	435	2	670	6	68	9.7	4.2	9.2
21. Lower Zog	65E	og	515	2	490	30	92	2.5	1.9	4.2
	D	og	515	2	490	5	88	4.6	1.2	16.7
22. Dartmouth	65E	og	565	2	850	21	125	21.1	2.4	3.5
	D	og	565	2	850	5	68	12.6	3.4	6.8
23. McQuade	65E	cc	578	2	790	11	31	11.1	4.8	6.7
	D	og	578	2	790	10	60	11.3	9.0	14.0
24. Warfield	65E	og	624	1	1460	27	90	5.5	3.5	4.8
	D	og	624	1	1460	20	60	16.7	2.9	8.6
	C	og	624	1	1460	25	65	7.3	2.7	4.0
25. Simmonds	78E	cc	1606	2	490	7	40	37.5	5.3	7.3
	D	cc	1606	2	490	4	35	28.2	8.4	12.5
	C	cc	1606	2	490	5	35	28.0	6.9	9.5
26. Squaw	65E	og	2834	2	730	24	94	6.5	3.3	6.6
	0	og	2834	2	730	18	85	11.1	4.4	6.7

APPENDIX XI.

Table 7. Pool morphology data for twenty six stream sites subject to debris torrents.

STREAM		POOL DEPTH Σm	POOL AREA Σm^2	POOL RATING: DEPTH	AREA	TOTAL*	% POOL AREA FORMED, BY MATERIAL TYPE: BO	LO	CO	BE	% POOL DEPTH FORMED, BY MATERIAL TYPE: BO	LO	CO	BE
1. Cedar	E	0.5	0.6	3	1	4	0	0	0	100	0	0	0	100
	D	0	0	3	1	4	0	0	0	0	0	0	0	0
2. South Fork Simpson	E	0	0	0	0	0	0	0	0	0	0	0	0	0
	D	0	0	0	0	0	0	0	0	0	0	0	0	0
3. Elk Tributary	E	1.6	4.2	16	18	34	12	11	2	75	17	18	18	47
	D	2.3	8.0	8	10	18	32	18	50	0	27	12	61	0
4. School 2	E	0	0	0	0	0	0	0	0	0	0	0	0	0
	D	0.7	4.0	3	15	18	0	0	0	0	0	0	100	0
5. Upper Canal	E	1.7	3.5	9	23	32	4	59	0	37	0	12	0	88
	D	3.7	20.3	18	35	53	0	40	0	60	0	54	9	33
6. Blowout	E	1.1	3.0	12	10	22	77	0	23	0	77	0	23	0
	D	1.5	7.5	9	9	18	23	77	0	0	70	30	0	0
7. Rebel	E	0.6	2.6	6	8	14	0	0	100	0	0	0	100	0
	D	0.9	5.8	7	11	18	99	1	0	0	87	13	0	0
8. Avenue 1	E	0.9	11.9	13	15	28	0	16	0	84	0	11	0	89
	D	4.2	16.5	26	30	56	12	84	4	0	0	84	7	9
9. Avenue 2	E	0	0	0	0	0	0	0	0	0	0	0	0	0
	D	1.8	12.1	15	11	26	.9	0	0	91	17	0	0	83
10. Lower Canal	E	0.6	1.1	6	2	8	75	0	25	0	50	0	50	0
	D	4.9	28.6	20	40	60	40	45	15	0	30	67	3	0
11. Lower Box Canyon	E	0.3	0.3	1	3	4	0	0	0	100	50	0	0	50
	D	1.9	2.8	19	15	34	0	100	0	0	0	100	0	0
12. Staley Tributary	E	2.0	5.6	15	15	30	19	0	0	81	19	0	0	81
	D	2.4	5.7	19	28	47	81	0	19	0	73	0	27	0
13. Detroit Reservoir	E	0.6	3.1	5	5	10	45	0	55	0	29	0	71	0
	D	2.5	36.3	16	26	42	57	0	0	43	66	0	0	34
14. School 1	E	0	0	0	0	0	0	0	0	0	0	0	0	0
	D	0.6	10.6	2	10	12	0	26	0	74	0	50	0	50
15. Whitepoke	E	2.3	8.1	10	14	24	11	0	0	89	23	0	0	77
	D	2.4	8.9	9	21	30	28	39	33	0	38	33	29	0
16. Upper Box Canyon	E	0	0	0	0	0	0	0	0	0	0	0	0	0
	D	4.7	15.3	16	20	36	·64	36	0	0	18	77	5	0
17. Slipout	E	0	0	0	0	0	0	0	0	0	0	0	0	0
	D	1.1	12.7	5	13	18	10	65	25	0	9	75	16	0
18. Bohemia	E	1.9	4.9	20	24	44	74	0	26	0	64	0	36	0
	D	1.9	8.5	13	25	38	31	0	62	7	30	0	63	7
19. Tom	E	2.9	30.9	9	25	34	100	0	0	0	100	0	0	0
	D	5.3	51.7	20	38	58	20	80	0	0	40	60	0	0
20. Upper Zog	E	2.2	13.9	23	25	48	22	43	21	14	38	20	14	28
	D	3.4	22.9	24	24	48	28	36	36	0	45	18	37	0
21. Lower Zog	E	0	0	0	0	0	0	0	0	0	0	0	0	0
	D	0.4	1.8	5	5	10	0	100	0	0	0	100	0	0
22. Dartmouth	E	1.6	19.6	4	10	14	0	0	0	100	0	0	0	100
	D	2.9	14.6	8	22	30	31	25	44	0	32	33	45	0
23. McQuade	E	8.1	56.5	37	37	74	100	0	0	0	100	0	0	0
	D	11.8	83.6	55	30	85	85	10	5	0	74	11	14	0
24. Warfield	E	0	0	0	0	0	0	0	0	0	0	0	0	0
	D	5.7	38.4	16	44	60	100	0	0	0	100	0	0	0
	C	6.9	40.8	53	52	105	75	13	3	9	71	17	5	7
25. Simmonds	E	4.8	74.9	8	30	38	100	0	0	0	100	0	0	0
	D	3.8	49.9	9	19	28	33	0	67	0	90	0	10	0
	C	5.6	107.8	10	32	42	17	0	83	0	0	0	100	0
26. Squaw	E	1.3	11.9	6	8	14	28	0	9	73	39	0	0	61
	D	4.1	22.2	15.	18	33	100	0	0	0	100	0	0	0

*TOTAL = DEPTH + AREA

APPENDIX XII.

Table 8. Total pool rating guide.

POOL RATING	POOL AREA	APPROXIMATE DISTANCE ACROSS CHANNEL	POOL DEPTH	APPROXIMATE DEPTH AS MEASURED
1	0-10% UCA*	<.33x a.c.w.	max. depth <4x a.c.d.	<27cm
3	11-25% UCA	.33x to .50x a.c.w.	max. depth 4x to 8x a.c.d.	27 to 52cm
5	>25% UCA	>.50x a.c.w.	max. depth >8x a.c.d.	>52cm

a.c.w. = average channel width, a.c.d. = average channel depth, UCA*(unit channel area)= acw^2

TOTAL POOL RATING = POOL AREA RATING + POOL DEPTH RATING