TFW-SH9-93-001

DAM-BREAK FLOODS IN LOW ORDER MOUNTAIN CHANNELS OF THE PACIFIC NORTHWEST

By

Carol Coho

and

Stephen J. Burges

TIMBER FISH & WILDLIFE

June 1994

Department of Civil Engineering
University of Washington
Seattle, Washington 98195

Dam-Break Floods in Low Order Mountain Channels of the Pacific Northwest

by

Carol Coho

and

Stephen J. Burges

Project Completion Report for the Award
"An Examination of the Forms of Initiation of Floods From the Breaching of Non Engineered Dams"
Administered by the State of Washington
Department of Natural Resources
Timber Fish & Wildlife
TFW-SH9-93-001

and

Supported by
US Department of Agriculture Forest Service
Pacific Northwest Research Station

Water Resources Series
Technical Report No. 138

June 1994

ACKNOWLEDGMENTS

This report was prepared from the first author's Master of Science in Engineering thesis. We appreciate comments as the work evolved from thesis committee members Professors Ron Nece, Terry Cundy, and Derek Booth. Special thanks go to Lee Benda and Paul Kennard for support that made this project possible and in particular for their advice about field techniques and identification of geomorphic processes. John Heffner provided valuable information about Huckleberry and Ware Creeks. Dan Boccia and Kurt Hansen provided tireless and enthusiastic field support. Gretchen Carlson provided invaluable editorial assistance in preparing the draft and final version of this report. We appreciate deeply the support and interest of the TFW SHAM committee members throughout this project.

ABSTRACT

Flood waves produced from dam breaks attenuate with distance traveled downstream (Costa 1985). Flood waves produced from dam breaks in low-order mountain channels, however, mobilize significant amounts of organic debris within the stream valley and may cause the formation of a moving dam composed almost exclusively of organic material. This dam is propelled downstream in a manner often destructive to riparian vegetation, fish habitat, and downstream dwellings, until riparian conditions, channel geometry, or supply of organic debris are altered causing the movement to cease. Initiation mechanisms, movement, and ultimate deposition locations of debris from dam-break floods are described for twenty locations in the Pacific Northwest. Four low-order mountain channels that experienced destructive dam-break floods are described in greater detail. A strategy for evaluating the potential for destructive dam-break floods in low-order channels is provided.

TABLE OF CONTENTS

LIST OF FIGURES

Number Page

LIST OF TABLES

Number **Page**

CHAPTER 1. INTRODUCTION

Destructive floods that involve the downstream movement of woody debris occur in low-order mountain channels of the Pacific Northwest. These phenomena are associated with periods of heavy precipitation during which mass wasting occurs in combination with high streamflow rate. Mass wasting refers generally to any rapid or slow downslope movement of large masses of earthen material. This includes phenomena such as debris avalanches, landslides, and debris flows. When mass wasting occurs in a steep, confined valley of the region, the displaced hillslope material may deposit in the stream channel at the valley bottom. This rapid accumulation of hillslope material may impound streamflow temporarily. Upon release of the impounded streamflow, a flood wave begins to propagate downstream. This process is called a dam-break flood.

Costa (1985) documented that a flood wave generated from a dam break in high-order, low-gradient rivers attenuates as it propagates downstream. In low-order, high-gradient mountain channels, however, the flood wave entrains large amounts of woody debris encountered in and near the channel, thereby greatly altering the behavior of the flood wave. It can be inferred from field evidence after passage of such a flood wave that at times this entrained mass of woody debris becomes large, acting as a moving dam that destroys riparian vegetation by uprooting and shearing off standing timber. After the passage of such a dam, stream valleys may be devoid of virtually all riparian vegetation along some reaches.

1.1 Objectives

Our goal is to provide a basic understanding of dam-break floods in low-order mountain channels. We focus on the phenomena that occur within the stream channel, beginning with the dam break. We explore the conditions necessary for initiation, propagation, and deposition of dam-break floods. Because of the destructive nature of these floods, we aim to provide enough information so that forest managers will know which, if any, stream within their jurisdiction is a likely candidate for floods, and how far downstream from the initial dam break the destruction will extend.

1.2 Definitions

There remain inconsistencies in the literature with respect to use of the terms "debris flow" and "debris torrent." The term "dam-break flood" is not used widely. The terms debris flow and debris torrent often are used interchangeably to describe any channelized flood in which significant amounts of sediment and organic debris are involved, regardless of the type of mass wasting, rheology of the medium, or composition of sediment deposits associated with the floods.

The term debris flow has been defined by some authors specifically with respect to rheology and will be used herein. We define dam-break flood and debris flow as:

Dam-Break Flood: The downstream surge of water caused by the breaching of a non-engineered impoundment within a stream channel. The impoundment is a combination of sediment and organic debris.

Debris Flow: "A highly mobile slurry of soil, rock, vegetation, and water that can travel kilometers from its point of initiation, usually in steep (> 5 degree slope) confined mountain channels. Debris flows form by liquefaction of landslide material concurrently or immediately after the initial failure. Debris flows contain 70 - 80% solids and 20 - 30% water by weight. Entrainment of additional material as the debris flow moves through first- and second-order channels (Type 4 and 5 waters - Washington State Department of Natural Resources classification) can increase the volume of the original landslide by a factor of ten or more, enabling debris flows to become more destructive with travel distance" (Benda and Cundy, 1990).

1.3 Regional Climate

The climate of the Pacific Northwest is classified as "marine west-coast." This mid-latitude west coast area is subject to frequent extra-tropical cyclonic weather systems that originate over the Pacific Ocean, and travel to the mainland with the prevailing westerly winds (Strahler & Strahler, 1983). Precipitation is distinctly higher in the winter. Figure 1.1 shows a climograph for the coastal city of Vancouver, B.C., illustrating the annual variation in precipitation and temperature. Nearly 92% of the annual precipitation occurs during fall, winter and spring, with nearly half the precipitation falling during November, December, and January. Consequently,

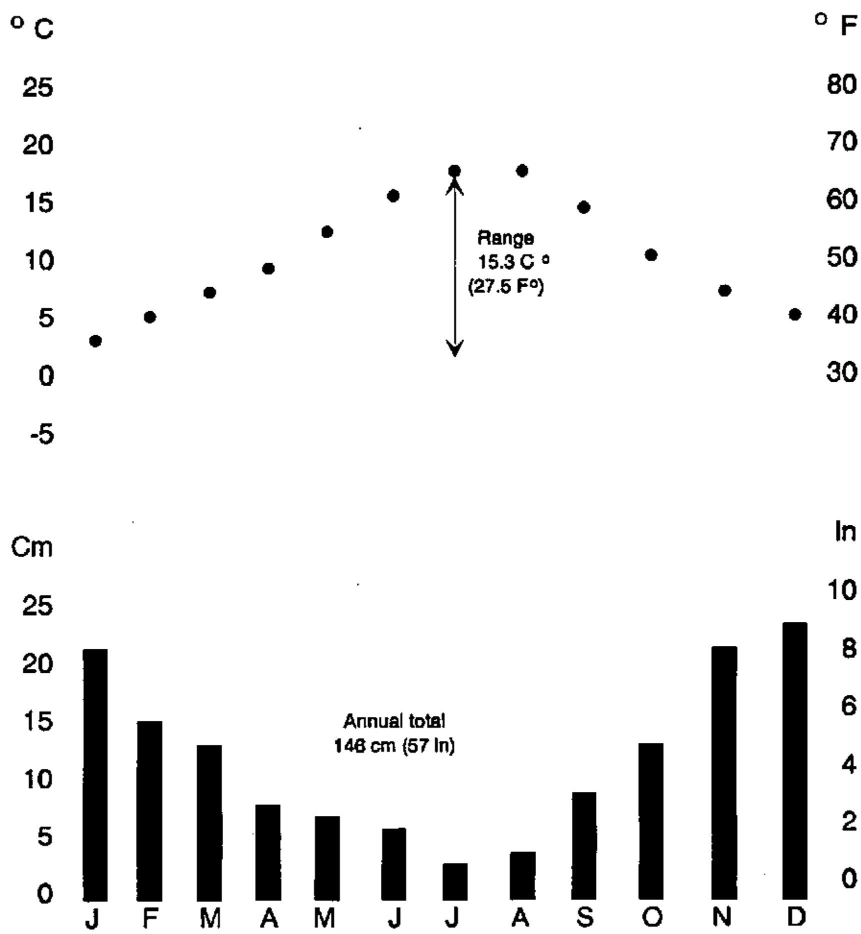


Fig. 1.1 Climograph of Vancouver, British Columbia, (from Strahler and Strahler, 1983).

precipitation throughout the remaining 3 summer months is sparse, with dry periods extending several weeks not uncommon in late summer. The annual average temperature range is 15.3°C (27.5°F). Both precipitation and temperature ranges are much greater in the immediate vicinity of the mountain ranges within this region because of orographic effects.

1.4 Slope Stability

The mountains within this climatic region are subject to erosion in the form of soil mass wasting because of the combination of the humid climate, steep topography, and shallow soils. Orographic influence causes annual precipitation in excess of 400 cm (150 in) in the low elevation rain forests of the Olympic Peninsula and North Cascades, and more commonly at the higher elevations within both mountain ranges. Precipitation during the summer months within these mountainous areas can be sparse creating drought-like conditions that last for several weeks to months.

The steep mountain ranges within the Pacific Northwest include the Cascade Range, the Olympic Mountains, and the Coast Range of British Columbia. These ranges consist of both glacial carved and stream-cut valleys, in the lowlands, and active glaciers and cirques in the highlands. Steep slopes, commonly above 90% (40°) are characteristic of the lower forested slopes in the ranges.

The forested slopes of these mountains generally are underlain by less than 1 meter of soil. This soil is overlaid by a highly organic and thus very porous with sufficiently large infiltration capacity such that Horton, i.e. infiltration-rate limited, overland flow does not occur in undisturbed forested areas. During periods of heavy rainfall, moisture commonly reaches the soil-bedrock interface approximately 1 meter below the surface.

In addition to the susceptibility of these slopes to mass wasting due to the combination of steep slopes, shallow soils, and a humid environment, timber harvesting practices in the form of clear-cutting and burning increase the potential for mass wasting. After trees are harvested, the remaining stumps decay causing the root strength, which is important for slope stability, to diminish (Croft and Adams, 1950). Slash burning, a common post-harvesting practice which removes potential forest floor fire fuel, accelerates the process of roof decay. Soils in the Pacific Northwest are nearly cohesionless and the soils on the steeper slopes may become unstable after roots decay. Bishop and Stevens (1964) found a fourfold to fivefold increase in the number of shallow landslides within 10 years after clear-cutting in southeast Alaska. O'Loughlin and Pearce (1976) studied a 5.5 km^2 area in New Zealand which had soil properties, vegetation, and topography similar to those of the Pacific Northwest. One-hundred-and-twenty-seven landslides occurred within a decade of clear-cut harvesting and burning, moving over 75,000 m^3 of material downslope. Landslides generally were initiated in shallow depressions on slopes of 25° or more. Additional studies on the importance of root strength with respect to stability of shallow soils on steep slopes, under intact coniferous forest and after forest harvesting in Western North America, have been undertaken by Swanston (1970, 1974a), O'Loughlin (1974b), Ziemer and Swanson (1977), Burroughs and Thomas (1977), Wu, et al. (1979), Wu and Swanston (1980), Ziemer (1981), and Gray and Megahan (1981).

The steep topography of the mountains of the Pacific Northwest generally allows the material displaced by mass wasting to enter "low-order" stream channels. Stream order is determined using the Strahler scheme (Figure 1.2) in which first-order streams are the first visible stream beds at higher elevations near divides, with the order increasing downstream of a confluence with a same-order tributary. The sudden introduction of hillslope material, including vegetation, sediment, and regolith, from mass wasting into a stream channel can create an obstruction large enough to form a dam and impede streamflow temporarily. Within minutes to a few hours, this dam may breach, sending a flood wave downstream.

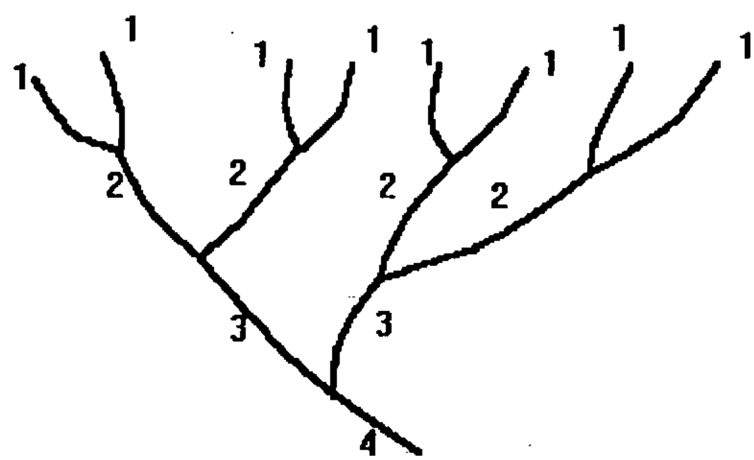


Fig. 1.2 Plan view of channel system showing Strahler's stream ordering scheme; flow is from low to high order.

1.5 Organic Debris in Streams

Large organic debris in streams influences the channel form, sediment movement, retention of organic matter, and the biological community (Bilby and Ward, 1989). Debris may be instrumental in the formation of gravel bars (Lisle, 1986), pools (Lisle and

Kelsey, 1982), waterfalls, and water-flow energy-reducing mechanisms (Heede, 1972). Large stable logs may provide sediment storage capacities many times greater than the annual stream transport volumes (Marston, 1982). The presence of large organic debris creates dams and "log steps" which increase retention of finer organic materials (Bilby, 1980; Gillilan, 1989). This fine organic material is the food source for many organisms, which, in turn, are the food source of salmonids (Veldhuisen, 1990).

1.6 Dam-Break Flood Process

Dam-break floods are common in confined mountain channels of the Pacific Northwest (Benda and Zhang, 1989). Dams may be composed of material deposited from landslides or debris flows, or they may be composed almost entirely of organic debris. For mass wasting generated dam-break floods, a landslide or debris-flow deposit dams a low-order channel, and the dam breaches send a surge of water, sediment, and organic debris downstream. For a moving organic debris dam, the initial dam is composed mostly of organic material and is not the result of mass wasting. Formation of this initial dam is likely to be caused by floatation and mobilization of organic debris resting in the stream channel. Downstream movement is likely to be similar to that of the mass wasting-induced impoundment. In low-order mountain channels of the Pacific Northwest, the moving mass may entrain additional organic material within its path during downstream travel. Entrainment involves the formation of a moving mass of organic debris which impounds some of the streamflow behind it. In both cases, accumulation of woody debris may continue until the flood exits a confining valley or the channel gradient decreases causing the debris to deposit and the previously impounded water to move downstream.

Analysis of observations of post-phenomenon flood heights suggest that after the initial dam breach, the sediment and organic debris form new dams which breach as the materials propagate downstream. The post-phenomenon flood heights observed over long distances of the stream valley are too high to have been associated with a single dam breach. To illustrate this point, rough estimates of discharge using the Manning equation and field-measured flood heights are calculated in Table 1.1 for four channels. The resulting discharge for Huckleberry Creek ranges from 155 to 217 m^3/s. The resulting discharge for Ware Creek ranges from 23 to 32 m^3/s. For these two cases, estimates of stream flow using simple catchment equilibrium discharge flow rate calculations yield for the same locations, 1.3 m^3/s and 0.2 m^3/s, respectively, discrepancies of two orders of magnitude. The calculated discharge values are unreasonably large because the cross sectional data used with the Manning equation represent extraordinarily high flood heights created because of the impoundment of organic debris. Once mobilized, this moving impoundment is highly erosive and capable of uprooting and shearing riparian vegetation within its path. This aspect of dam-break floods makes them one of the most damaging processes in mountain drainage basins in the Pacific Northwest.

1.7 Methods

Information about locations of sites where dam-break floods may have occurred was provided by various U.S. Forest Service, University of Washington, and Indian tribal personnel who had detailed knowledge of these phenomena. Each of the twenty sites shown in Figure 1.3 and Table 1.2 (Section, Township, Range notation) was visited during the summer of 1991 or 1992. All sites with the exception of Twin Creek were in managed watersheds. Each stream was investigated at the initiation and deposition areas. Investigation included measurement of elevation using an altimeter, channel gradient using a clinometer, and cross-sectional area of the valley covered by the flood using a tape measure and clinometer. Qualitative information about vegetation, organic material, erosion, and mass wasting also were recorded.

Table 1.1 Estimates of discharge using Manning's equation, field measured flood heights, and flow cross-sectional geometry.

Stream	Elevation (m)*	Flow Contributing Area (m^2)*	Channel Cross-Sectional Area (m^2)*	Wet Perimeter (m)	Slope	n	Q (m^3/s)
Carter	1125	72846	21	12.6	0.29	0.07	226
Huckleberry	357	1,900,000	31	18.4	0.06	0.07	155
Twin	627	283,000	32	14.1	0.21	0.07	364
Ware	734	259,000	4	4.4	0.25	0.07	23

* at initiation

Table 1.2 Summary field information collected at the twenty study sites.

Site No.	Creek Name	Initiation Location	Year	Dam Type [d]	Dam Ht (m)	Water Type[a]	Stream Order[b]	Stream Order	Slope (deg)	Slope (deg)	Valley Width (m)	Valley Width (m)	Travel Length (m)[c]
					init.		init.	dep.	init.	dep.	init.	dep.	
1	Bear1	S25T30NR8E	1990	DF	9	3	1	3	20	2	14	36	1500
2	Bear2	S25T30NR8E	1990	Canyon	6	3	2	3	10	2	3	36	1600
3	Carter	S20T22NR10E	1991	Organic	4	3,4,5	1	3	24	N/D	8	>100m	3300
4	DeForest	S36T34NR7E	1990	DF	2.4	4	2	3	8	N/D	11	N/D	1800
5	Huckleberry	S29T15NR3E	1990	DF	2.2	3,4	3	4	4	2	14	32	3600
6	Ware	S12T14NR3E	1990	Organic	1.8	5	2	3	20	3	8	25	1900
7	Iron Maiden	S5T26NR10W	1990	DF	N/D	1,4,5	2	3	N/D	2	N/D	>100m	1500
8	Virginia	S4T26NR10W	1990	LS	N/D	4,5	3	3	N/D	3	N/D	30	2400
9	Split	S3T26NR10W	1989	LS	N/D	4,5	2	3	N/D	3	N/D	50	1500
10	H1070	S3T26NR10W	1990	LS	N/D	4	2	2	N/D	4	N/D	30	1800
11	Maple	S13T26NR11W	1990	LS	6	3,5	2	4	13	2	15	35	3600
12	Twin	S17T27NR10W	1990	LS	2	3,4,5	2	4	12	2	8	>100m	2200
13	Rainey1	S31T13NR6E	1990	LS	3.5	3,4	3	3	12	3	8	>100m	2500
14	Rainey2	S31T13NR6E	1990	DF	2	3,4	3	3	8	3	8	>100m	3100
15	Olsen	S19T38NR4E	1983	Canyon	9	2,3,4	4	4	3	N/D	3	N/D	4000
16	Benson	S15T30NR8E	N/D	DF	4	3	4	4	3	2	10	N/D	2500
17	Finney1	S29T34NR8E	N/D	Canyon	4	3	5	6	2	N/D	3	N/D	N/D
18	Finney2	S6T34NR9E	N/D	DF	3	3	5	6	2	N/D	15	N/D	N/D
19	Sauk	S29T30NR11E	1986	LS	7	3	5	6	4	N/D	40	N/D	7000
20	Gywnn	S6T15SR12W	1981	LS	7	N/D	2	3	10	3	11	N/D	2000

[a] Washington Department of Natural Resources classification
[b] Strahler System
[c] Distance from initiation (init) to deposition site (dep)
[d] DF - Debris Flow
Canyon - Canyon Constriction
Organic - Logjam
LS - Landslide
N/D - Not Determinable

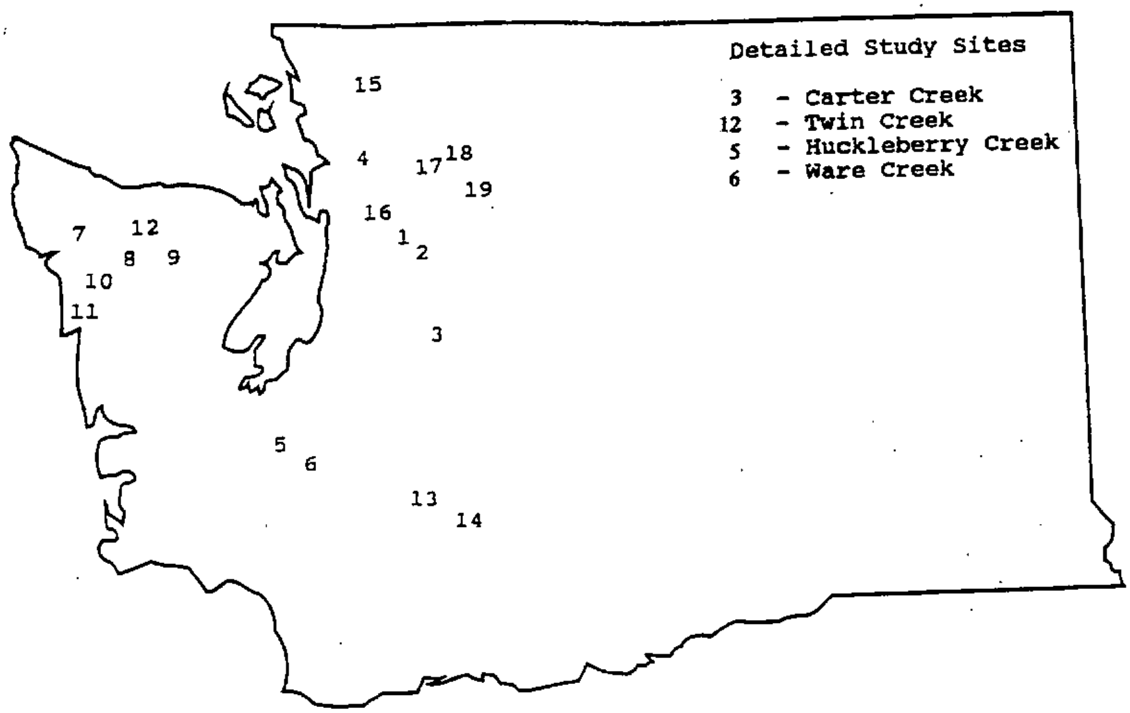


Fig. 1.3 Locations of investigated dam-break floods within the State of Washington.

More detailed investigations were conducted at four sites: Carter, Huckleberry, Twin, and Ware Creeks, shown respectively as 3, 12, 13, and 14 in Figure 1.3. Carter Creek and Ware Creek were chosen for detailed investigation because both experienced dam-break floods that were initiated by breaching of organic dams within the stream channels; mass wasting was not involved. Huckleberry Creek was chosen because of the large size of the organic dam that resulted from a small dam-break upstream. Twin Creek was chosen because it was the only site found where there has been no timber harvesting. At all sites, particular attention was given to the presence or absence of woody debris in the stream valley, deposition locations of woody debris and sediments, identification of vegetation, and indicators of scour locations at the stream valley sides. At approximately 100 meters intervals, channel geometry was recorded for the purpose of constructing a stream profile relating flood heights with distance traveled. Information gathered from these four sites was used to estimate the sequence of events from the initial dam break location as the debris moved downstream to the ultimate deposition location of the organic debris.

CHAPTER 2. LITERATURE REVIEW

2.1 Dam-Break Floods

The analysis of dam-break floods in mountain drainage basins is an ongoing research topic in the Department of Geological Sciences at the University of Washington. Benda, Zhang, and Dunne (research in progress) employ the National Weather Service dam-break model (Fread, 1982) and a one-dimensional flow routing model in their analysis. The dam-break model, using physical characteristics of dams in the Pacific Northwest, indicates that dams formed by natural landslide and debris flows may fill with water during storms in 3 to 5 minutes and that a full breach and drainage can be accomplished in 2 to 5 minutes. The routing model predicts a rapid attenuation of the initially extreme flood wave.

Though the routing model predicts flood heights satisfactorily in large (fifth- and sixth-order) rivers, it fails to predict flood height accurately in low- to medium-order steep (second- to fourth-order) channels. This discrepancy may result from the model's use of the Manning equation to represent fluid energy dissipation. The Manning equation reaches its limits of applicability as slopes increase up to about 4° (Chow, 1958). Estimates of the Manning roughness coefficients have been made by Jarret (1984) and Bathurst (1986) for slopes up to approximately 4°. We are unaware of appropriate roughness coefficients for steeper channels and lack of suitable coefficients may explain in part the inability of the model to describe flood movement adequately in steep second to fourth-order channels. A more probable reason for inaccurate flood height prediction is that dam-break floods in these low-order channels entrain large quantities of organic material. This entrainment impounds some of the flood wave and streamflow behind it, causing a higher stage that is sustained longer than the rising stage of an unimpeded flood wave.

Benda and Zhang (1989) identified dam-break floods in narrow mountain valleys as an important geomorphic process in Washington and Oregon and distinct from debris flows. They identified debris flows and landslides as the primary mode of initiation of dam-break floods. Floods from dam breaks travel entire lengths of stream segments and trigger significant secondary erosion processes, such as streamside landslides (Benda and Zhang, 1989).

2.2 Debris Torrent

The majority of the literature describing the dam-break flood process has referred to the phenomena as debris torrents. A sample of the literature on debris torrents is presented below.

Early investigators inventoried debris torrents to examine their rate of occurrence in both managed and unmanaged forests. Swanston and Swanson (1976) estimated that debris torrents originating in managed forests in the Oregon Cascade Range from logging roads and clearcuts occurred at rates 41 and 4.5 times greater, respectively than the rates in unmanaged forests. Morrisson (1975), also working in Oregon, found rates of debris torrents associated with logging roads and clearcuts and 13 and 8.8 times greater, respectively, than those rates associated with unmanaged forests. Syverson (1984) estimated that the majority of debris torrents that occurred in Smith Creek basin in Northwest Washington originated from second-growth forests and clearcuts. No literature was found that addressed the characteristics of initiation, propagation, and deposition of these phenomena.

2.3 Ice Dam Floods

The literature on ice dam floods suggests an analogy between ice dam floods, and dam-break floods. Ice drives, often called ice flows, ice runs, or ice dam floods, are a phenomenon similar to the low-order dam-break flood process. Ice drives occur on high latitude Northern Hemisphere rivers in which the water surface has frozen solid during winter. Heavy spring precipitation, rain-on-snow induced snowmelt, or rapid snowmelt caused by chinook winds can increase significantly the discharge of these rivers causing the ice sheet on top to break quickly. This broken ice then forms a moving dam which scours and widens the channel as the ice is transported downstream. Figure 2.1, from Smith (1980), shows a schematic representation of the stages of ice break-up and drive. The stage-time diagram shows a slight increase in discharge during the first few hours before ice break-up. The river stage (water plus ice melt) rises quickly upon break-up because of the damming effect of the ice. As this dam moves downstream, the stage decreases slowly, showing the effect of release of the ponded water from storage. This

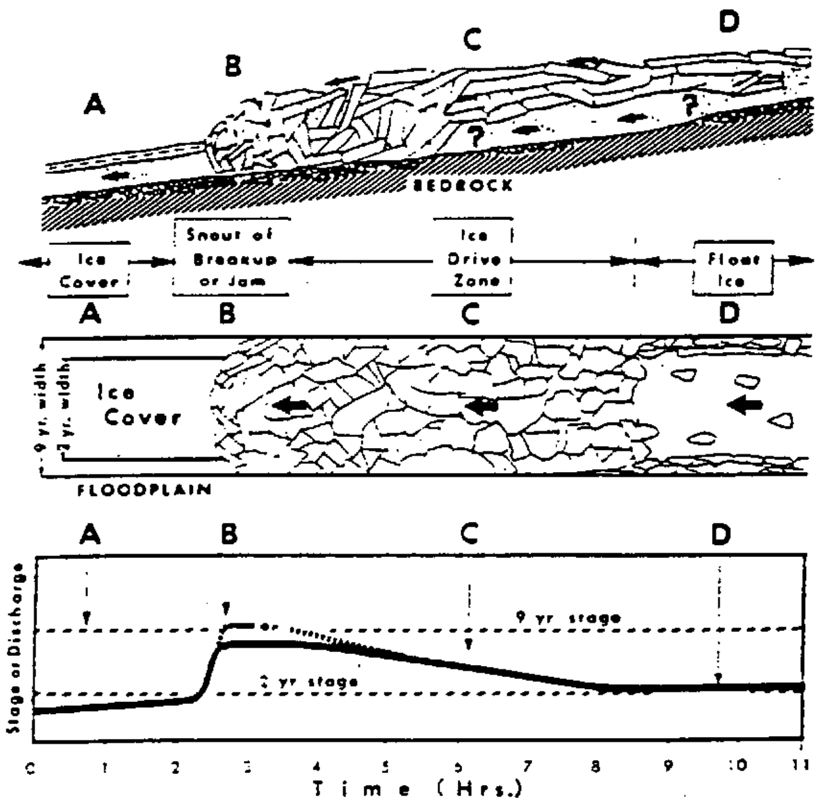


Fig. 2.1 Stages of ice break-up and drive over distance and time (reproduced from Smith, 1980).

progression has characteristics similar to the progression of an organic material laden dam-break flood wave within low-order channels of the Pacific Northwest. The utility of this analogy is that, unlike for ices drives, no direct observations of the movement of organic debris floods have been reported.

CHAPTER 3. CHARACTERISTICS OF TWENTY DAM-BREAK FLOODS IN WASHINGTON STATE

3.1 Initiation of Dam-Break Floods

3.1.1 Characteristics of Initiation Mechanisms

From the nineteen sites investigated in Western Washington and one in Oregon (Table 1.2), we identified four apparent initiation mechanisms: landslide, debris-flow, canyon constriction, and organic dam. The number of occurrences of each initiation mechanism is shown in Figure 3.1. Landslides, debris-flows, and organic dams were discussed in the first two chapters. Debris dams in canyons (canyon constrictions) occurred when sediment and organic debris accumulated upstream of narrow bedrock canyons.

Of the twenty sites examined, it appears that in two cases, Carter amd Ware Creeks, organic (woody debris) dams failed and caused floods. Both of these dams were located in narrow stream valleys within recently clearcut basins in which the channel contained large quantities of logging slash and debris. The initiation point was recognizable because of the marked absence of woody debris in the channel from the initiation point downstream. In both cases, immediately upstream of the initiation point, and continuing as far up the channel as the channel is recognizable, the large quantity of organic material completely obscured the underlying stream from view. Without more data, we can only hypothesize that a sufficiently large water flow rate caused the mobilization of organic debris within the channel. No streamflow data are available for Carter Creek. Stream gauges were in place on Ware and Hard Creeks prior to the dam-break flood on Ware Creek. The Ware Creek gauge was destroyed during the flood but the Hard Creek gauge remained functional. A regression relationship for Ware Creek flow rate against Hard Creek flow rate was used to estimate the hydrograph at Ware Creek that would have occurred in the absence of a dam-break flood. We have not been able to determine the time at which debris movement occurred but have included the estimated hydrograph (Figure 4.15) so that should information become available as to the initiation time, an estimate can be made of the flow rate needed to initiate debris movement.

For both Carter and Ware Creeks, the organic debris dams either breached, sending small floods of water and woody debris downstream, or began to migrate. In either case, enlargement of the dam by entrainment of additional organic material and water from upstream led to the large magnitude of the floods. Inspection of these two initiation sites revealed a high concentration of small-diameter logging slash in the channels immediately upstream of the initiation sites. Figure 3.2 shows the size distribution of organic material found immediately above the initiation site at Carter Creek.

According to the present, limited, inventory of dam-break floods, landslide and debris-flow deposits were the primary method of initiation in managed forests. These two mechanisms accounted for 75% of the failures.

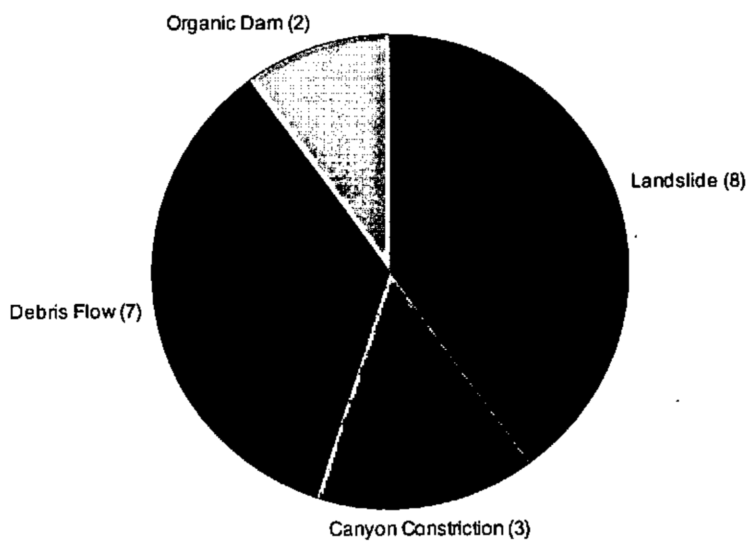


Fig. 3.1 Number of dam-break sites and corresponding initiation modes.

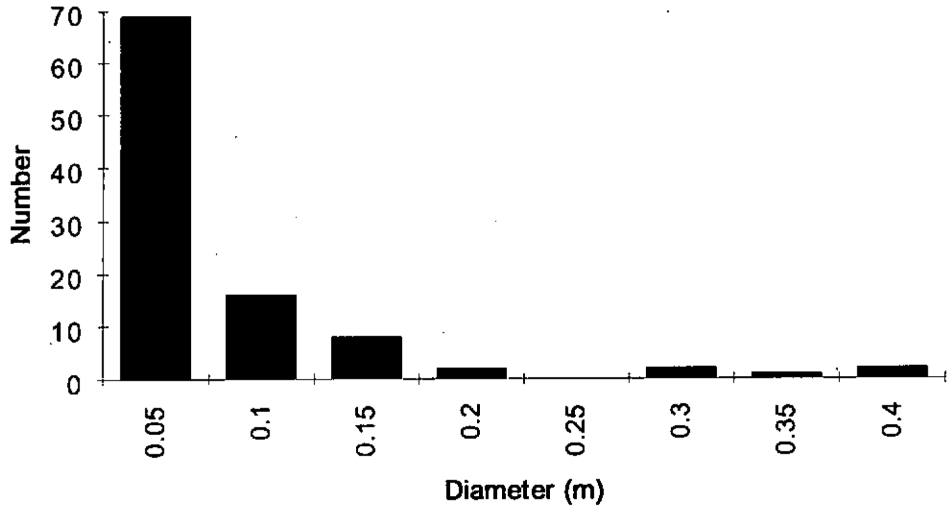


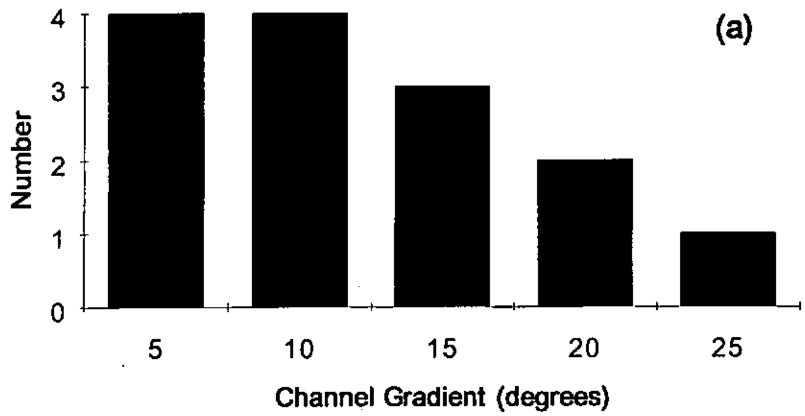
Fig. 3.2 Relative frequency of diameters of debris in Carter Creek immediately upstream of the initiation site, (n=100), class interval 0.05 m.

3.1.2 Valley Geometry at Initiation Sites

The distributions of channel gradients and valley widths at initiation sites in which both of these data were collected are plotted in Figure 3.3. Based on observations at twenty sites, a locally low gradient and narrow valley are conducive to dam formation. The low-gradient data are in agreement with Benda and Cundy (1990), who found that relatively low channel gradients less than 20° are necessary for deposition of landslides and debris flows, and thus dam formation; higher channel gradients may cause the flow to continue to travel down the valley, thereby precluding dam formation.

3.1.3 Stream Order of Dam-Break Flood Initiation Sites

The frequency distribution of order of streams at the initiation sites of dam-break floods is presented in Figure 3.4. The distribution of order at initiation appears to



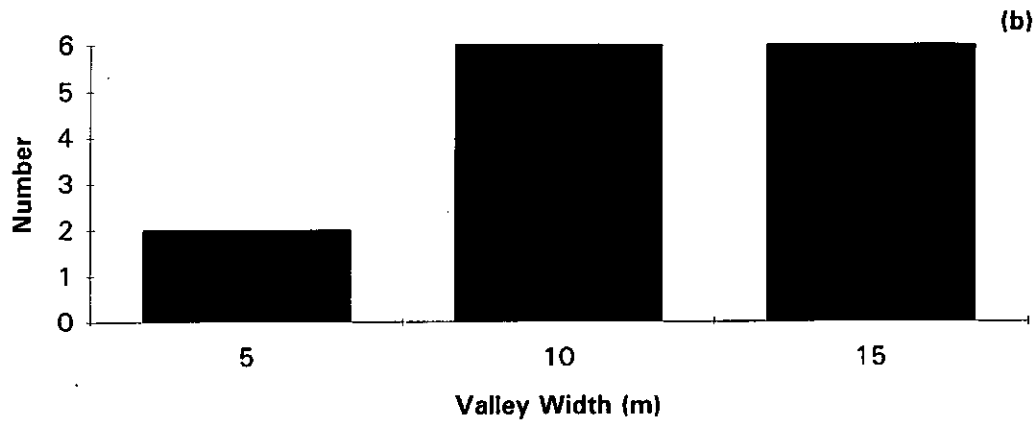


Fig. 3.3 Number of dam-break initiation sites having corresponding (a) channel slopes, and (b) valley widths. (n = 14, channel gradient class interval 5°, valley width class interval 5 m.)

be positively skewed. Values range from first- to fifth-order, with a mode of second order. This supports the earlier findings with respect to channel gradient and width. The narrower, steeper channels, typical of low-order streams, are the most common sites for dam formation.

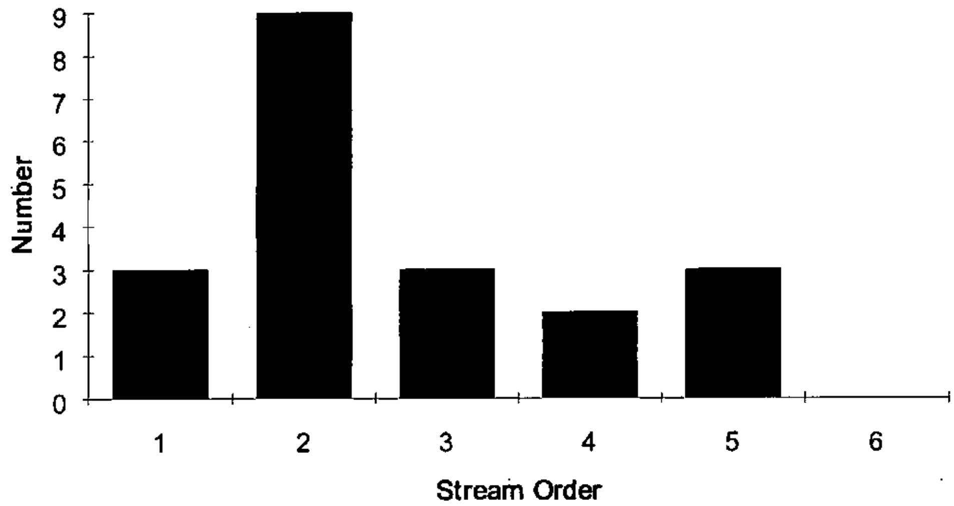


Fig. 3.4 Number of streams of order m where dam-break initiation occurred (n = 20).

We chose to delineate streams by Horton stream order. This classification is used widely by forest managers to categorize streams within their watershed. However, the variability in valley geometry of streams within a given order make stream order classification non-definitive. Therefore, we also analyzed the data more specifically, in terms of channel gradient and valley width (Chapters 3.1.2 and 3.2.1).

3.2 Dam-Break Flood Deposition Locations

3.2.1 Valley Geometry at Deposition Locations

The distributions of channel gradients and valley widths at the 8 deposition sites in which both these characteristics were identifiable from debris remnants are plotted in Figure 3.5. The channel gradient at deposition sites is approximately 2° to 3°. Valley width at deposition ranged from 30 to 50 m. For the 14 sites where the channel gradient (but not the valley width) at the debris dam deposition location could be identified clearly, seven occurred where the local channel slope was 3° or less. Six deposition sites had a local channel slope between 2° to 3°. At the bulk of these sites the channels had stream orders of three and four and the valley widths were largely between 30 and

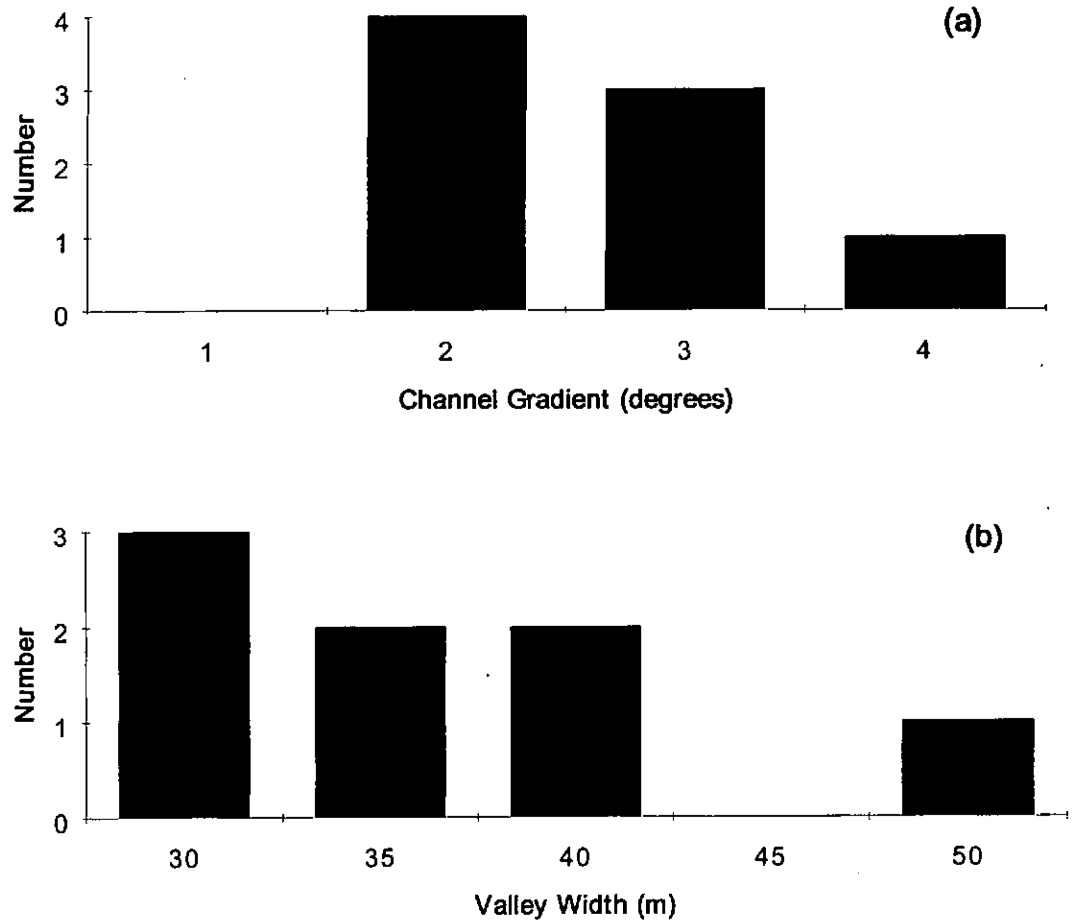


Fig. 3.5 Number of dam-break deposition sites with respect to (a) channel slopes (class interval 1°), and (b) valley widths (class interval 5 m), (n = 8).

40 m. The corresponding upstream initiation widths were typically on the order of 10 to 15 m.

3.2.2 Stream Order at Dam-Break Flood Deposition Sites

The order of the channels at the locations of deposition of sediment and organic debris from the dam-break floods follow a right skewed distribution that is shifted slightly to the right of the corresponding distribution for initiation sites, with a mode of third order (Figure 3.6). Of the twenty sites examined, the debris from only one flood was deposited in a second-order channel. Three floods deposited debris in sixth-order channels. The positive shift of this distribution with respect to the distribution of stream order at initiation can be explained by wider and lower gradient channels characteristic of higher order streams. The channel geometry in these higher-order streams does not support dam formation or sustenance of moving debris.

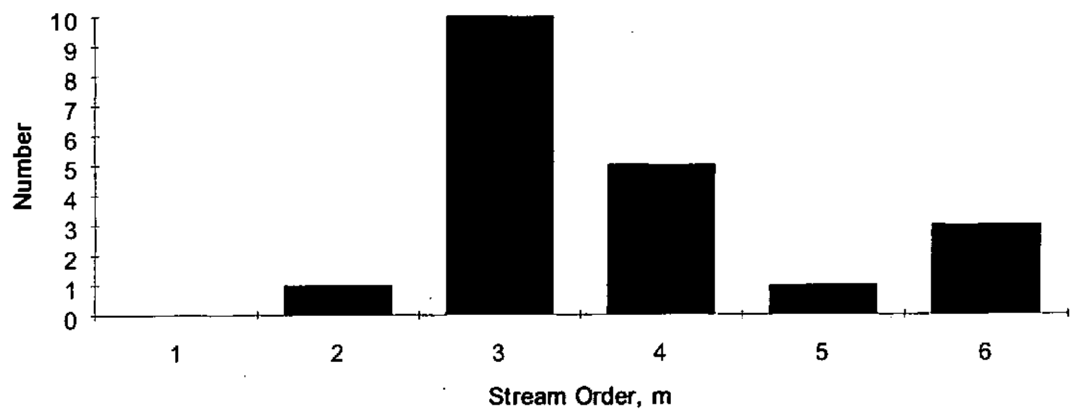


Fig. 3.6 Number of streams of order m where dam-break deposition occurred (n=20).

3.3 Debris Transport Distance from Dam-Break Floods

The number of dam-break floods and their corresponding travel distances over which they transported organic debris are shown in Figure 3.7. Most of these floods traveled between 2 and 4 km. The controlling factor in travel distance is most likely the valley geometry. It seems that the movement of the organic debris dams progress until the gradient decreases to 2° to 3°, and the valley widens to at least 30 meters and is unable to contain the previously impounded water as the debris moves into the wider channel.

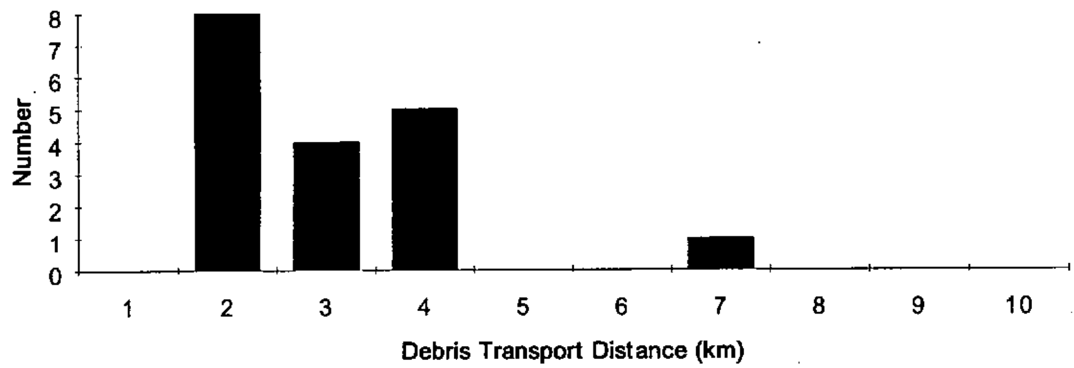


Fig. 3.7 Number of dam-break floods versus debris transport distance (class interval 1 km, n = 18).

3.4 <u>Classification of Streams in Which Dam-Break Floods Occurred</u>

3.4.1 <u>Channel Classification by Strahler Stream Order</u>

Each of the twenty streams examined was delineated by stream order using field observations and U.S.G.S. topographic maps. Information for each site is given in Tables 1.2 and 3.1. Table 3.1 shows that dam-break floods that begin in low-order channels may travel eventually through long distances of higher-order (low-gradient) valley floors, influencing riparian vegetation and aquatic habitat during and after passage. In ten instances, deposition occurred in a channel one order higher than the order of the channel in which initiation occurred. In four instances, deposition occurred in a channel two orders larger than the order of channel at initiation. In six cases, the initiation and deposition occurred within the same order channel.

The lengths and orders of channels affected by dam-break floods are summarized in Table 3.1. For each site, the total debris transport distance and the relative fraction of that distance associated with stream orders between the initiation and termination points are shown. For example, on Carter Creek (site number 3 in Figure 1.3) the travel distance was 3300 m; 15% of this distance corresponded to the first-order

Table 3.1 Stream name, debris travel distance, and percent of debris travel distance associated with each stream order.

Site No.	Creek Name	Debris Transport Distance(m)	Stream Order 1	Stream Order 2	Stream Order 3	Stream Order 4	Stream Order 5	Stream Order 6
1	Bear1	1500	20	25	55			
2	Bear2	1600		35	65			
3	Carter	3300	15	50	35			
4	DeForest	1800		20	80			
5	Huckleberry	3600			20	80		
6	Ware	1900		40	60			
7	Iron Maiden	1500		5	95			
8	Virginia	2400			100			
9	Split	1500		75	25			
10	H1070	1800		100				
11	Maple	3600		10	35	55		
12	Twin	2200		40	30	30		
13	Rainey1	2500			100			
14	Rainey2	3100			100			
15	Olsen	4000				100		
16	Benson	2500				100		
17	Finney1	*						
18	Finney2	*						
19	Sauk	7000						
20	Gywnn	2000		10	90			

*Deposition location not known with certainty.

channel where the debris flood originated, 50% (or 1650 m) corresponded to the second-order channel fed by the first-order channel, and the remaining 35% occurred in the third-order channel which drains the second-order channel. This third-order channel provided, in the pre-debris flood state, habitat for resident fish species. This habitat was destroyed during the flood and remained diminished afterwards with no evidence of recovery after two years.

The dam-break floods are associated with first- to sixth-order channels. It is clear that significant impacts of dam-break floods on aquatic habitat and riparian zones occur in second and third-order channels (14 of 20 failures examined) with the majority of the impact in third-order channels. By contrast, data from Benda (1988) show that debris flows travel infrequently beyond third-order channels; most debris flows originate in zero-order basins and terminate at the confluences of first- and second-order channels with a higher order receiving channel.

3.4.2 Stream Classification by Washington Department of Natural Resources (DNR) Water Type

Each stream in which a dam-break flood occurred was delineated by water type using Washington State Department of Natural Resources (DNR) water type maps (Washington State Forest Practices Board, 1988). All lengths within each type were summed and the results plotted in Figure 3.8. The distribution has an approximate mean of Type 3. Both anadromous and resident fish habitat are associated with this DNR classification.

3.5 Deleterious Effects of Dam-Break Floods

3.5.1 Effects of Dam-Break Floods on Riparian Vegetation

Dam-break floods can be extremely damaging to riparian vegetation. Johnson (1991) documented swaths of destruction up to 60 meters wide and found them to be greatest in valleys of widths of at least 20 meters and channel gradient no greater than 4°. This destruction consists of uprooting of riparian vegetation in which the trunk diameters were up to 25 cm diameter, breast height (DBH).

Nineteen of the twenty dam-break floods inventoried were in managed forests. Old growth trees on the valley floors were not involved because these trees had been logged previously. The dam-break floods destroyed numerous alders, which are found commonly in the riparian zones of both managed and unmanaged forests. The alder

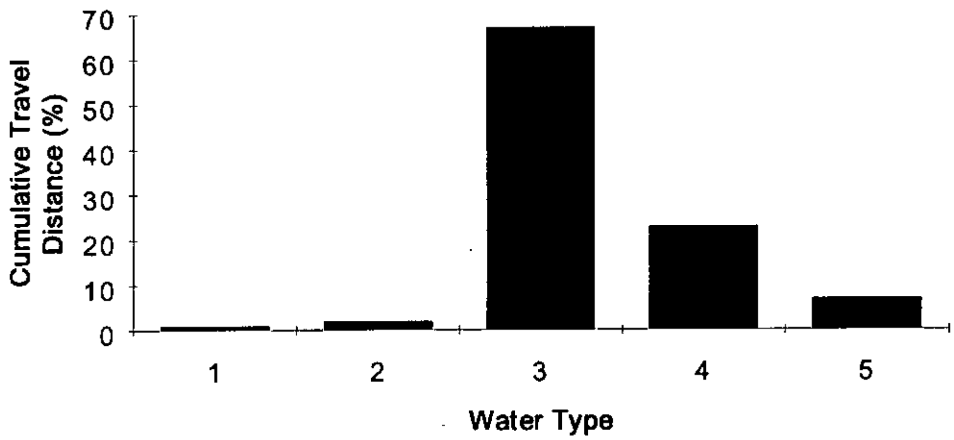


Fig. 3.8 Percentage of cumulative travel distance versus Washington Department of Natural Resources water type.

were uprooted and sheared off by the moving debris relatively easily compared to conifers of similar diameter.

Twin Creek is the only site surrounded by old growth timber from the headwaters to the organic debris deposition site (fourth-order channel), 2.2 km below the initiation site (second-order channel). The moving organic debris appeared to have been prevented from further migration down Twin Creek by large conifers growing adjacent to the channel. These conifers ranged from 30 to 100 cm DBH. In contrast, 30 cm DBH alders found at other sites were unable to withstand the forces of the organic dams and were either uprooted or sheared off.

3.5.2 Effects of Dam-Break Floods on Fisheries and Structures

Table 3.2 shows a summary list of the non-economic effects of the twenty dam-break floods on fisheries and structures. Eleven of the twenty streams provided habitat for anadromous fish species before the floods occurred. The habitat appeared to be diminished severely after the occurrence of the floods. Habitat for resident species was damaged similarly. The long-term effects of these floods on fish habitat are unknown.

Figure 3.9 shows the types and number of engineered structures that were damaged. Twelve forest roads were damaged by nine dam-break floods. In three cases

Table 3.2 Non-economic summary of resource effects of dam-break floods.

Site No.	Creek Name	Fish Habitat Affected	Infrastructure Damage
1	Bear1	resident, anadromous	State Highway 92
2	Bear2	resident	State Highway 92
3	Carter	resident	Railroad Grade, 2 service roads
4	DeForest	resident	1 forest road
5	Huckleberry	resident, anadromous	3 forest roads
6	Ware	resident	1 forest road
7	Iron Maiden	resident, anadromous	1 forest road
8	Virginia	resident, anadromous	1 forest road
9	Split	resident, anadromous	1 forest road
10	H1070	resident, anadromous	1 forest road
11	Maple	resident	2 forest roads
12	Twin	resident	none
13	Rainey1	resident	U.S. Highway 12
14	Rainey2	resident	U.S. Highway 12
15	Olsen	resident	private dwellings
16	Benson	anadromous	private dwellings
17	Finney1	resident, anadromous	none
18	Finney2	resident, anadromous	none
19	Sauk	resident, anadromous	forest roads
20	Gywnn	resident, anadromous	U.S. Highway 101, private dwelling

the floods destroyed more than one road crossing. Three state-maintained highways and one railroad grade were damaged by dam-break floods. At least five private dwellings, all of which were built on alluvial fans, were damaged by these types of floods. In the narrow valleys of the Cascade and Olympic Mountains, most main thoroughfares pass close to the mountain fronts making them susceptible to damaging effects of dam-break flooding.

3.6 Organization of Analyses of Dam-Break Floods

We discuss in the following chapters dynamic and static characteristics of the dam-break floods that occurred on four creeks: Carter, Huckleberry, Twin and Ware Creeks. Chapter 4 provides information about each site, including flood heights and

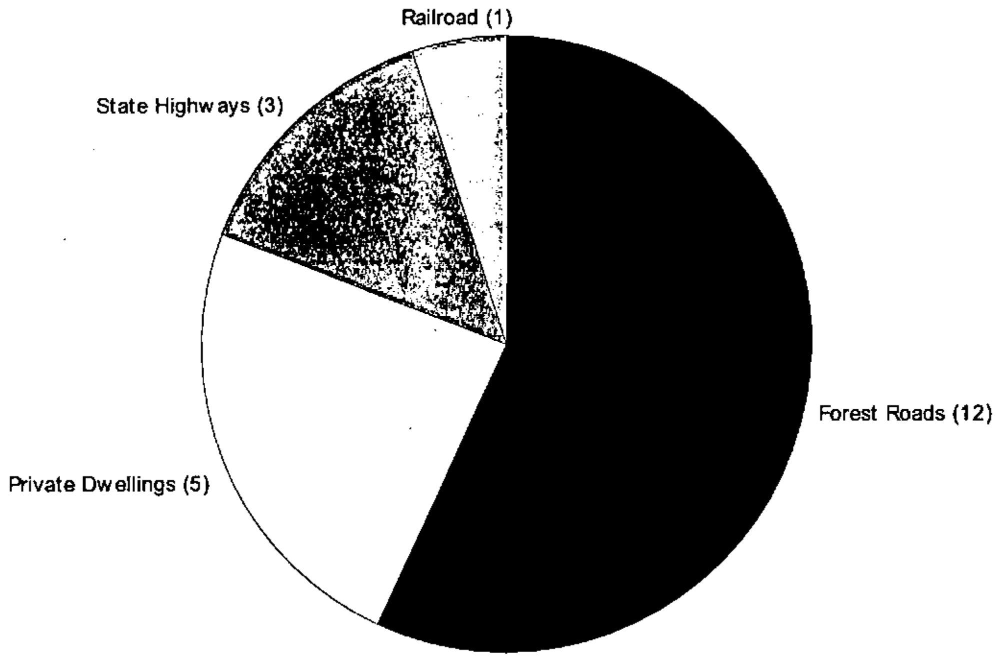


Fig. 3.9 Types and numbers of engineered structures damaged by dam-break floods (n = 20).

impoundment volumes determined from debris marks measured in the field, and precipitation associated with the floods. In chapter 5 we estimate the forces exerted by the moving organic dams and breaking strengths of conifers. Chapter 6 provides a simple method to aid in determining which streams are susceptible to these phenomena and how far downstream damage can be expected should a dam-break flood occur. Chapter 7 summarizes our findings.

CHAPTER 4. CHARACTERISTICS OF FOUR WESTERN WASHINGTON CATCHMENTS THAT EXPERIENCED DAM-BREAK FLOODS

Four creeks were examined in detail: Carter, Huckleberry, Twin, and Ware Creeks. Carter and Ware Creeks were chosen because organic dam-break floods were initiated solely by mobilization of organic debris already present in the channel; there is no evidence that mass wasting was involved. Huckleberry Creek was chosen because of the vast amount of debris deposited at the terminus which resulted from a small debris flow dam break upstream. Twin Creek was chosen because none of the timber within the catchment has been harvested. Graphs of measured flood heights and estimated volumes of impounded water at several downstream locations are included with catchment summaries below.

4.1 Carter Creek

Carter Creek experienced a flood of woody debris-laden water between November 21 and November 26, 1990, which caused the removal of two US Forest Service roads and a railroad embankment where they crossed the creek (Figure 4.1). The heavy rain that caused this flooding followed approximately 515 mm of rain in the preceding 3 week period. Two hyetographs from stations flanking Carter Creek are shown in Figure 4.2. (The precipitation station reference numbers are the same as used by Earth Info, suppliers of precipitation data on CD-ROM optical data disks.) The relationships between flood height and estimated volume of impounded water (and debris) at eleven downstream locations are shown in Figure 4.3.

4.1.1 Location and Catchment Landscape Features

Carter Creek is a second-order channel at its confluence with the South Fork Snoqualmie River, approximately 13 km east of North Bend, Washington, along Interstate 90. The creek flows slightly east of north and drains an area of 4 km^2 on the north side of Mount Gardner (1358 m). The total relief of the basin is 900 m.

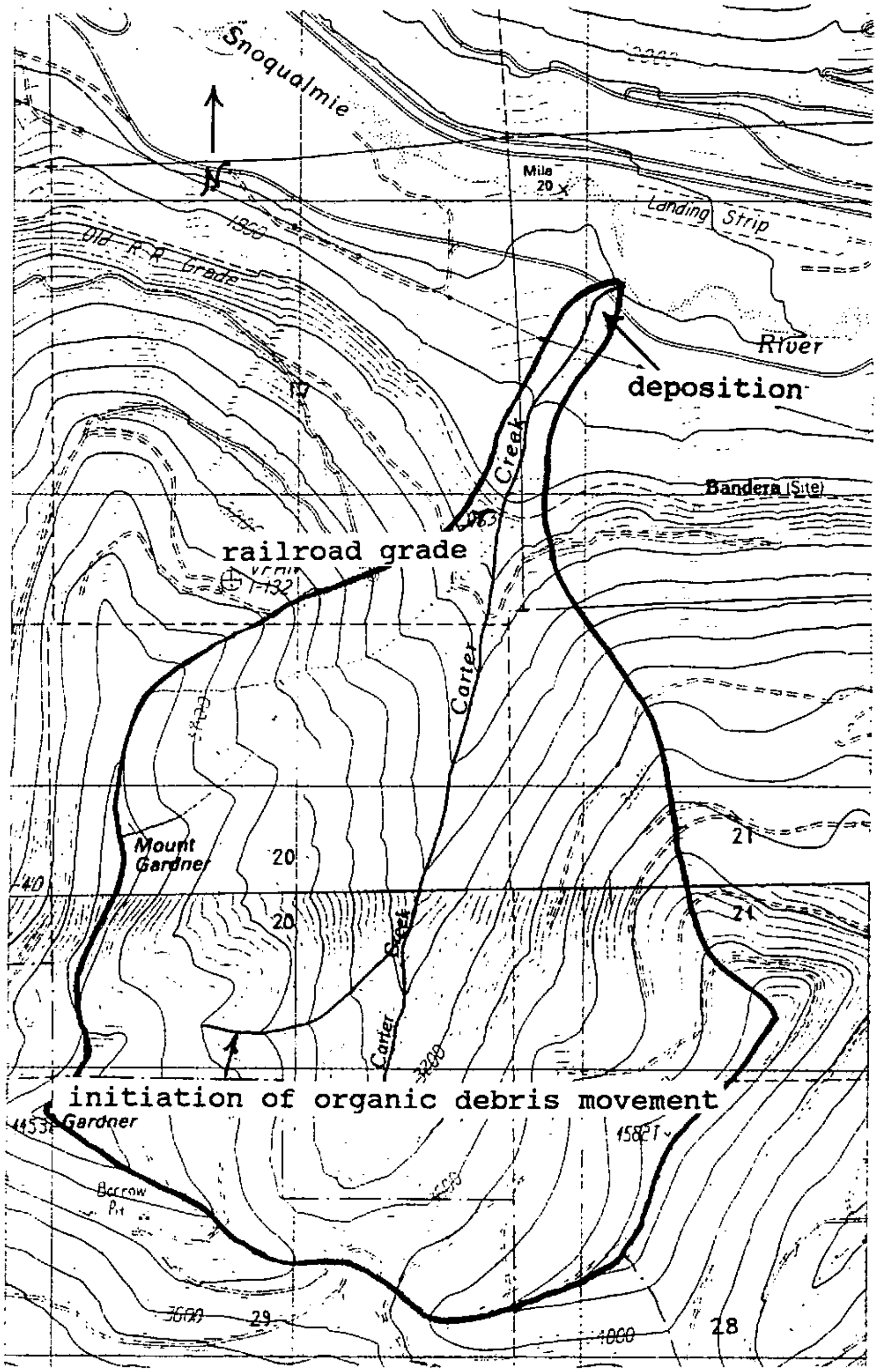


Fig. 4.1 Topographic map of Carter Creek basin (scale 1:24,000, contour interval 40 ft).

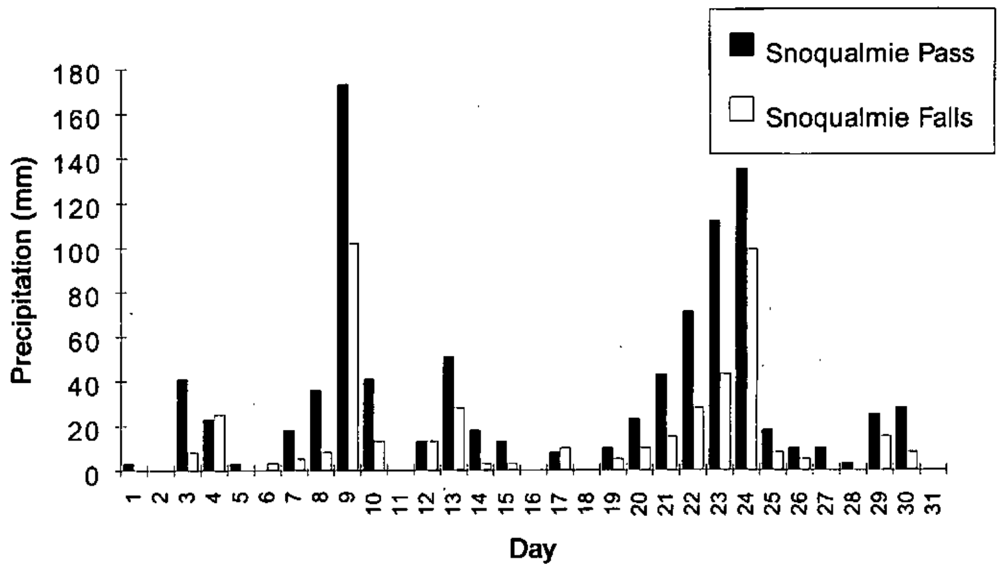
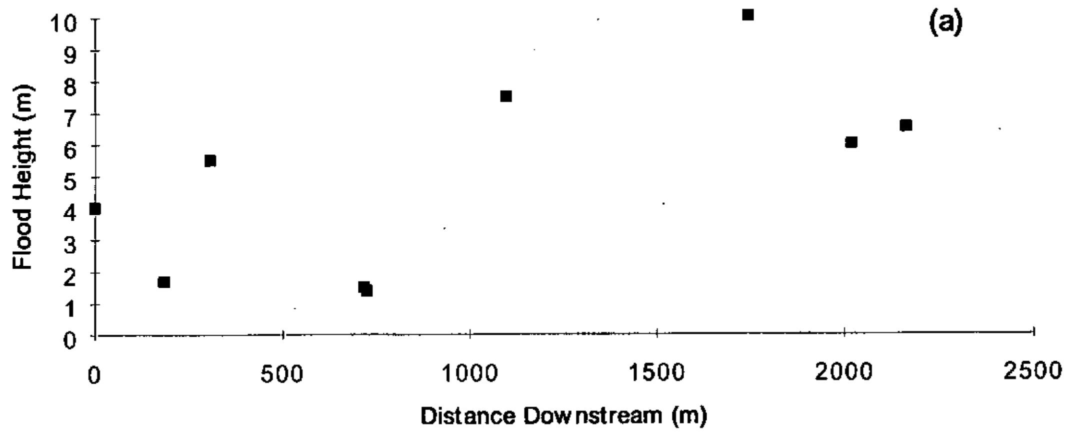


Fig. 4.2 Snoqualmie Falls (Station No. 7773) and Snoqualmie Pass (Station No. 7781) daily precipitation depth for November 1990.

Approximately half of the watershed was logged in the last 20 years. An unlogged buffer zone exists along the main stem from slightly below the confluence with the tributary in which the flood originated downstream for 300 m. The entire catchment of the tributary in which the flood originated had been clearcut and replanted in the decade preceding November, 1990.

The location of initiation of movement of organic debris within the channel (Figure 4.1) was evident during the first site visit. There was a marked absence of organic debris in the stream valley from this location downstream to the railroad grade, a distance of 2 km. Above the initiation site, the channel was filled with a 1-m thick layer of logging slash and debris, obscuring the channel bed from view. From this initiation point downstream, small piles of organic debris (1 to 3 logs high) were present along the top of the inner gorge. Downstream of the railroad grade, evidence of a large



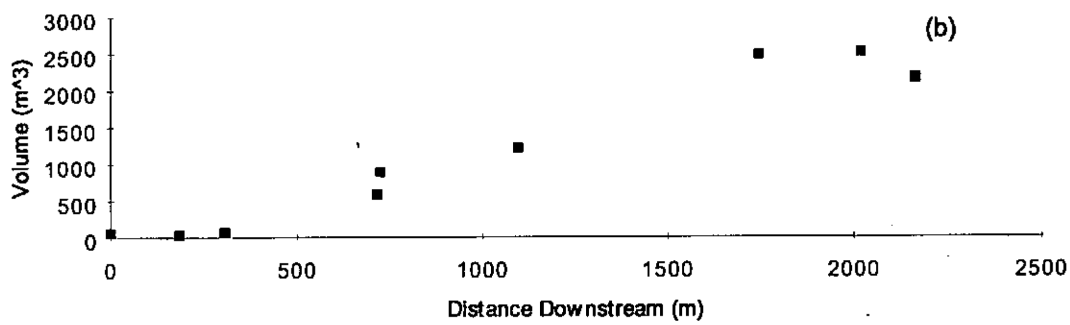


Fig. 4.3 (a) flood height and (b) estimated volume of impounded water on Carter Creek.

dam breach was present where several new stream valleys had been carved. There was significant surface erosion and minor mass wasting in these valleys. Large cobbles and various sizes of organic debris were found randomly throughout this new stream network. There were many uprooted broadleaf trees (~30 cm DBH) and a few coniferous trees (~25 cm DBH).

4.2 Huckleberry Creek

A debris flow, resulting from the failure and movement of a portion of a service road, deposited into Huckleberry Creek on January 9, 1990, and caused a temporary dam to form. The location is shown in Figure 4.4. This debris-flow deposit dammed the channel temporarily. After the dam breached, the flood wave and associated woody debris damaged another service road 1 km downstream. Two kilometers downstream from the initial debris-flow dam, an organic dam 100 meters long and 38 meters wide was deposited. Figure 4.5 shows photographs taken immediately upstream of the deposited organic debris dam. Figure 4.6 shows a stalled dam at the location indicated in Figure 4.4. This dam-break flood occurred after 200 mm of precipitation in the preceding 24 hours. The hyetograph from Ware Creek (10 km away) and the hydrograph which would have occurred in the absence of the dam-break for Huckleberry Creek are shown in Figures 4.14 and 4.7, respectively. The hydrograph was obtained by regression of measured flow rate at Huckleberry Creek with neighboring Thurston Creek; The information for estimating this hydrograph was provided by J. Heffner, (Weyerhauser Corporation, personal communication, 1993). The relationships between flood height and estimated volume of impounded water (and debris) at five downstream locations are shown in Figure 4.8.

4.2.1 Location and Catchment Landscape Features

Huckleberry Creek is a fourth-order tributary at its confluence with the Deschutes River, near Yelm, Washington. The creek flows south and drains an area of 5 km^2 on the south side of Bald Mountain (elevation 1000 m). The total relief of the basin is 800 m. The entire watershed was logged between 1950 and 1952 and was replanted with Douglas fir. Approximately 20% of this second growth forest had been harvested by January, 1990.

The original debris-flow dam, located at creek elevation 357 meters and approximately 100 meters downstream from the collapsed roadway that caused it, was partially intact when the site was visited in April 1990. Below this elevation, random clumps of organic debris were deposited against the upstream side of trees standing within the stream valley. The density of trees within the stream valley was less than

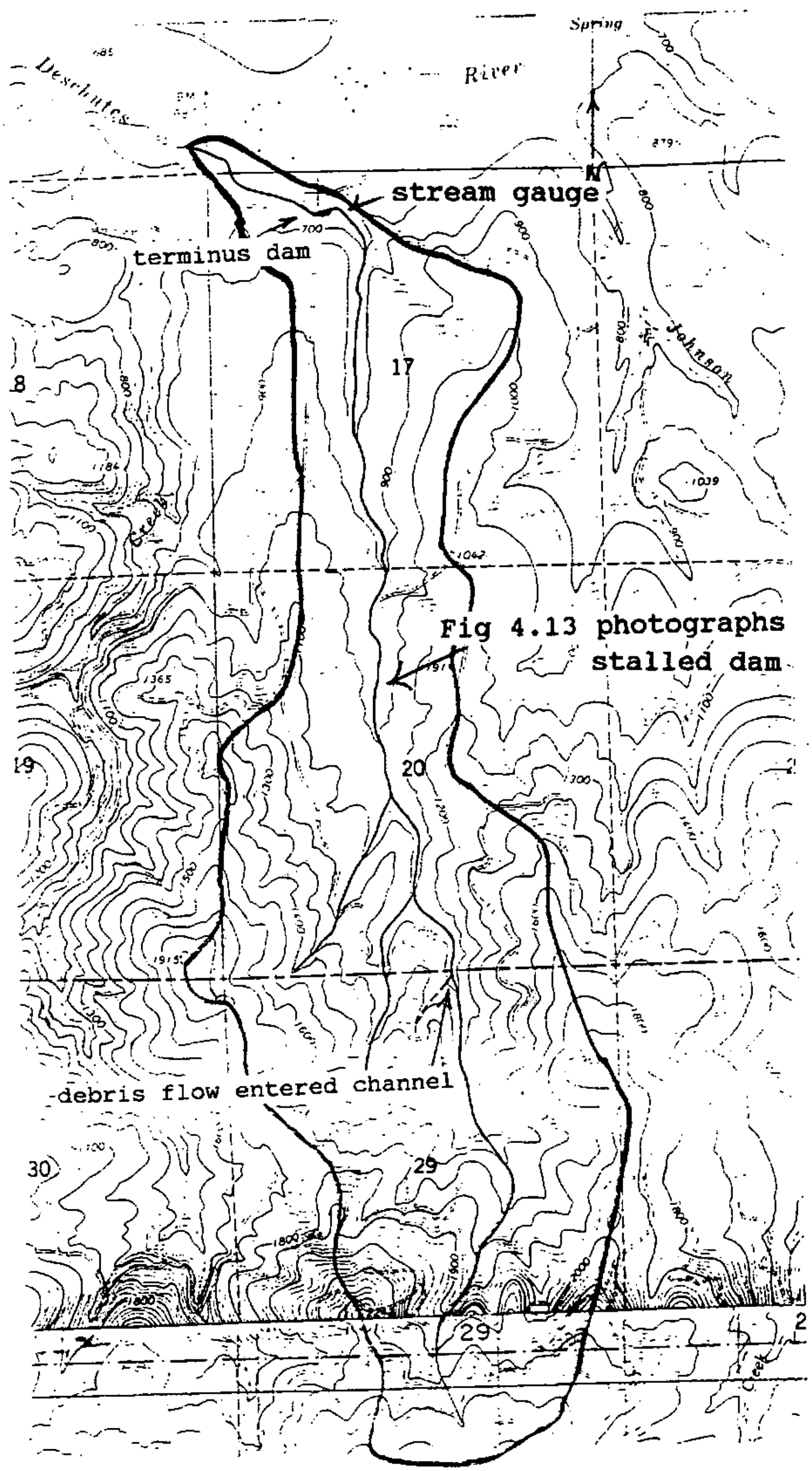


Fig. 4.4 Topographic map of Huckleberry Creek basin (scale 1:24,000, contour interval 20 ft).

Fig. 4.5 Upstream view of stalled organic dam on Huckleberry Creek (location shown in Figure 4.4, approximate elevation 300 m).

above the location where the debris flow dammed the channel. Detritus and small debris were found on the valley walls at heights that corresponded to the dam remnant heights. The organic dam came to rest within the stream valley at elevation 245 m, 4 km downstream. Most logs within this dam were oriented cross-channel except the logs around the perimeter of the dam which were oriented approximately longitudinally (Fig. 4.6b).

4.3 Twin Creek

A debris flow entered and dammed temporarily the west fork of Twin Creek (Figure 4.9) sometime between November 21 and November 26, 1990. Upon breaching of the debris-flow dam, a flood wave traveled through a bedrock canyon for 200 meters and then through a mature coniferous stream valley. Several piles of organic debris were snagged on the stream valley conifers that were able to withstand the movement of

Fig. 4.6 a) Upstream and b) downstream views of Huckleberry Creek immediately upstream of dam terminus (approximate elevation 200m).

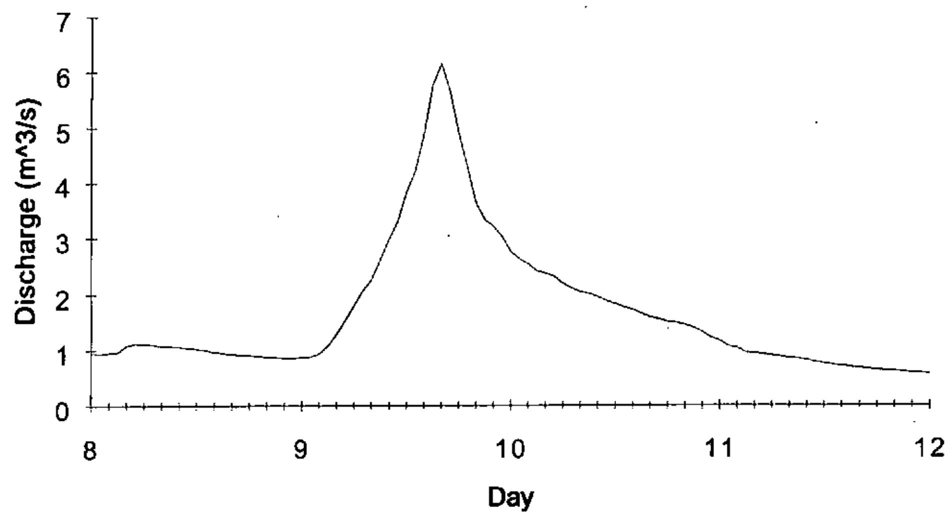


Fig. 4.7 Estimated downstream hydrograph of Huckleberry Creek in the absence of debris-dam failure for January 8-12, 1990; gauge location shown in Figure 4.4.

the organic dam. These conifers prevented the mass movement of the types of organic debris dams that were observed on Huckleberry and Ware Creeks and inferred on Carter Creek. This dam-break flood occurred after 420 mm of precipitation within the preceding 20 days (Figure 4.10). The relationships between flood height and estimated volume of impounded water at five downstream locations are shown in Figure 4.11.

4.3.1 Location and Catchment Landscape Features

Twin Creek is a fourth-order channel at its confluence with the Hoh River, near the west entrance of Olympic National Park, Washington. The creek flows slightly east of south and drains an area of 5.6 km^2. The total relief of the basin is 800 m. The catchment contains of old growth forest; no forest management of any kind has taken place.

The debris-flow dam was partially intact when inspected in July 1991. Immediately below this dam there was a marked absence of organic debris in the stream

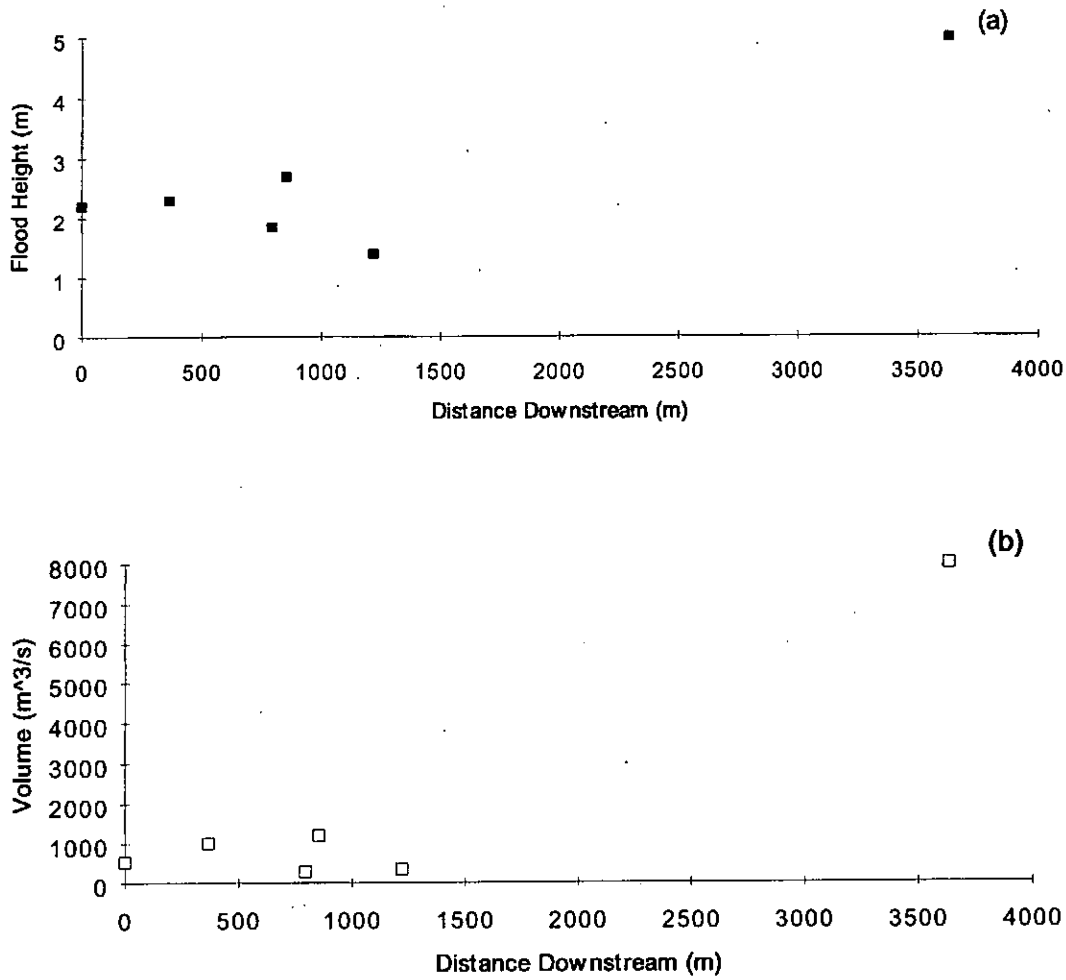


Fig. 4.8 (a) Flood height and (b) estimated volume of impounded water as a function of distance from the initiation site along Huckleberry Creek.

valley. A 20-m-wide swath of broadleaf riparian vegetation had been removed from the confluence with the main stem downstream for 300 m. Downstream of this section the valley contained mature conifers with dam remnants deposited on their upstream sides. Fine organic material and sediment, evident along the valley walls, indicated the height of the flood as it propagated downstream.

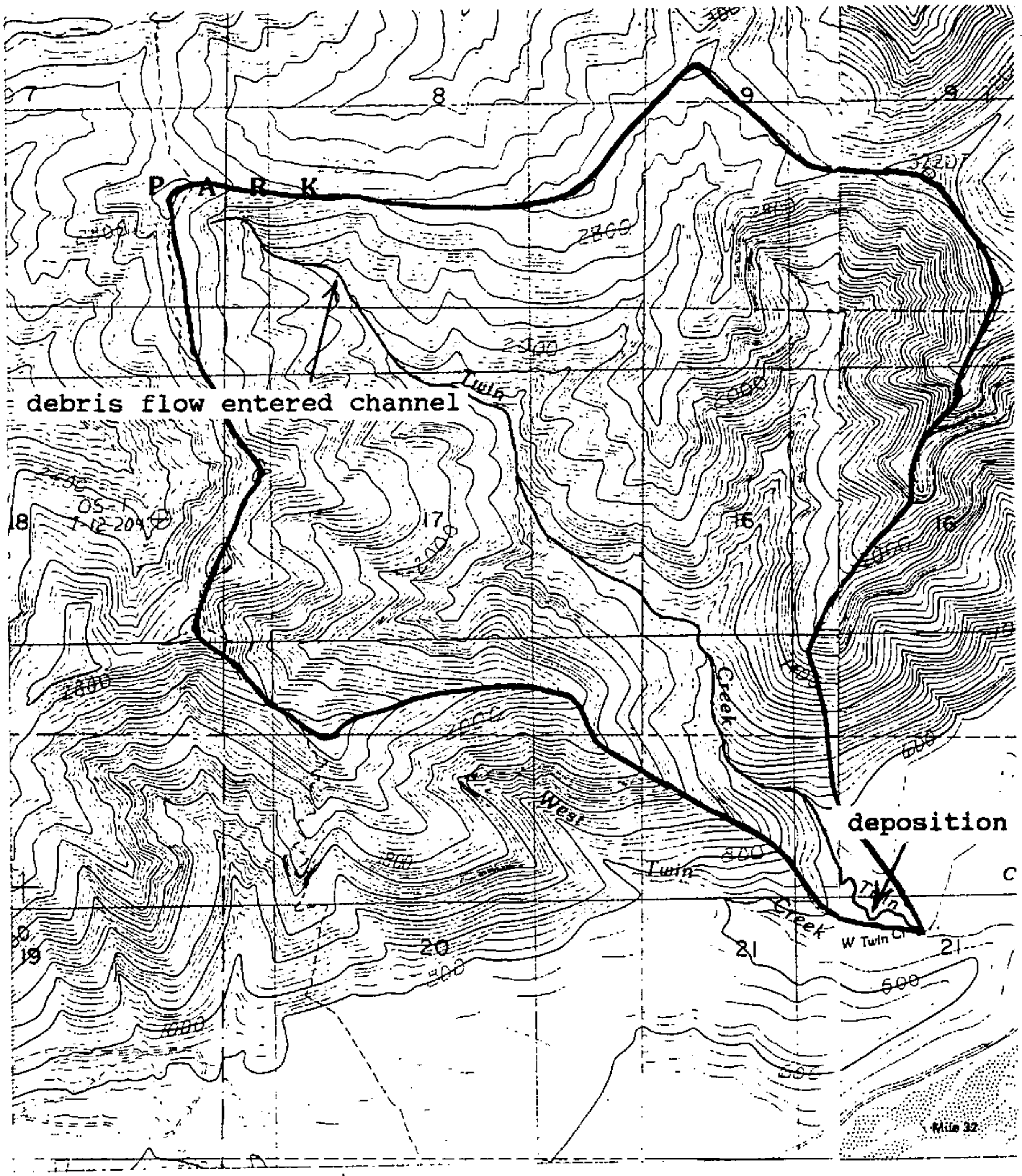


Fig. 4.9 Topographic map of Twin Creek basin (scale 1:24,000, contour interval 40 ft).

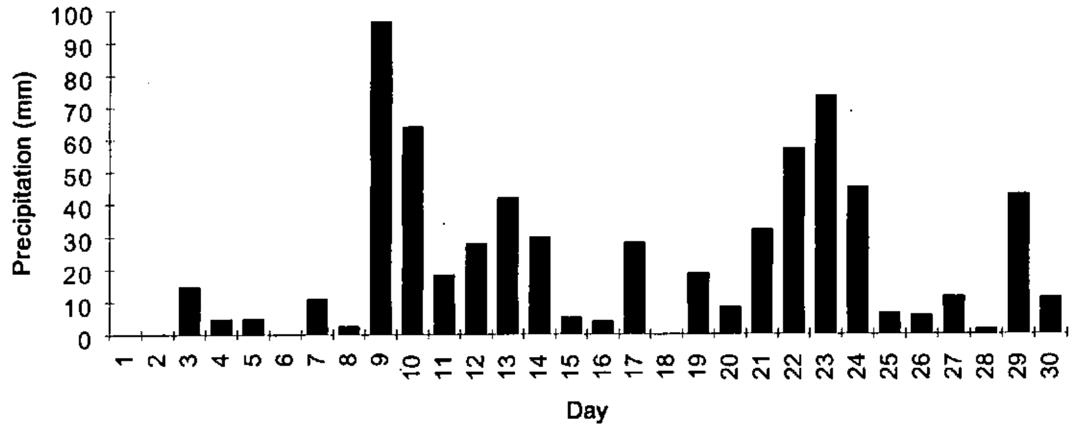
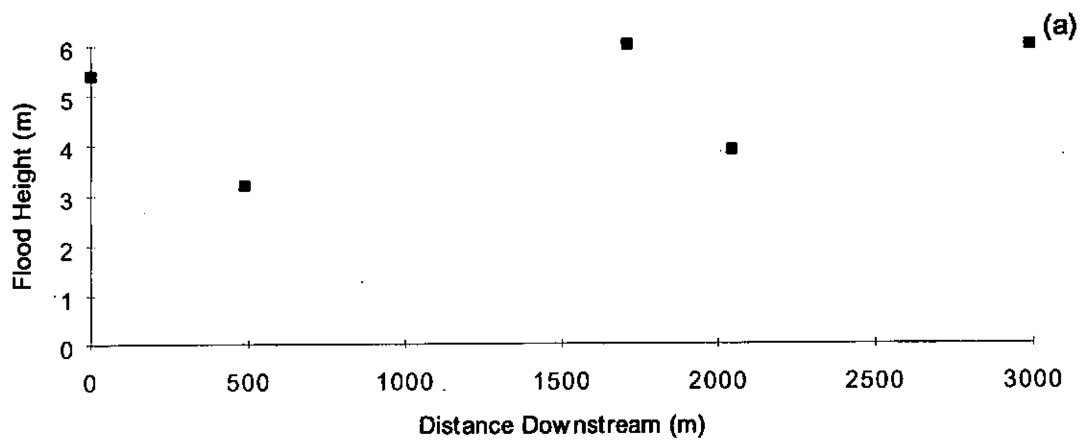


Fig. 4.10 Forks (Station No. 2914) daily precipitation depth for November, 1990.



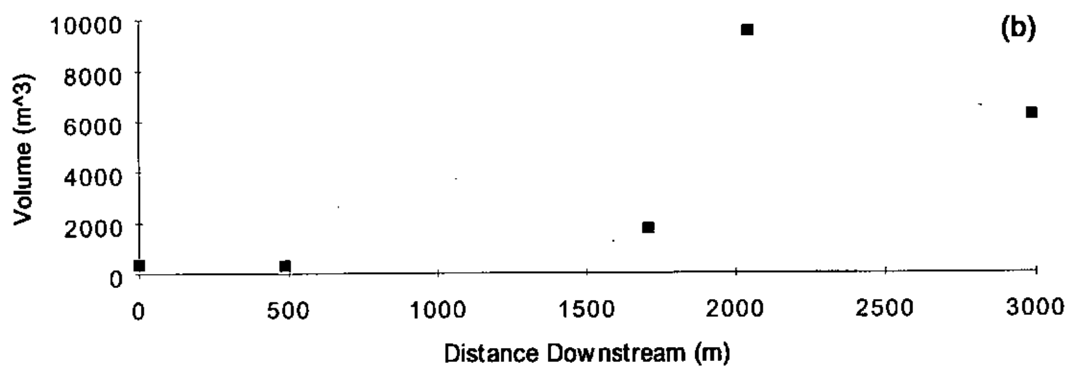


Fig. 4.11 (a) Flood height and (b) estimated volume of impounded water as a function of distance from the initiation site along Twin Creek.

4.4 Ware Creek

Ware Creek, which is located close to Huckleberry Creek (Figure 1.3), experienced a flood of woody debris-laden water on January 9, 1990, the same day that the dam-break flood occurred on Huckleberry Creek. A plan view of the Ware Creek catchment showing the woody debris initiation location, debris deposit terminus, rain gauge and stream gauge locations, and location of Figure 4.13 is given in Figure 4.12. Mobilization of logging slash and debris within the stream channel occurred without any apparent introduction of material displaced from mass wasting into the stream valley. The moving mass of organic debris traveled 1.5 km downstream where it was stopped by a service road crossing. Photographs of the remnants of a stalled dam and organic debris deposited along the base of the valley walls which define the channel are shown in Figure 4.13. This dam-break flood occurred after 200 mm of precipitation in the preceding 24 hours. The hyetograph is shown in Figure 4.14, and the estimated hydrograph in the absence of a debris flood is shown in Figure 4.15. The data for Figure 4.14 were provided by Weyerhauser Corporation (J. Heffner, personal communication, 1993). The estimated hydrograph is based on a regression of Ware Creek flow rate against recorded flow rate in neighboring Hard Creek (J. Heffner, personal communication, 1993). We do not know the time movement began but have included Figures 4.14 and 4.15 for use by others should the initiation time become known. The relationships between flood height and estimated volume of impounded water (and debris) at six downstream locations are shown in Figure 4.16.

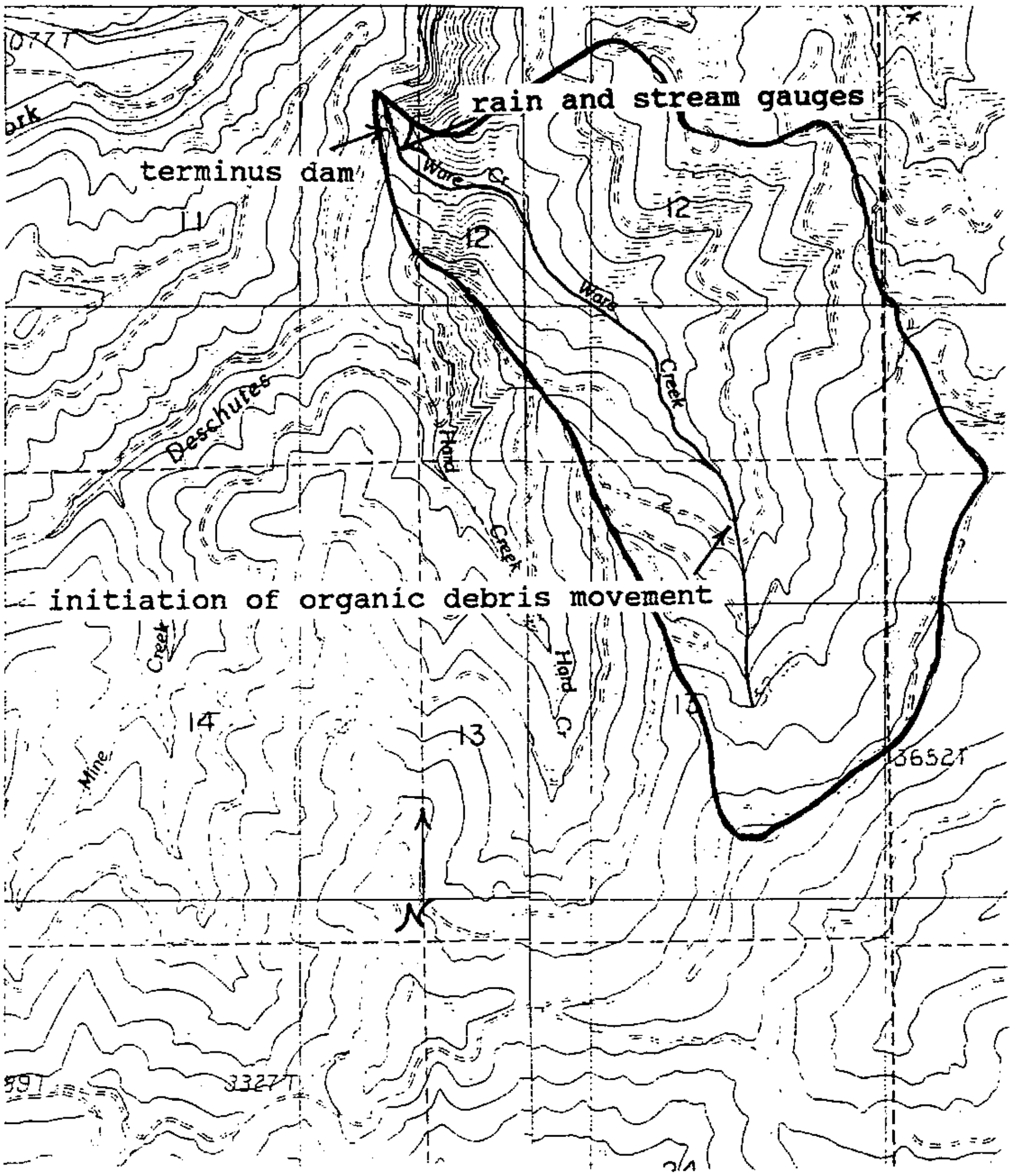


Fig. 4.12 Topographic map of Ware Creek basin (scale 1:24,000, contour interval 40 ft).

Fig. 4.13 Photographs of debris remnants, Ware Creek: (a) organic dam remnants snagged on a boulder, location 1, Figure 4.12a, and (b) deposition of organic debris along the creek, location 2, Figure 4.12b.

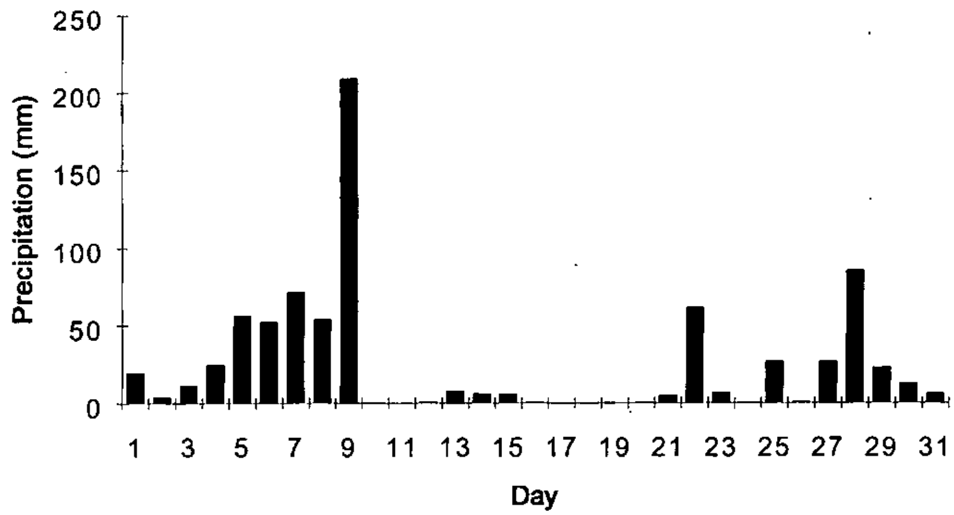


Fig. 4.14 Daily precipitation depth at Ware Creek gauge (location shown in Figure 4.12).

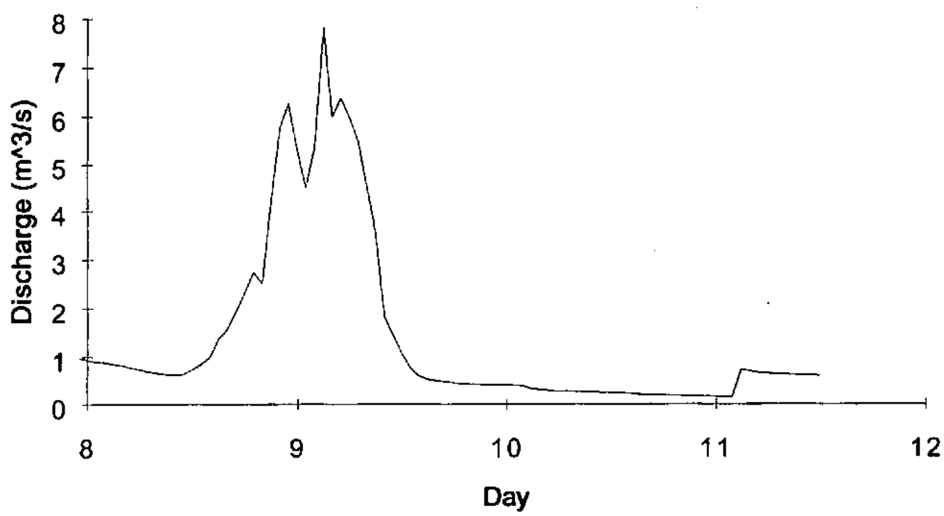


Fig. 4.15 Estimated hydrograph of Ware Creek in the absence of debris dam failure, January 8-12, 1990; gauge location shown in Figure 4.12.

4.4.1 Location and Catchment Landscape Features

Ware Creek is a third-order tributary at its confluence with the Deschutes River, near Yelm, Washington. The creek flows northwest and drains an area of 2.8 km on the west slope of Cougar Mountain (1150 m). The total relief of the basin is 700 m. Most of the basin was clearcut and replanted in the last decade. No riparian buffer zones exist along the stream.

The location of initiation of movement of organic debris looked very similar to the situation at Carter Creek. It consists of the demarcation between the upstream channel which was covered with a 1-m layer of organic debris (obscuring the streamflow from view), and the downstream channel which was devoid of virtually all organic debris. There was no evidence of material from mass wasting having entered the stream channel. A large mass of organic debris came to rest at approximately elevation 1450 m. Like the mass of organic debris found at Huckleberry Creek, most

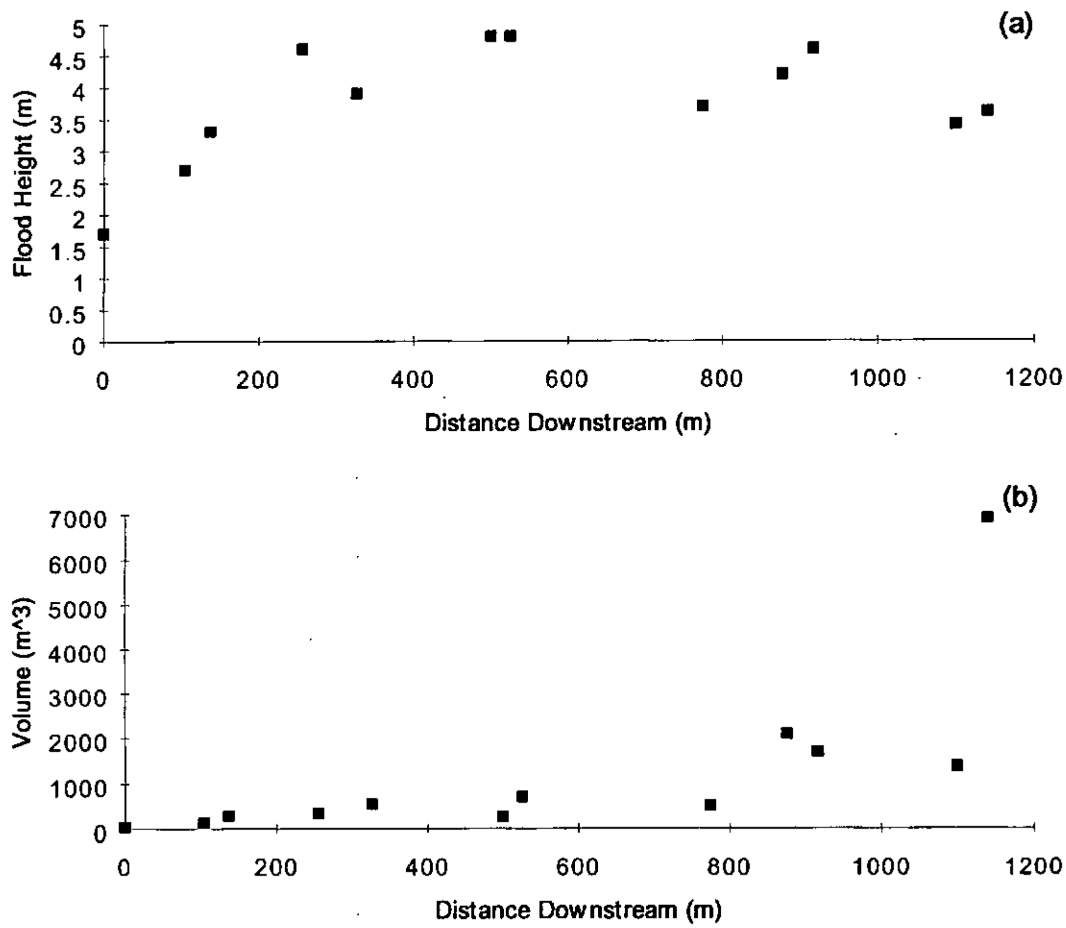


Fig. 4.16 (a) Flood height and (b) estimated volume of impounded water as a function of distance from the initiation site along Ware Creek.

logs were oriented cross-channel, except the logs around the perimeter which were oriented approximately longitudinally.

Field data collected at these four sites, where flood heights were estimated from debris at locations where water had been impounded temporarily as the debris migrated downstream, are used in the next chapter to estimate forces exerted by the organic dams.

CHAPTER 5. ANALYSIS OF DAM VELOCITY, FORCES, AND INTERACTION WITH THE RIPARIAN ZONE

5.1 Introduction

In chapters 3 and 4, we discussed initiation mechanisms and stream valley environments in which dam-break floods occurred. Here we analyze movement characteristics of organic debris dams, particularly estimates of velocities and forces. The forces of these debris dams are of interest because trees in excess of 30 cm DBH that were in the path of the debris dams were uprooted and sheared off. Consequently, large swaths of riparian zones were destroyed. We think, but do not have direct observations, that the motion of the debris dams is unsteady. The evidence supporting the hypothesis of unsteady movement is remnants of dams along each stream investigated. Information needed to estimate the debris-water velocity is scarce. The opportunity existed at only one location at one of the four detailed study sites (Carter Creek) to estimate the velocity of the organic debris dam movement.

5.2 Velocity of Organic Debris Dam

An estimate of the one-dimensional average velocity, v, around a bend of the frontal portion of the debris dam is made from the difference in elevation of debris piles deposited along the inside and outside of the bend. Equation 5.1 yields v:

$$v = (((\Delta h)/w)rg)^{1/2} \tag{5.1}$$

where Δh = the difference in elevation between the debris deposited at inner and outer bend edges

w = the width between bank debris deposits

r = the radius of curvature of the bend

g = the acceleration due to gravity

Of the four sites, only one bend was found from which all measurements could be made with some confidence. The radius of curvature at this bend, located on Carter Creek (Figure 4.1), was estimated from a tape-and-compass map of the bend (Figure 5.1). Radius of curvature was then estimated by fitting an arc to the plan view map. The width of debris movement and elevation difference between the inside and outside radii of the bend were measured also.

This calculation yields an average velocity of 3.8 meters/sec for $\Delta h = 0.5$ meters, $w = 7.4$ meters, and $r = 22.2$ meters. There are uncertainties in determining the radius of curvature, r, width, w, and difference in superelevation, Δh. If we consider some approximate joint uncertainty in these measured quantities and assume these measurements are uncorrelated, we can estimate, to first order, the joint variability in the estimate and express it as the standard deviation of v, S_v, given in Eq. 5.2.

$$S_v = [\delta_1^2 S_{\Delta h}^2 + \delta_2^2 S_r^2 + \delta_3^2 S_w^2]^{1/2} \tag{5.2}$$

where $\delta_1 = \partial v/\partial(\Delta h) = 1/2\ (\Delta h)^{-1/2}\ (rg/w)^{1/2}$

$$\delta_2 = \partial v/\partial r = 1/2\ r^{-1/2}\ (\Delta h/w)^{1/2}$$

$$\delta_3 = \partial v/\partial w = -1/2\ w^{-3/2}\ (\Delta hrg)^{1/2}$$

If we assume a uniform probability distribution about the mean estimated values of ±10% for each of Δh, r, and w, we can approximate Δh as a uniform distribution (lower bound 0.45 meters and upper bound 0.55 meters) having mean $\Delta h = 0.5$ meters and standard deviation, $S_{\Delta h} = [0.55-0.45]/(12)^{0.5} = 0.03$ meters, r as a uniform distribution having mean = 22.2 meters, $S_r = 1.28$ meters, and w as a uniform distribution having mean = 7.4 meters, and $S_w = 0.43$ meters. Use of these values in Eq. 5.2 yield $S_v = 0.19$ meters/sec. Repeating for 20% uncertainty in w, Δh, and r yields $S_v = 0.39$ meters/sec. The contributions of each of the three terms in Eq. 5.2 to S_v are approximately equal. The probability distribution of v is approximately normal. These expressions of joint uncertainty suggest that for Carter Creek, where the measurements were taken, the velocity was about 3.8 meters/sec with a standard deviation of about 0.2 to 0.4 meters/sec.

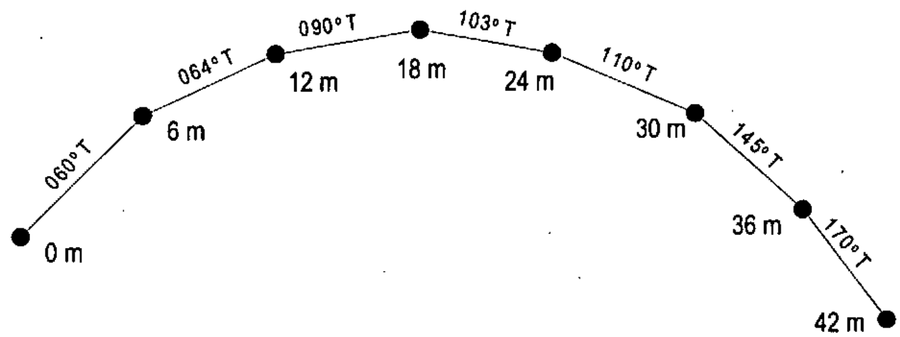


Fig. 5.1 Plan view of bend on Carter Creek and recorded true compass bearings (location shown in Fig. 4.1)

This estimated velocity, v, on Carter Creek is likely to be an upper limit of velocity in this location because as the organic dam moves around a bend some of the floating wood on the frontal portion of the dam may be pushed onto the outer stream bank by the floating wood upstream of it. If this happens, the height of the wood stacked on the outer bend of the channel is higher than the height of the superelevated moving water. The post-flood field evidence would cause overestimation of the superelevation, and consequently overestimation of average velocity.

5.3 Forces Exerted by Debris on Channel Bed and Riparian Zone

The forces of moving organic dams are significant. As the debris dams moved, they uprooted and sheared off riparian vegetation, and greatly altered the stream valley's vegetative and sediment characteristics. Huckleberry Creek, for example, had a swath 32 meters wide cleared completely of vegetation along the previously shaded stream channel at the location of the stream gage (Figure 4.12).

The organic dam is assumed to be deforming constantly as it propagates downstream and encounters standing riparian vegetation. In most situations, momentum of the organic dam would be transferred to obstructions within the stream valley incrementally, as the mass of organic debris that impounds the water deforms. Impoundment of water behind the organic debris was inferred from field investigations because flood heights measured along the stream valley were extraordinarily high; these flood heights alone eliminate the possibility that the organic debris was floated downstream and became snagged on the riparian vegetation. Also, the organic dam is assumed to propagate in an unsteady manner, stopping and increasing in height when a valley obstruction has been encountered. The increased dam height prevails until either the dam deforms, releasing the impounded water and wood, or the valley obstruction that supports the dam fails. In the latter case, the valley obstructions consist of riparian vegetation. Riparian vegetation that had been uprooted was observed downchannel of locations where the dam had stalled.

The fundamentals of engineered dam theory are applicable to organic debris-dam analysis. Arch dams transfer hydrostatic forces to the canyon walls in which the dam is built. Because arch dams are made usually of concrete, or a composite, the arch shape, as seen in plan view in Figure 5.2, is necessary to withstand the hydrostatic forces of the impounded water. The net hydrostatic force F is resisted by abutments with $F = 2R_x$; R_x is the component of R in the x direction, and R is the resultant force at each abutment that is transmitted to the arch structure shown. The organic dams of interest here are assumed to exhibit some characteristics of arch dams. Because organic dams are composed mainly of buoyant organic material elements with specific gravities of around 0.4, the individual

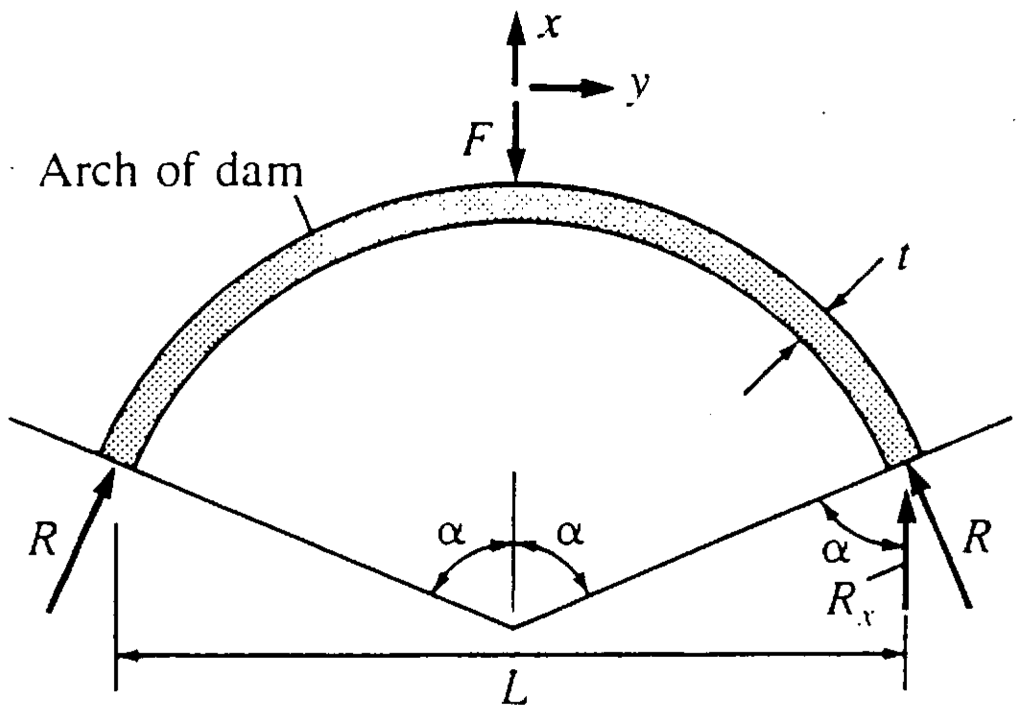


Fig. 5.2 Plan view of arch dam showing applied hydrostatic force F and the resulting force R from each abutment transmitted to the arch structure.

elements are incapable of withstanding hydrostatic and uplift forces, so they are subject to movement. However, in the presence of valley obstructions, such as bedrock controls and riparian vegetation, these dams become snagged (stationary) and transfer their load to valley obstructions, in a similar manner that the arch dam transfers its load to the canyon walls. Organic dams are highly deformable, and composed of intertwined rigid members. Therefore, in plan view, the dam shape is controlled by valley obstructions. A schematic diagram of likely arrangements is shown in Figure 5.3. Structural controls of the stream valley such as canyon constrictions and outcrops are assumed capable of withstanding organic dam forces. Riparian vegetation, consisting of small diameter conifers and broad leaf species in the four catchments described in Chapter 4, was observed to be unable to withstand the dam forces.

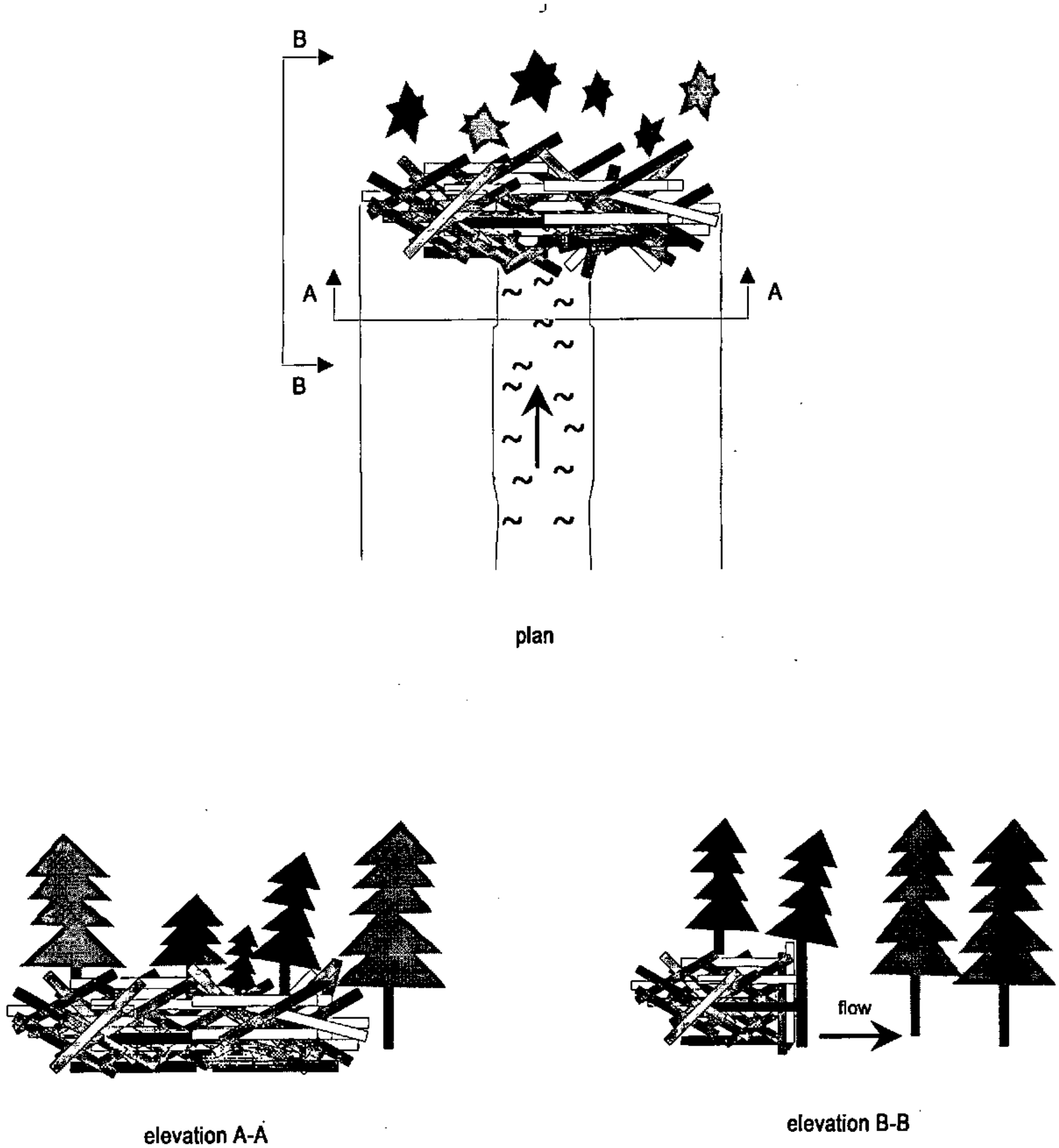


Fig. 5.3 Schematics of the plan, front elevation, and side sectional view of an organic debris dam.

We use hydrostatic analysis for the organic dams because hydrostatic forces create the maximum force that can be imparted to obstructions (trees) within the stream valley. Impact forces of the constantly deforming organic dam colliding with valley obstructions are likely to be less than hydrostatically produced forces. Hydrostatic forces of organic dams that would be transmitted to resisting media were estimated at various locations along each of the four streams described in Chapter 4. These estimates are given in Tables 5.1 - 5.4. For simplicity, the valley was assumed to be a rectangular cross-section at each of the dam locations. The total hydrostatic force on the dam , F is:

$$F = 0.5\gamma\, h_u^2 w \qquad (5.3)$$

where γ = specific weight of water, h_u = water depth at the upper face of the dam, and w = width of water impounded by the dam. The location of the line of action of the hydrostatic force is at 2/3 the depth below the water surface.

In Tables 5.1 to 5.4, the locations of each temporary impoundment, i.e., where ponding occurred as the debris migrated downstream, and the elevation of that location are given. Also given are the estimated water depth and width of channel corresponding to the high water (debris mark) elevation. The resulting force elevation above the channel bed, Z_p, is given. From Eq. 5.3 the hydrostatic force is estimated and the moment, $F \cdot Z_p$, determined.

We chose to analyze each dam as a beam when it was stationary and supported by valley obstructions. There is great variation in length of logs found within the dam; however, the dams are many logs thick (measured both in the direction of movement and measured vertically), so the effect of variation in log length would be dampened and rigid beam analysis would be appropriate. Therefore, since a force is estimated, and the height at which it acts is known, a resulting moment is calculated.

5.4 Breaking Resistance of Riparian Vegetation to Uprooting

Swaths of riparian vegetation were removed during the downstream passage of the organic dams along much of the travel paths. In other areas, clumps of trees within the path

Table 5.1 Estimated hydrostatic forces and moments at nine locations on Carter Creek.

Downstream Distance (m)	Channel Elevation (m)	Water Depth (m)	Width w (m)	Estimated Pond Volume (m^3)	Z_p (from base) (m)	Hydrostatic Force, F (kN)	Moment F Z_p (kNm)
0[a]	1125	4	8	63	1.33	627	837
183	1067	1.7	6	30	0.57	85	48
305	1021	5.5	8	67	1.83	1186	2175
686	908	1.5	10	584	0.50	110	55
716	904	1.4	11	890	0.47	106	49
1097	838	7.5	22	1222	2.50	6066	15164
1743	724	10	32	2476	3.33	15685	52283
2017	674	6	27	2515	2.00	4764	9529
2163[b]	636	6.5	27	2168	2.17	5591	12115

[a] Initiation site
[b] Deposition site (maximum downstream location)

Table 5.2 Estimated hydrostatic forces and moments at six locations on Huckleberry Creek.

Downstream Distance (m)	Channel Elevation (m)	Water Depth (m)	Width w (m)	Estimated Pond Volume (m^3)	Z_p (from base) (m)	Hydrostatic Force, F (kN)	Moment F Z_p (kNm)
0[a]	357	2.2	14	524	0.73	332	244
366	341	2.3	23	995	0.77	596	457
793	323	1.85	16	281	0.62	268	166
854	317	2.7	20	1192	0.90	715	643
1220	302	1.4	20.5	327	0.47	197	92
3635[b]	195	5.5	32	20900	1.83	4745	8699

[a] Initiation site
[b] Deposition site (maximum downstream location)

Table 5.3 Estimated hydrostatic forces and moments at five locations on Twin Creek.

Downstream Distance (m)	Channel Elevation (m)	Water Depth (m)	Width w (m)	Estimated Pond Volume (m^3)	Z_p (from base) (m)	Hydrostatic Force, F (kN)	Moment $F Z_p$ (kNm)
0[a]	627	5.4	8	347	1.80	1143	2058
488	516	3.2	9	287	1.07	452	482
1708	366	6	24	1738	2.00	4235	8470
2043	329	3.9	25	9522	1.30	1864	2423
2988[b]	237	6	22	6193	2.00	3882	7764

[a] Initiation site
[b] Deposition site (maximum downstream location)

Table 5.4 Estimated hydrostatic forces and moments at six locations on Ware Creek.

Downstream Distance (m)	Channel Elevation (m)	Water Depth (m)	Width w (m)	Estimated Pond Volume (m^3)	Z_p (from base) (m)	Hydrostatic Force, F (kN)	Moment $F Z_p$ (kNm)
0[a]	734	1.7	3.5	38	0.57	50	28
104	713	2.7	6	124	0.90	214	193
256	671	4.6	7.5	338	1.53	778	1193
500	639	4.8	5	270	1.60	565	903
774	588	3.7	7	506	1.23	470	579
1140[b]	534	3.6	21	6899	1.20	1334	1601

[a] Initiation site
[b] Deposition site (maximum downstream location)

of the moving organic mass withstood the movement. Coniferous trees within the riparian zone withstood dam movement at the same location where broadleaf species of comparable diameter were uprooted or sheared off. Since some riparian vegetation withstood the organic debris movement and some did not, the following question arises: What sort of riparian zone is needed to withstand or stop such movement?

Data on breaking strengths of trees is scarce. Data from milled pieces of "clear" wood, that which is nearly isotropic and free of knots, is not applicable. Whole trees with knots, and widened trunks near the ground surface behave differently when loaded than milled wood. Pyles (1987) experimented with static loads applied to the stumps of freshly cut coniferous trees. A schematic of his loading apparatus is shown in Figure 5.4. He fit to his data the relationship shown in Figure 5.5. The largest conifer he loaded was 16.5" (0.42 meters) DBH which could support an ultimate supplied load of 62,000 lbs. All of Pyles' loads were applied 1 ft from the average ground surface surrounding the tree stump. From his measurements, we produced the metric relationship, shown in Fig 5.6, for the ultimate overturning moment that could be resisted by a tree stump of a given diameter. Vertically standing trees will resist lesser moments than those shown in Fig 5.6 because as loads are applied, the tree will start to rotate slightly from the vertical and an added overturning moment is created by the tree's (now eccentric) weight.

5.4.1 Relationship Between Ultimate Moment and Riparian Zone

We transformed the graph of ultimate moment versus tree diameter to show how many trees of a given smaller diameter would be needed to resist the ultimate moment of the 0.45 meters diameter tree, the largest diameter used in Figure 5.6. This relationship is given in Figure 5.7, which shows that ten 0.15-meter DBH, or 25 0.10- meter DBH trees would resist the same ultimate load or ultimate moment. These data and the moments estimated in Tables 5.1 - 5.4 suggest that a few large diameter trees located in riparian zones should be able to withstand moments that would be applied by temporarily stalled organic debris as a

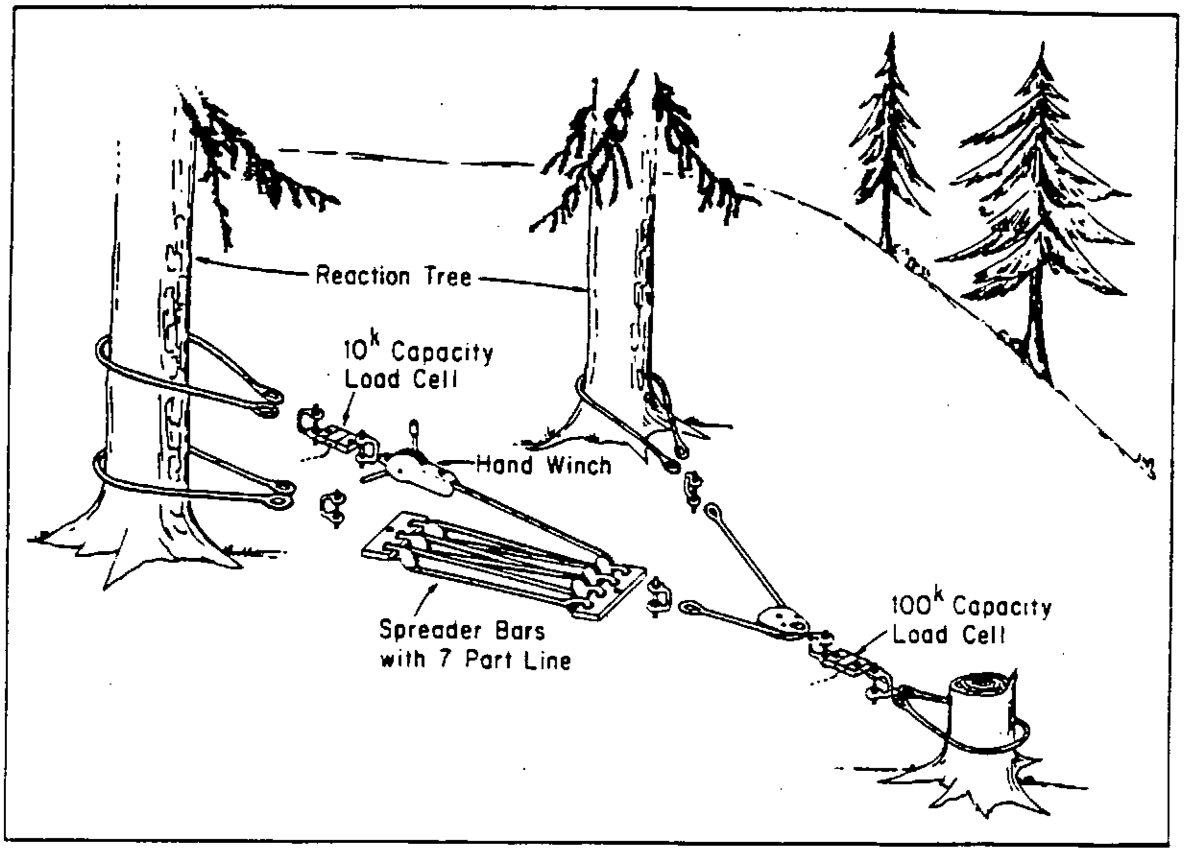


Fig. 5.4 Schematic diagram of Pyles' experiment in which ultimate static loads on tree stumps were measured (load applied 1 ft. above ground surface).

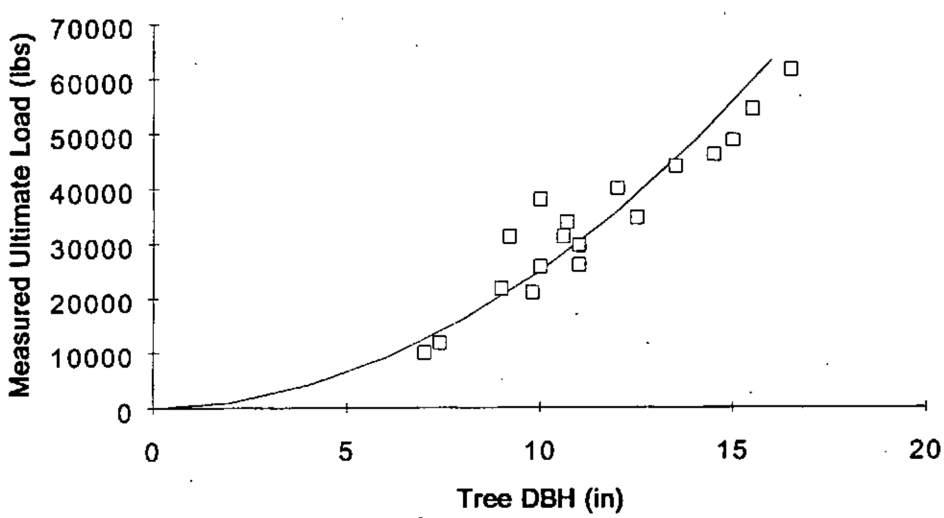


Fig. 5.5 Relationship between ultimate load and tree diameter breast height (DBH).

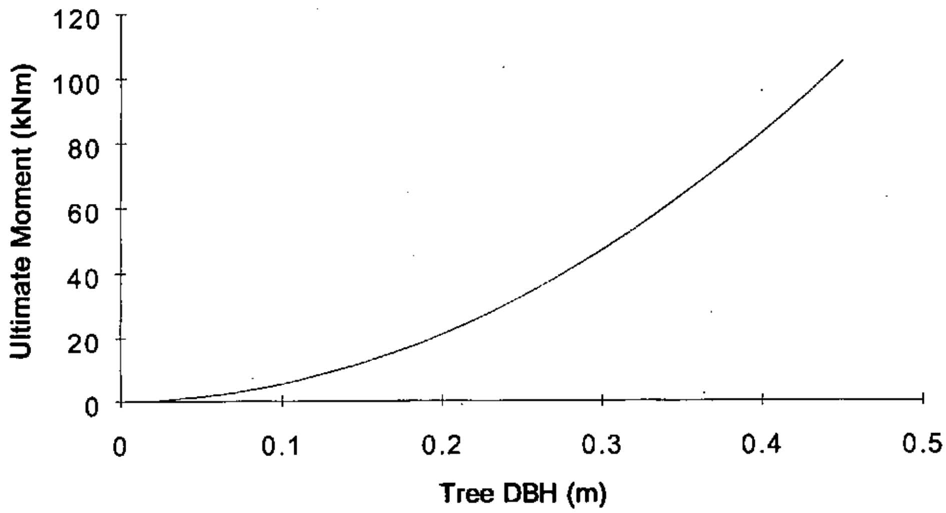


Fig. 5.6 Relationship between ultimate breaking moment and tree diameter breast height (DBH).

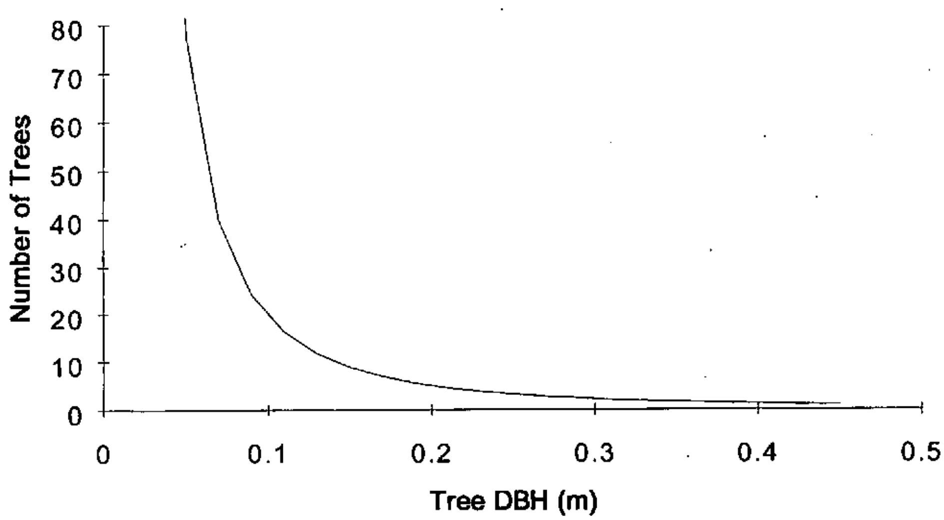


Fig. 5.7 Number of trees necessary for ultimate load to equal that of 1 tree 0.45 meters diameter breast height (DBH).

dam forms. The lower limit on the number of trees, and consequently, the maximum tree spacing depends on the length of wood pieces within the moving organic dam.

Frequency distributions of wood length sampled from the debris terminus on Huckleberry Creek and above the initiation site on Carter Creek are shown in Figure 5.8. The distribution from Huckleberry Creek is right skewed with a mean length of 6 meters. There is a notable increase in the wood sizes when compared to those from the initiation point on Carter Creek where the mean length is approximately 3 meters. The distribution of wood lengths from Huckleberry Creek included wood from riparian vegetation that had been uprooted and entrained during passage of the organic dam. The distribution from Carter Creek consisted mainly of logging slash and debris.

The calculated hydrostatic moments exerted by the dams on the four streams ranged from 28 kNm at the initiation of debris movement on Ware Creek to 52,283 kNm on Carter Creek. Figure 5.9 shows the relationship between calculated dam moments of the four sites and distance downstream from the initiation point. Within the first 1000 meters of travel, the dam moments on all four streams did not exceed 3000 kNm. Even 3000 kNm, according to Pyles' data, requires an extraordinarily strong riparian zone to withstand passage. Carter and Ware Creeks had been recently clearcut to the stream's edge for the first 1000 meters of travel. Huckleberry Creek had large conifers removed from the riparian zone before the dam-break floods occurred, and the riparian zone consisted almost exclusively of alder. Twin Creek is contained within a bedrock canyon for the first few hundred meters of travel. In all four cases, resistance to passage of the organic dams was low within the first 1000 meters of travel.

We used Pyles' relationship between tree diameter and ultimate breaking strength and related it to estimated moments that would be exerted by the organic dams. For instance, for an applied moment of 3000 kNm, the maximum moment exerted by organic dams in all four streams within the first 1000 meters of travel, a cross-valley row of 30 trees of 0.45 meters

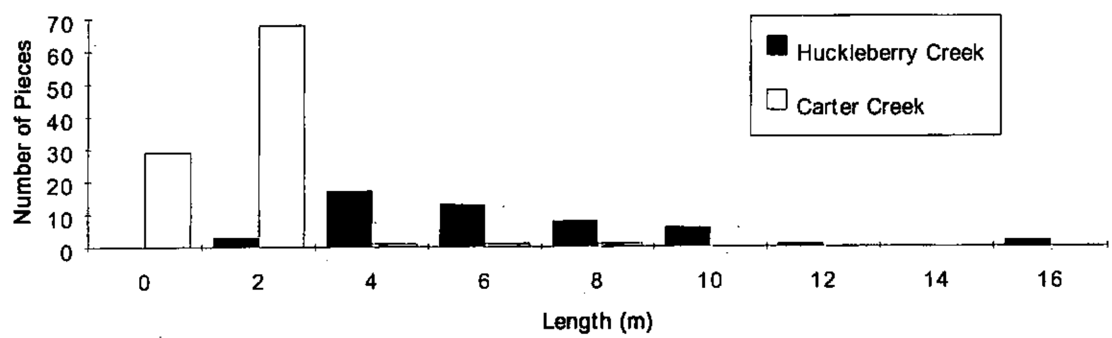


Fig. 5.8 Frequency distributions of lengths of wood in organic debris dams at the initiation site on Carter Creek, and the dam terminus on Huckleberry Creek.

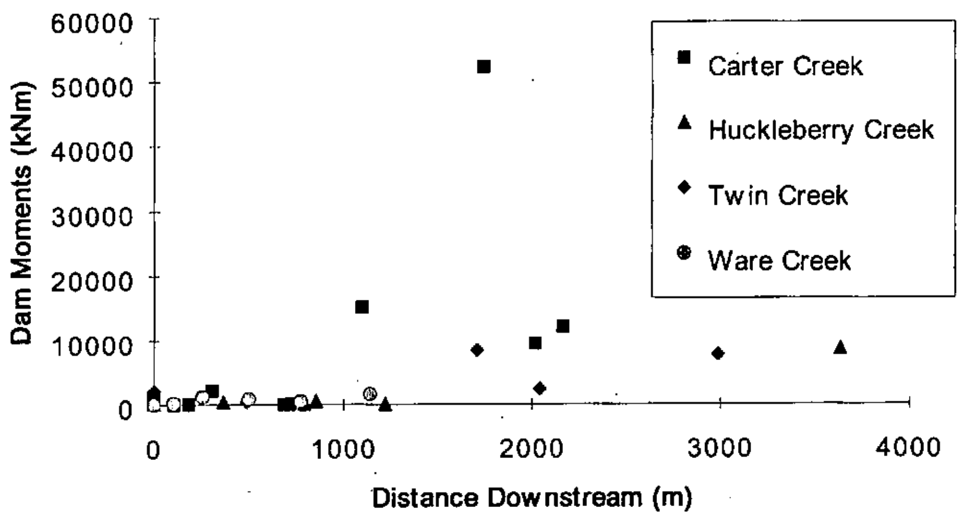


Fig. 5.9 Calculated dam moments as a function of distance downstream from the initiation point.

diameter, or 100 trees of 0.25 meters diameter would be required to withstand such a moment. The natural occurrence of both these combinations of stand density and tree diameter are unrealistic in small stream valleys that contain low-order channels.

Reaches of stream valleys that are only several hundred meters long and have been cleared of coniferous riparian vegetation set the stage for propagation of dam-break floods. The above examples show unlikely riparian zone stand density and tree diameter combinations needed to withstand the relatively low dam forces which occur within the first

1000 meters of travel. Therefore, to prevent formation and passage of these organic dams from dam-break floods, contiguous mature coniferous riparian zones extending through reaches in which initiation can be expected (first-order) may be necessary. Figure 5.9 shows that dangerously high dam forces and resulting propagation of debris can occur within the first several hundred meters of relatively unimpeded travel.

5.5 Conjecture of Dam Movement With Respect to Presence of Organic Debris

The four sites investigated in detail differ with respect to the presence of organic debris in the stream valley. Carter and Ware Creeks were covered completely with a 1-meter thick layer of logging slash and debris in the vicinity of initiation of movement of organic debris. Both of these dam-break floods initiated from organic debris dam breakage within the channel. The nearly continuous layer of organic debris encountered by the organic dam would have provided significant roughness and impeded movement. This roughness slowed the dam movement, and increased the flood height. After passage of the organic dam, the channels are free of almost all organic debris. The channel and valley roughness are smaller than before the dam-break flooding occurred. Future dam formation and propagation is not possible until a sufficient amount of organic debris has once again accumulated in the stream valley. Until then, high stream flows will occur with little impedance.

CHAPTER 6. STRATEGY FOR ASSESSING DAM-BREAK FLOOD POTENTIAL

A simple method is presented for determining which streams are susceptible to dam-break floods, and if a dam-break flood occurs, how much of the downstream channel system will be affected. This method reflects all observations that have been made in the preceding chapters, and it is intended to provide guidance for forest management decision-making where the objective is to eliminate dam-break flooding or minimize any deleterious effects. If a dam-break flood has occurred on the stream, then the stream is susceptible to a recurring dam-break flood if sufficient organic material has reaccumulated.

The method is shown as a flow chart in Figure 6.1 and uses a series of questions to determine the potential for dam-break flood damage. Question 1 is concerned with stream valley width. For the twenty sites examined, the largest valley width associated with the initiation of debris dam movement was 40 meters. The flattest channel slope at which a debris dam fanned and moved was 2°. This information is contained in Question 2. Question 3 asks if hillside mass wasting enters the stream channel. If it does, the potential for dam formation and breaching exists. Question 4 concerns the accumulation of logging slash. If logging slash has accumulated within steep first- and second-order stream valleys, the potential for organic dam formation and mobilization exists. Once a dam-break flood has been initiated, it will propagate downstream unless either of the following happens: the flood wave encounters a predominantly mature coniferous riparian zone with conifers near the channel, or the channel slope decreases to approximately 2°.

We do not provide any guidance for managerial decisions. Our simple non-quantitative method makes clear which channel reaches and what lengths of channels are susceptible to organic dam-break floods. Any stream for which the answers to the questions

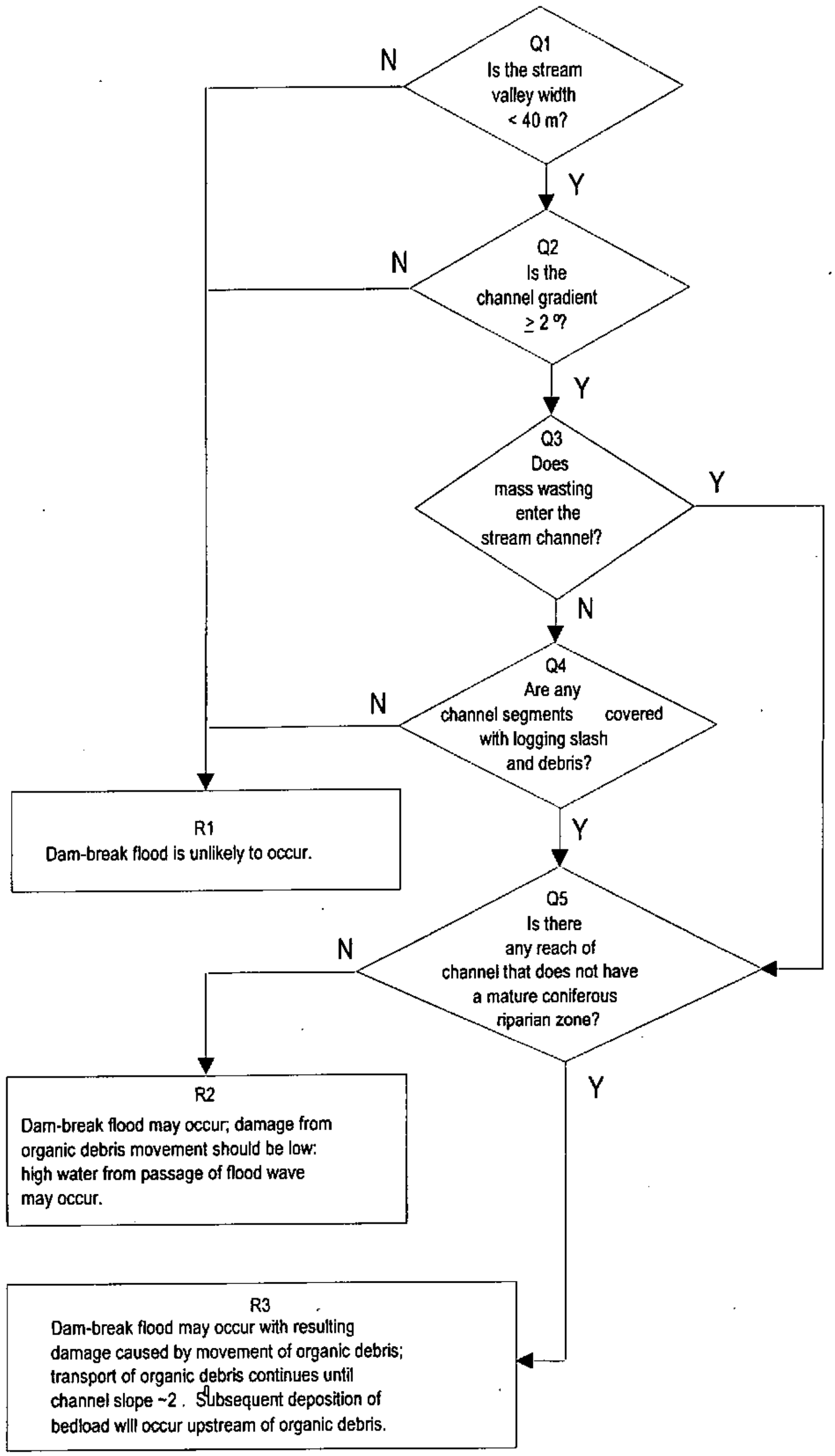


Fig 6.1 Questions for determining potential for dam-break flood damage in mountain streams in the Pacific Northwest.

indicate situations R2 and R3 require remedial action. Mitigative measures and logging practices to minimize the effects of such floods are well known to forest managers.

Figure 6.1 is based on what has been learned about debris dam formation and movement for twenty streams in the Pacific Northwest. Any methodology needs to be tested for a range of situations. The scheme presented here is a guide to potential hazard situations and may be refined as more experience is gained until its use.

CHAPTER 7 SUMMARY

All findings in this report are based on detailed field observations at 20 sites in Pacific Northwest catchments. We are unaware of any prior systematic observations of dam-break floods in low order mountain channels in the region.

Dam-break floods in low-order mountain channels are caused most often by landslides and debris flows, but they also can be caused by stream-flow mobilization of organic debris already within the stream channel. Flood flows produced from these dam-breaks may incorporate a destructive front of organic debris that removes riparian vegetation and modifies the channel shape and bed material within its path. Movement of organic debris may begin in first-order channels and deposit in higher-order channels where either the channel gradient decreases to approximately 2° or mature coniferous riparian zones are encountered. Of the 20 sites examined, most of the floods traveled between 2 and 4 km from the initiation point.

By using the principle of superelevation for debris laden flow as it moves around a bend we estimated a velocity of 3.8 meters/s for one location on Carter Creek. We have no other direct or indirect measures of debris dam velocity.

The estimated hydrostatic moments exerted on organic debris dams ranged from 10 to 490 kN per meter of width measured across channel sections. Pyles' (1987) static load tests to determine the resistive force of mature conifers up to 0.45 meters DBH indicate that a substantial mature conifer riparian zone is required to resist movement of organic debris and debris dams. The most obvious schemes for avoiding the destructive forces of organic debris movement are maintaining contiguous riparian zones of mature conifers around low-order channels and minimizing deposition of logging slash and debris into those channels.

REFERENCES

Bathurst, J.C. (1986), "Slope-area discharge gazing in Mountain Rivers", Journal of Hydraulic Engineering, 112(5), 376-391.

Benda, L. (1989), "The influence of debris flows on channels and valley floors in the Oregon Coast Range, USA", Earth Surface Processes and Landforms.

Benda, L. and T.W. Cundy (1990), "Predicting deposition of debris flows in mountain channels", Canadian Geotechnical Journal, V 27, pp. 409 - 417.

Benda, L. and W. Zhang (1989), "The hydrologic and geomorphological characteristics of landslide/dam-break floods in the Cascade Range of Washington", EOS:1124.

Bilby, R.E. (1980), "Importance of debris jams in the structure and function of stream ecosystems", Ecology 61:1107-1113.

Bilby, R.E., and J.W. Ward (1989), "Changes and Characteristics and Function of Woody Debris with Increasing Size of Streams in Western Washington", Transactions of the American Fisheries Society, 118: 368-378.

Burroughs, E.R., and B.R. Thomas (1977), "Declining root strength in Douglas-Fir after falling as a factor in slope stability", Res. Pap. INT-190, 27 pp., For. Serv., U.S. Dept. of Agric., Ogden, UT.

Costa, J. E. (1985), "Floods by dam failures", U.S. Geological Survey Open File Report, 85-560.

Costa, J. E. (1988), "The formation and failure of natural dams", Geological Society of America, vol. 29, 191-206.

Chow, V.T., (1959), *Open Channel Hydraulics*, McGraw-Hill, New York, 680 p.

Croft, A.R. and J.A. Adams (1950). "Landslides and sedimentation in the north fork of Ogden River," Res. Pap. 21, Forest Service, U.S.D.A., Ogden, UT

Earthinfo, Inc. (1990), "Climate Data, Summary of the Day-West 2," CD-ROM, Vol. 3.3.

Eide, J. (1990), "A 48 year sediment budget (1942-1989) for Deer Creek Basin, Washington", Master's Thesis, Western Washington University, Bellingham, WA.

Fiksdal, A.J. and M.J. Brunengo (1980), "Forest slope stability project - Phase 1", Washington State Department of Ecology.

Fread, D.L. (1982), "DAMBRK: The NWS dam-break flood forecasting model", Office of Hydrology, National Weather Service, Silver Spring, Maryland.

Gillilan, S.E. (1989), "Storage dynamics of fine woody debris for two low-order coastal streams in southeast Alaska. M.S. Thesis, Oregon State University, Corvallis. 97 pp.

Gray, D.H., and W.F. Megahan (1981), "Forest vegetation removal and slope stability in the Idaho Batholith", Res. Pap. INT-271, 23 pp., For. Serv., U.S. Dept. of Agric., Ogden, UT.

Heede, B.H. (1972), "Influences of a forest on the hydraulic geometry of two mountain streams", Water Resources Bulletin, 8:523-530.

Heffner, John (Jan 1993), personal communication, Weyerhauser Corporation, Tacoma, WA 98477.

Jarret, R. D. (1984), "Hydraulics of high gradient streams", Journal of Hydraulic Engineering, 110 (11), 1519-1539.

Johnson, A.C. (1991), "Effects of Landslide-Dam-Break Floods on Channel Morphology", Master's Thesis, College of Forest Resources, University of Washington, Seattle, WA.

Lisle, T.E. (1986), "Stabilization of a gravel channel by large streamside obstructions and bedrock bends, Jacoby Creek, northwestern California", Geological Society of America Bulletin, 8:999-1011.

Lisle, T.E. and H.M. Kelsey (1982), "Effects of large roughness elements on the thalweg course and pool spacing",pp. 134-135 in L.B. Leopold, editor. American geomorphological field group field trip guidebook, 1982 conference, Pinedale, Wyoming. American Geophysical Union, Berkeley, CA.

Marston, R.A. (1982), "The geomorphic significance of log steps in forest streams", Annals of the Association of American Geographers, 72:99-108.

Morrison, P.H. (1975), "Ecological and geomorphological consequences of mass movements in the Alder Creek Watershed and implications for forest land management", University of Oregon, Eugene, OR.

O'Loughlin, C.L. (1974b), "A study of tree root strength deterioration following clearfelling", Can. J. For. Res., 4(1), 107-113.

O'Loughlin, C.L., and A.J.Pearce (1976), "Influence of Cenozoic geology on mass movement and sediment yield response to forest removal, North Westland, New Zealand", Bull. Int. Assoc. Eng. Geol., 14,41-46.

Pyles, M. R. and J. Stoupa (1987), "Load-Carrying Capacity of Second-Growth Douglas-Fir Stump Anchors", Western Journal of Applied Forestry, 2(3):72-80.

Selby, M.J. (1985), "Earth's changing surface", Clarendon Press, Oxford, p 298.

Smith, D.G. (1980), "River ice processes: Thresholds and geomorphologic effects in northern and mountain rivers", Thresholds in Geomorphology, Dowden and Culver, Inc., Stroudsburg, PA, 323-343

Strahler, A.N. (1952), "Dynamic basis of geomorphology", Bulletin of the Geological Society of America, 63,923-38.

Strahler, A.N., and A.H. Strahler (1983), "Modern Physical Geography", second edition, John Wiley & Sons, New York, plate c2.

Swanston, D.N. (1970), "Mechanics of debris avalanching in shallow till soils of southeast Alaska", Res. Pap. PNW-103, 17 pp., For. Serv., U.S. Dept. of Agric., Portland, OR.

Swanston, D.N. (1974a), "The forest ecosystem of southeast Alaska. 5. Soil mass movement.", Gen. Tech. Rep. PNW-17, 22 pp., For. Serv., U.S. Dept. of Agric., Portland, OR.

Swanston, D.N., and F.J. Swanson (1976), "Timber harvesting, mass erosion, and steepland forest geomorphology in the Pacific Northwest", Geomorphology in Engineering, Dowden, Hutchison and Ross, Stroudsburg, PA.

Syverson, T.L. (1984), "History and origin of debris torrents in the Smith Creek Drainage, Whatcom County, Washington", Master's Thesis, Western Washington University, Bellingham, WA.

Veldhuisen, C.N. (1990), "Coarse Woody Debris in Streams of the Drift Creek Basin, Oregon", M.S. Thesis, Oregon State University, Corvallis, 109 pp.

Washington State Forest Practices Board (1988), "Washington Forest Practices Rules and Regulations".

Wu, T.H., W.P. McKinnel, and D.N. Swanston (1979), "Strength of tree roots and landslides on Prince of Wales Island, Alaska", Can. Geotech. J., 16(1), 19-33.

Wu, T.H., and D.N. Swanston (1980), "Risk of landslides in shallow soils and its relation to clearcutting in southeastern Alaska", For. Sci., 26(3), 495-510.

Ziemer, R.R., and D.N. Swanston (1977), "Root strength changes after logging in southeast Alaska", Res. Note PNW-306, 10 pp., For. Serv., U.S. Dept. of Agric., Portland, OR.

Ziemer, R.R. (1981), "Roots and the stability of forested slopes", IAHS Publ. 132, 343-357.