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ANALYSIS OF INITIATION MECHANISMS OF DAM-BREAK FLOODS IN MANAGED FORESTS

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1.0 INTRODUCTION

1.1 Aims and Objectives

This is the first of two reports that examine dam-break floods. This first report describes the general physical characteristics of dam-break floods including an inventory of the mechanisms of initiation. The dam-break floods described occurred in the Cascade and Olympic Mountains of Washington and Oregon during the last decade. The second report, expected to be completed by December 1992, will include quantitative analysis of the dam-break flood process that focuses on that aspect of the floods that leads to increasing magnitudes with distance travelled (migrating organic dams). The aims of that analysis will be to produce a better understanding of the dam-break flood process and develop qualitative and quantitative descriptions of initiation and travel distance of dam-break floods that can be used by forest managers.

This report describes the initiation mechanisms of twenty dam-break floods, the geometry of the valley floor at each of the initiation and deposition sites of the floods, and their lengths of travel. The stream types and stream orders, and resources impacted by the floods are discussed.

1.2 Definitions

Debris Torrent: This term has been used to describe dam-break floods and debris flows in mountain regions of the Pacific Northwest. Because these events are initiated by different mechanisms and occur in different areas of the landscape, they should be treated separately.

Debris Flow: Benda and Cundy (1990), define a debris flow as "A highly mobile slurry of soil, rock, vegetation and water that can travel kilometers from its point of initiation, usually in steep (> 5 degrees) 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. 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".

Slump: A deep rotational failure, caused by increased pore water pressure in mechanically weak, and often clay-rich rocks and sediments (Swanston, 1974). Slumps are easily distinguishable from landslides or debris flows because the disturbed material does not travel far from the initial failure location.

1.3 The Dam-Break Flood Process

Dam-break floods frequently occur in confined mountain channels of the Pacific Northwest (Benda and Zhang, 1989). Dams may be composed of material deposited from landslides, debris flows, slumps or may be composed entirely of organic debris in mountain channels. These floods frequently entrain organic debris thereby creating a moving, enlarging wedge of organic material in the frontal portion of the flood. The enlarging wedge of organic debris entraps additional streamflow and causes the event to increase in volume with distance travelled. This aspect of dam-break floods makes them one of the most damaging processes in mountain drainage basins in the Pacific Northwest. Accumulation of woody debris may continue until the flood has exited a confining valley at which point the debris is deposited, and the previously impounded moves downstream. These floods are extremely destructive because they destroy riparian vegetation and cause significant erosion along channels and valley walls over the entire length of travel.

2.0 RELATED PREVIOUS AND CURRENT RESEARCH

2.1 Previous Debris Torrent Research

The majority of previous work involving the dam-break flood process is contained in literature describing the process of debris torrents. Because debris torrents encompass both debris flows and dam-break floods, a direct comparison between this investigation and those studies is not possible. A brief sample of this type of research 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 from logging roads and clearcuts in managed forests in the Oregon Cascade Range occurred at a rate 4,100 and 450 percent higher than the rate in unmanaged forests. Morrison (1975), also working in Oregon, found an 880 and 1300 percent increase in debris torrents associated with clearcuts and logging roads compared to unmanaged forests. Syverson (1990) estimated that the majority of debris torrents that occurred in Smith Creek basin (R4E T38N), in Northwest Washington originated from second-growth forests and clearcuts.

Debris torrents have also been used to infer erosion in the context of sediment budgets. Eide (1990) measured erosion along valley walls impacted by debris torrents in first- through third-order channels in the Deer Creek basin (R7E T33N) in Washington.

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. Floods of dam breaks travel entire lengths of stream-order segments and trigger significant secondary erosion processes, such as streamside landslides (Benda and Zhang, 1989).

2.2 Current Dam-Break Flood Research at the University of Washington

2.2.1 Research within the Department of Geological Sciences

The analysis of dam-break floods in mountain drainage basins is a current research topic in the Department of Geological Sciences at the University of Washington (Benda, Zhang, and Dunne, research in progress). They employ the National Weather Service dam breach 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 natural landslide and debris flow dams may fill with water during storms in three to five minutes and that a full breach and drainage can be accomplished in two to five minutes. The routing model predicts an immediate attenuation of the initially extreme flood wave.

Though the routing model predicts flood heights satisfactorily in large rivers (fifth and sixth order), it fails to predict flood height accurately in low to medium order channels (second to fourth order). This is because dam-break floods in these channels entrain large quantities or organic material relative to the volume of water thereby creating a migrating and enlarging wedge of debris in the frontal positions of the flood which increases the volume of the moving mass as it propagates downstream.

2.2.2 Research within the College of Forest Resources and College of Fisheries

The effects of dam-break floods on salmonid habitat were examined in several streams in the North Cascades of Washington by Beechie (1990). The geomorphic effects of dam-break floods on mountain channels have been characterized in a recent TFW funded project (Johnson, 1991).

3.0 METHODS

3.1 Site Selection

Information about locations of sites where dam-break floods have been observed was provided by various U. S. Forest Service, University of Washington, and Indian Tribal personnel who had detailed knowledge of these events. Site locations cover three physiographic regions of the state as defined by Fiksdale and Brunengo (1980) and are shown in Figure 1.

3.2 Field Methods

Each stream was inspected upstream of the initiation site and downstream to the deposition area. Field surveys for each stream included measurement of elevation, channel gradient, and cross sectional area of the valley covered by the flood. Measurements were obtained at regular intervals along the channel beginning at the initiation point. The area adjacent to the initiation point was examined carefully to assess the cause of formation of the dam. Stream orders (Horton/Strahler scheme) were determined from U.S.G.S. topographic maps and field observations. Stream types were determined using published D.N.R. Stream Type maps.

4.0 RESULTS AND DISCUSSION

4.1 Initiation Mechanisms of Dam-Break Floods.

Five apparent initiation mechanisms were inferred during this investigation (see Table 1). They include landslide, debris flow, canyon constriction, organic dam, and a slump within a glacial deposit. The relative numbers are shown in Figure 2. Landslides, debris flows, and slumps have been described in the introduction. Debris dams in canyons occurred when sediment and organic debris accumulated upstream of the narrow bedrock canyons. This

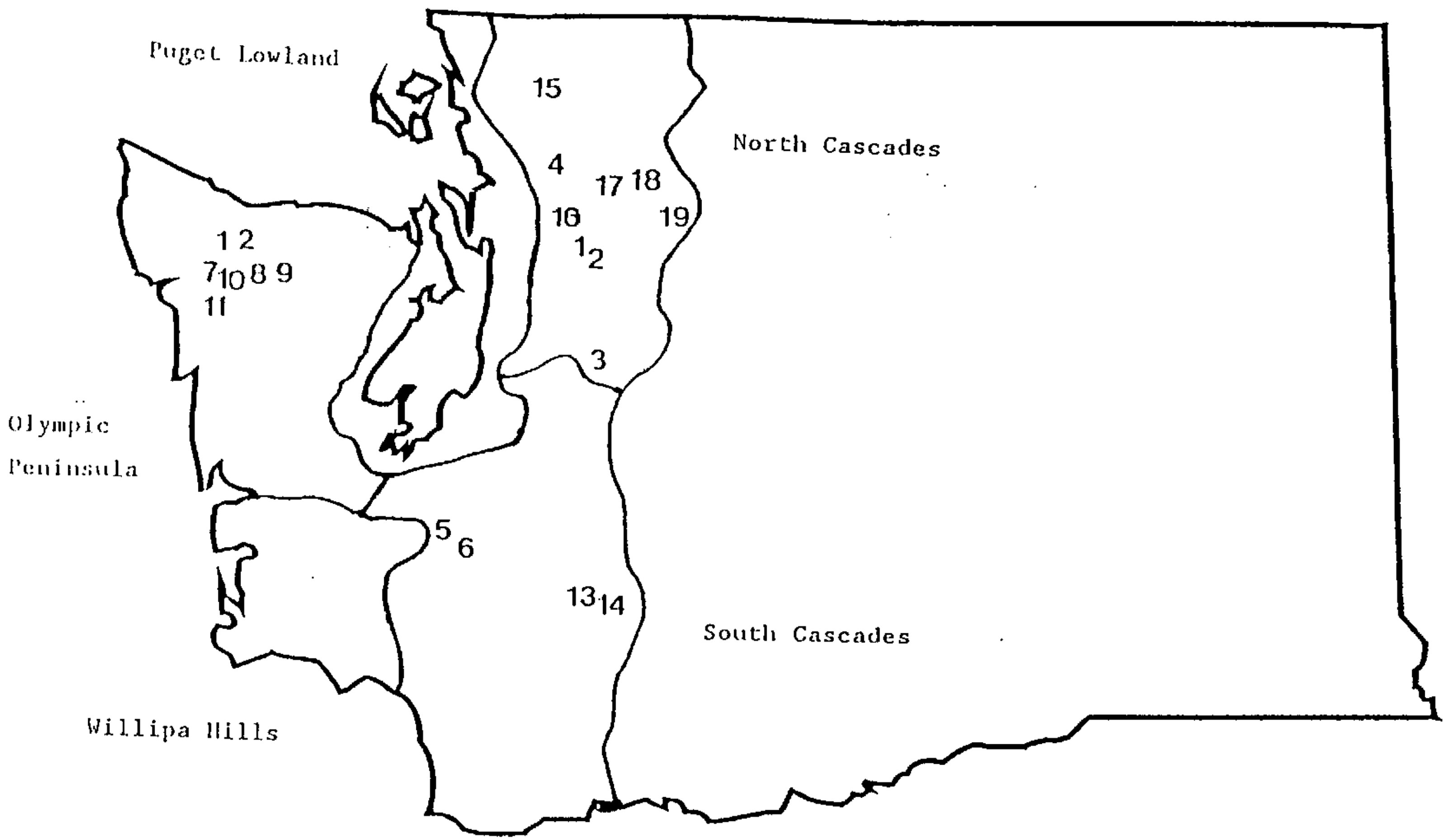

Figure 1. Locations of investigated dam-break floods within the State of Washington. Physiographic regions defined by Fiksdale and Brunengo (1980)

Table 1. Dam-break location and type; initial dam height; stream type, geometry, and order; and debris geometry.

Site Number	Creek Name	Location	Year*	Dam Type	Dam Ht (m) (init)	Stream Type	Stream Order (init)	Stream Order (dep)	Slope (deg) (init)	Slope (deg) (dep)	Width (m) (init)	Width (m) (dep)	Travel Length (m)
1	Bear1	R 8ET30NS25	1990	DF	9	3	1	3	20	2	14	36	1500
2	Bear2	R 8ET30NS25	1990	Canyon	6	3	2	3	10	2	3	36	1600
3	Carter	R10ET22NS20	1991	Organic	4	3,4,5	1	3	24	N/D	8	>100m	3300
4	DeForest	R 7ET34NS36	1990	DF	2.4	4	2	3	8	N/D	11	N/D	1800
5	Huckleberry	R 3ET15NS29	1990	DF	2.2	3,4	3	4	4	2	14	32	3600
6	Ware	R 3ET14NS12	1990	Organic	1.8	5	2	3	20	3	8	25	1900
7	Iron Maiden	R10WT26NS 5	1990	DF	N/D	1,4,5	2	3	N/D	2	N/D	>100m	1500
8	Virginia	R10WT26NS 4	1990	LS	N/D	4,5	3	3	N/D	3	N/D	30	2400
9	Split	R10WT26NS 3	1989	LS	N/D	4,5	2	3	N/D	3	N/D	50	1500
10	H1070	R10WT26NS 3	1990	LS	N/D	4	2	2	N/D	4	N/D	30	1800
11	Maple	R11WT26NS13	1990	LS	6	3,5	2	4	13	2	15	35	3600
12	Twin	R10WT27NS17	1990	LS	2	3,4,5	2	4	12	2	8	>100m	2200
13	Rainey1	R 6ET13NS31	1990	LS	3.5	3,4	3	3	12	3	8	>100m	2500
14	Rainey2	R 6ET13NS31	1990	DF	2	3,4	3	3	8	3	8	>100m	3100
15	Olsen	R 4ET38NS19	1983	Canyon	9	2,3,4	4	4	3	N/D	3	N/D	4000
16	Benson	R 8ET30NS15	N/D	DF	4	3	4	4	2.7	1.3	10	N/D	2500
17	Finney1	R 8ET34NS29	N/D	Canyon	4	3	5	6	1.3	N/D	3	N/D	20000
18	Finney2	R9ET34NS 6	N/D	DF	3	3	5	6	2	N/D	15	N/D	N/D
19	Sauk	R11ET30NS29	1986	S.G.D.	7	3	5	6	4	N/D	40	N/D	7000
20	Gywnn	R12WT15SS 6	1981	LS	7	N/D	2	3	10	3	11	N/D	2000

DF - Debris Flow
Canyon - Canyon Constriction
LS - Landslide
Organic - Logjam
S.G.D. - Slump of Glacial Deposit
N/D - Not Determinable

* - Actual Occurrence Time Unknown

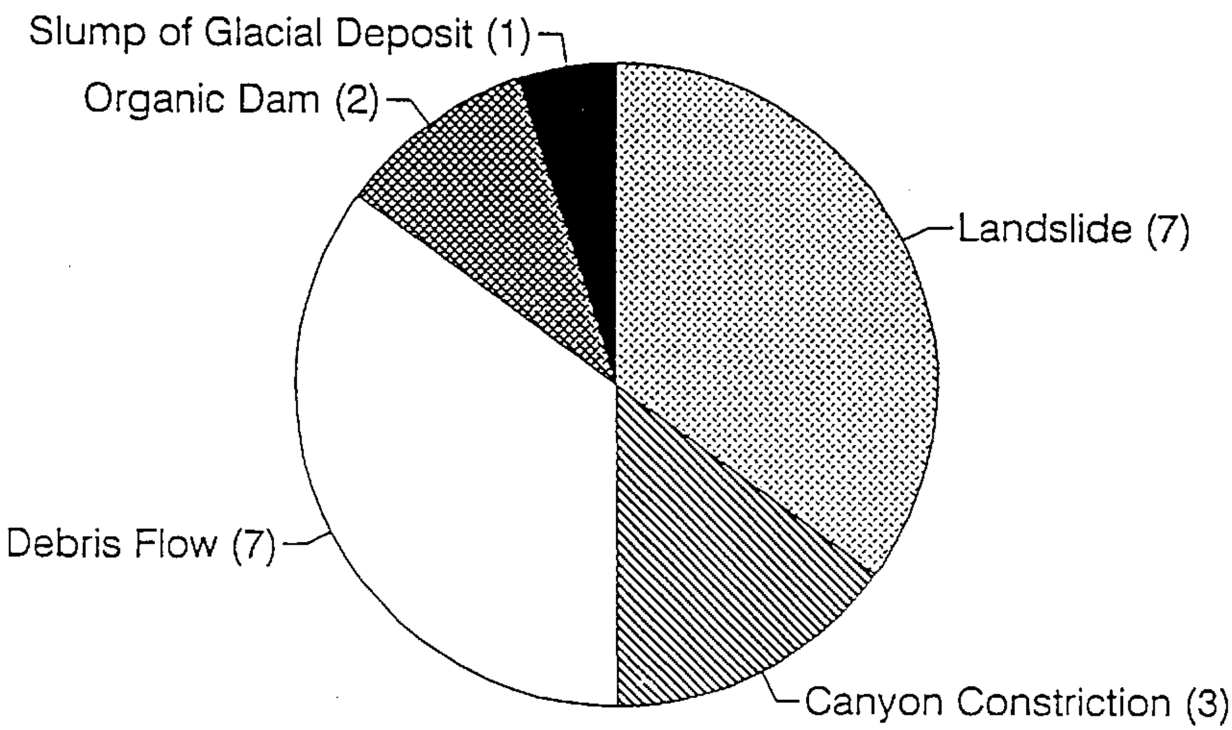

Figure 2. Number of Dam-Break Sites and Corresponding Initiation Mode.

would happen when either a debris flow deposited at the mouth of a canyon or floatable organic debris became entrapped in the canyon.

Of the twenty sites examined it appears that in two cases organic (woody debris) dams failed and caused floods. Both of these dams were located in recently clearcut basins in which the channel had large quantities of logging slash. We hypothesize that a sufficiently large water flow rate caused the intermittent mobilization of organic debris within the channel to form an alternately locally stationary then moving dam. The dam either breached sending a small flood of water and woody debris downstream, or the dam began to migrate. In either case enlargement of the dam by entraining additional debris and entraining water flow from upstream led to the large magnitude of the floods. Inspection of these initiation sites revealed a higher concentration of short, small diameter pieces of organic debris in the channel immediately upstream of the initiation site than at the sites of all other forms of initiation.

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

4.2 Valley Geometry

4.2.1 Gradient and Width at Initiation Sites

The joint distribution of channel gradient and valley width at the initiation site is plotted in Figure 3. Based on observations at twenty sites, the figure indicates that a locally low gradient and narrow valley is conducive to dam formation. Relatively low channel gradients (< 20 degrees) are necessary for deposit of landslides and debris flows (Benda and Cundy, 1990). High channel gradients may result in mobilization of landslide and debris flow sediment causing the debris flow to continue to travel down valley.

4.2.2 Gradient and Width at Deposition Sites

The joint distribution of channel gradients and valley width at deposition sites is plotted in Figure 4. Channel gradient at deposition is closely distributed around two to three degrees. Valley width at deposition

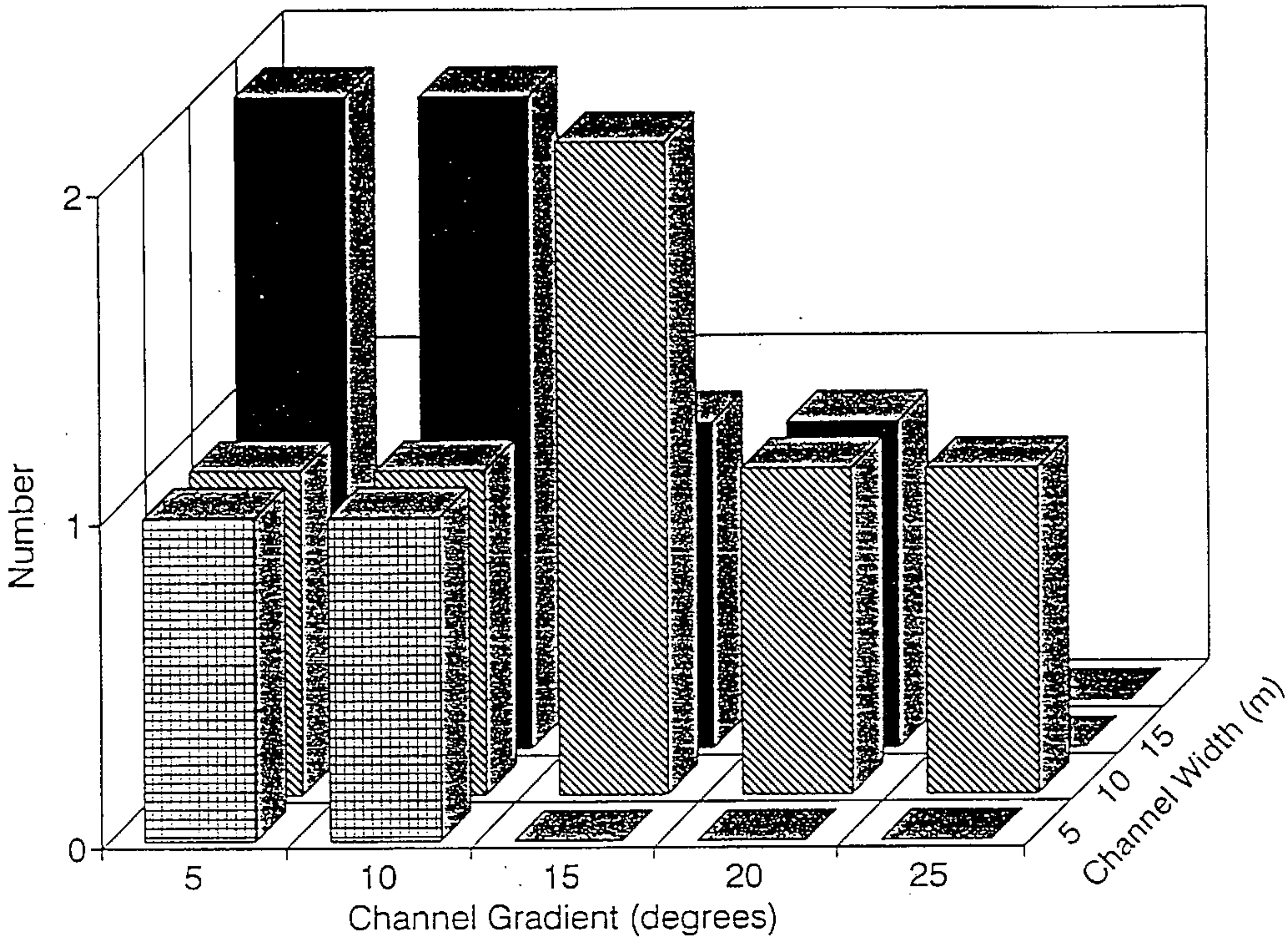

Figure 3. Number of Dam-Break Initiation Sites and Corresponding Channel Slopes and Valley Widths.

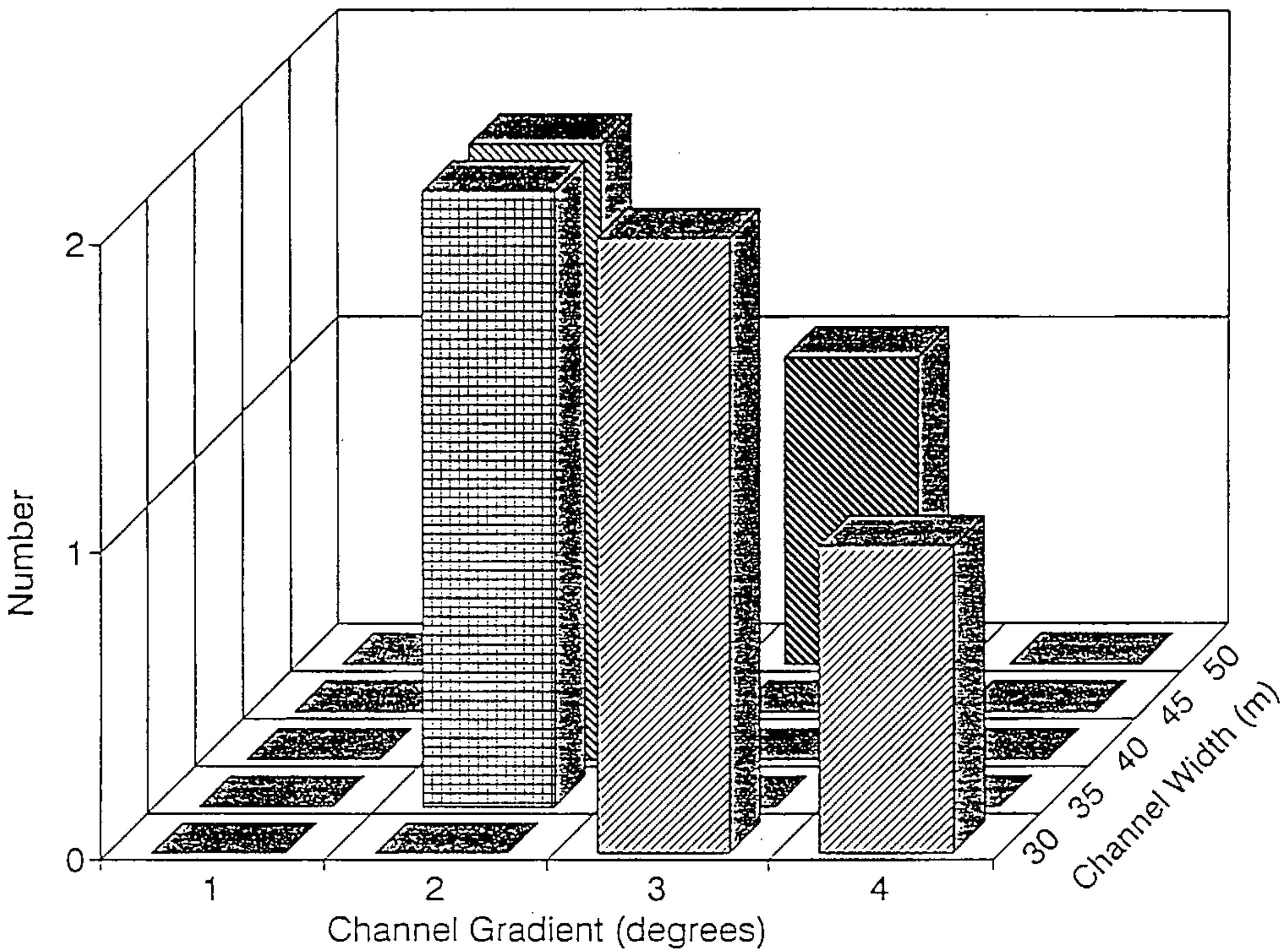

Figure 4. Number of Dam-Break Deposition Sites and Corresponding Channel Slopes and Valley Widths.

ranged from thirty to fifty meters. For the fourteen of the twenty sites where the debris dam deposition could be identified clearly, seven occurred where the local channel slope was three degrees or less. Six deposition sites had a local channel slope between two and three degrees. At the bulk of these sites the channels had Horton/Strahler stream orders of three and four and the channel widths were largely between thirty and forty meters. The corresponding upstream initiation widths were typically on the order of ten to fifteen meters.

The two variables, channel gradient and valley width at deposition, will be studied more completely in the second phase of the project for the purpose of developing a method for qualitative and quantitative prediction of the dam-break flood process in mountain drainage basins.

4.3 Classification of Streams Impacted by Dam-Break Floods

The order of streams at initiation and deposition sites of dam-break floods are presented in Figure 5. The order at initiation appears to 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 site for dam formation.

The order of the channels at the deposition locations of sediment and organic debris from the dam-break floods is a right skewed distribution that is shifted slightly to the right of the initiation curve, with a mode of third order. Of the twenty sites examined, only one flood 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 may make dam formation or sustenance unlikely.

Each stream impacted by a dam-break flood was delineated by stream order using field data and U.S.G.S. topographic maps. All stream lengths within each order were then summed to produce the results shown in Figure 6 which represents the sum of all stream orders impacted by dam-break floods. The result is a right skewed distribution with a mode of third order. Approximately 60% of the cumulative travel distance of the twenty dam-break floods occurred in valleys of orders four, five, and six (Figure 6). (More

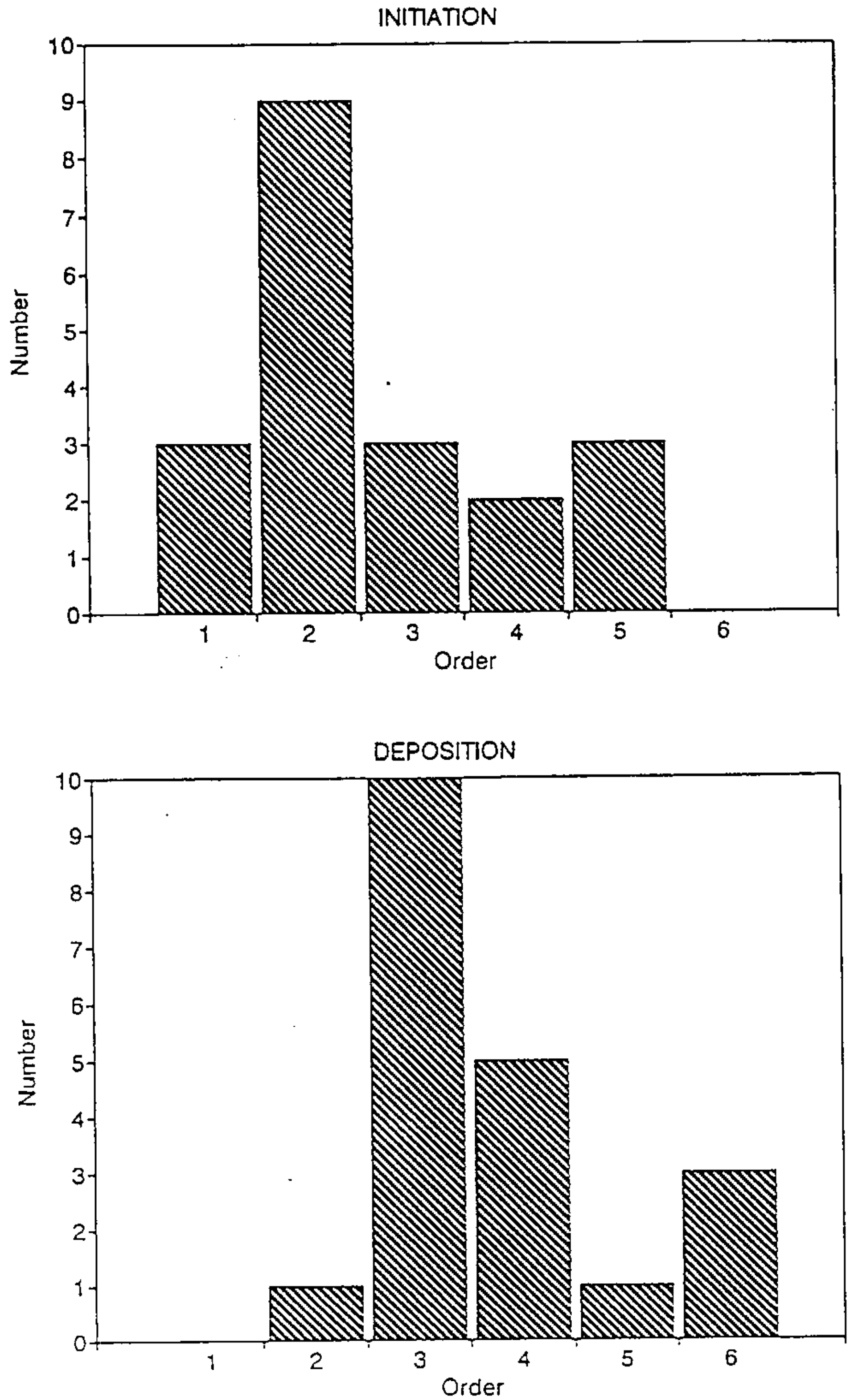

Figure 5. Stream Order at Initiation and Deposition (Data from Table 1).

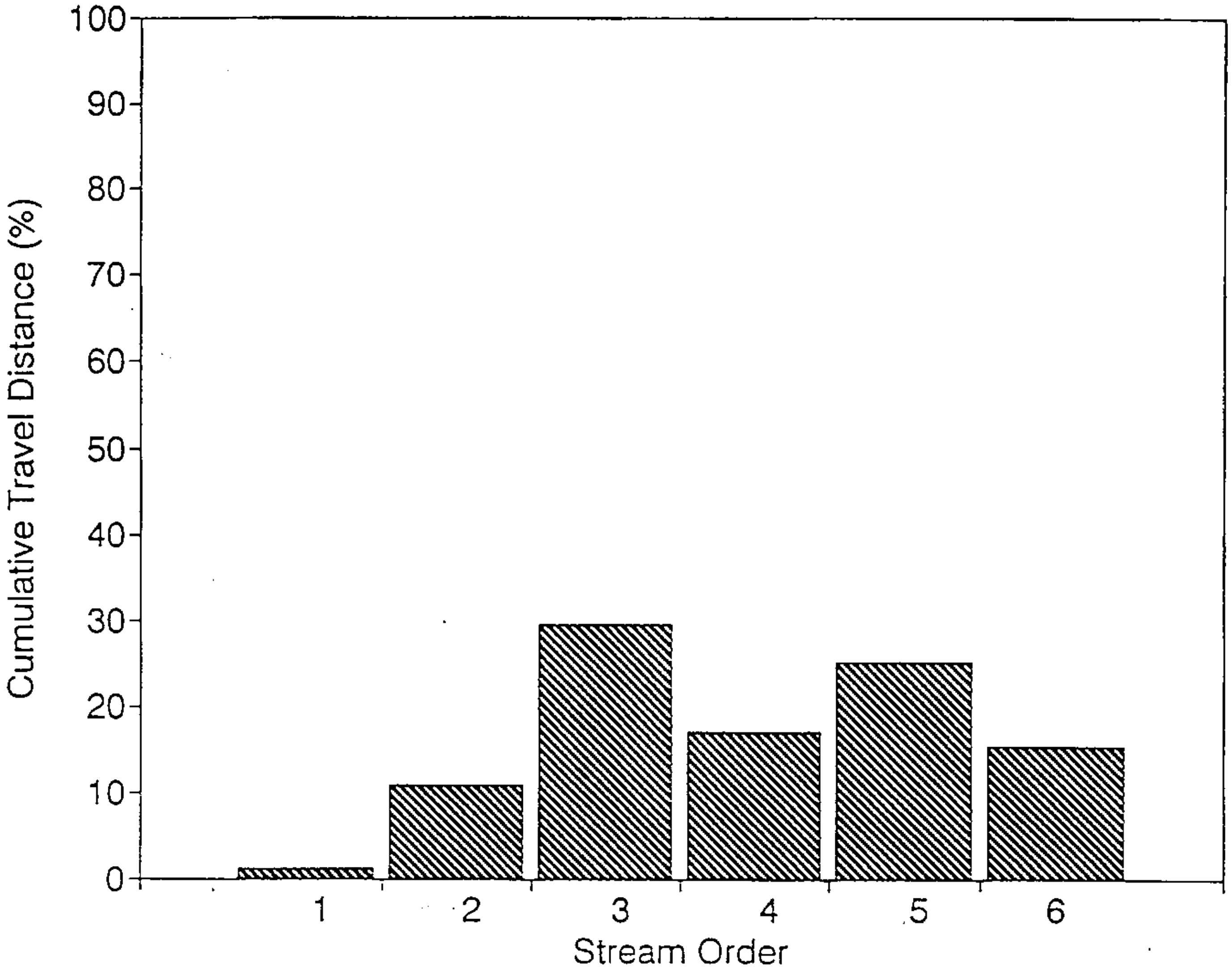

Figure 6. Percentage of Cumulative Travel Distance Versus Stream Order (data from Table 1).

completed information for each site is given in Table 3). Dam-break floods that begin in low order channels (Figure 5) may eventually travel through long distances of higher order low gradient valley floors influencing riparian vegetation and aquatic habitat during and after their passage.

4.4 Stream Types Impacted by Dam-Break Floods

Each stream impacted by a dam-break flood was delineated by stream type using D.N.R. Stream Type Maps. All lengths within each type were summed and the results plotted in Figure 7. The distribution has an approximate mean of Type 3. This D.N.R. classification represents anadromous fish habitat.

4.5. Travel Distance of Dam-Break Floods

The number of dam-break floods and corresponding travel distances are shown in Figure 8. Most of these floods travelled between two and four kilometers with the extreme event of Finney Creek travelling over twenty kilometers. The length of dam-break flood events in managed forests appear to be controlled by the network geometry of channels in mountain drainage basins. Because dam-break floods attenuate and deposit where the valley widens, such as tributary junctions, the length of the flood should reflect the length of individual stream order segments which is on the order of two to four thousand meters (Figure 8).

4.6 Impacts on Resources Caused by Dam-Break Floods

4.6.1 Effects of Dam-Break Floods on Riparian Vegetation

Dam-break floods can be extremely damaging to riparian vegetation. Johnson (1991) documented these effects in a recent TFW funded research project.

The majority of dam-break floods inventoried in managed forests did not encounter old growth trees on the valley floor because these trees have been previously logged as evidenced by numerous stumps. The dam-break floods encountered numerous Alder, which are commonly found in the riparian zones of managed forests. The Alder were downed and sheared off by the moving debris relatively easily compared to conifers of similar diameter. Twin Creek, Site 12, is the only site surrounded by old growth timber from the headwaters to the site of deposition of organic debris. The moving wedge of organic debris

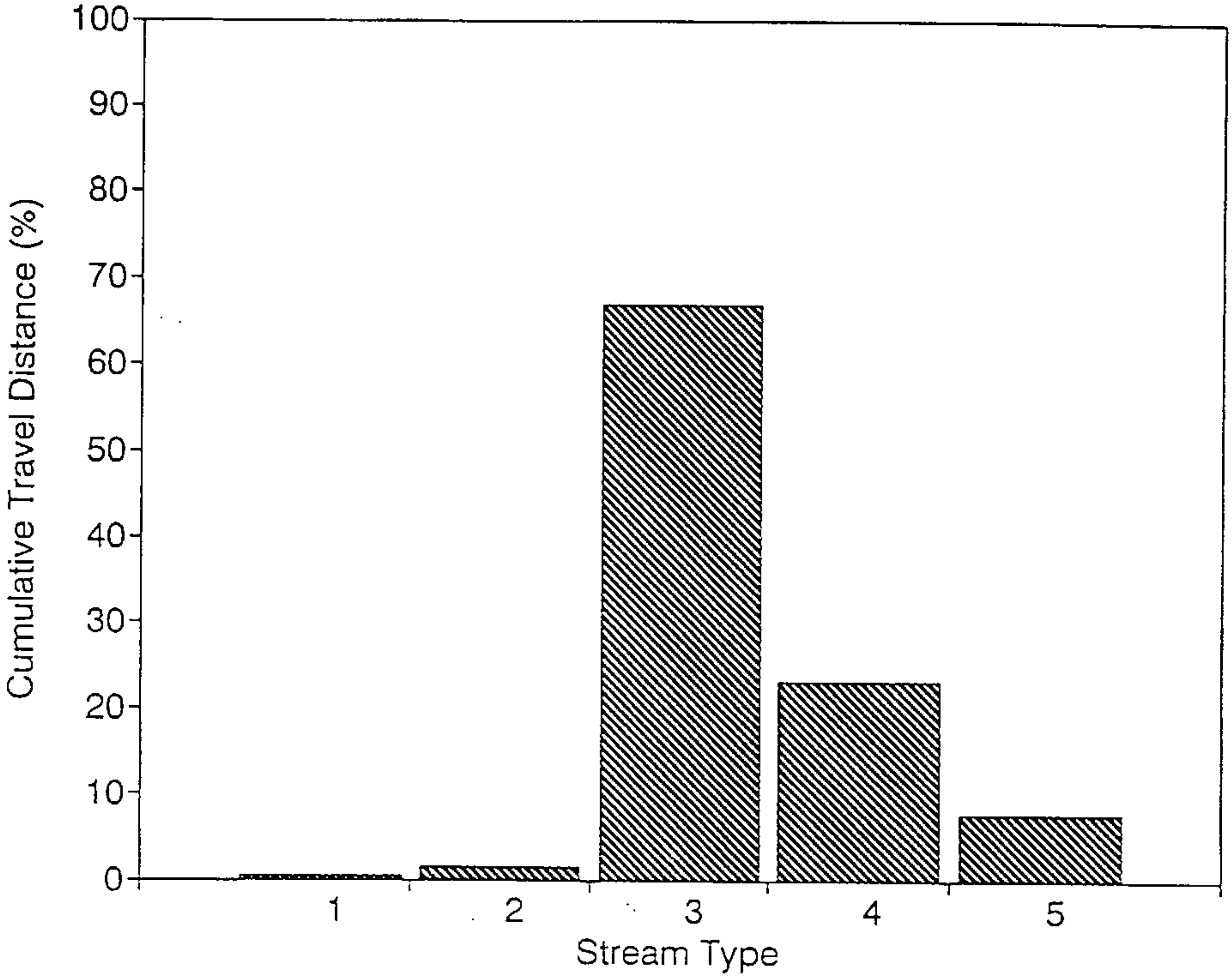

Figure 7. Percentage of Cumulative Travel Distance Versus Stream Type (Data from Table 1).

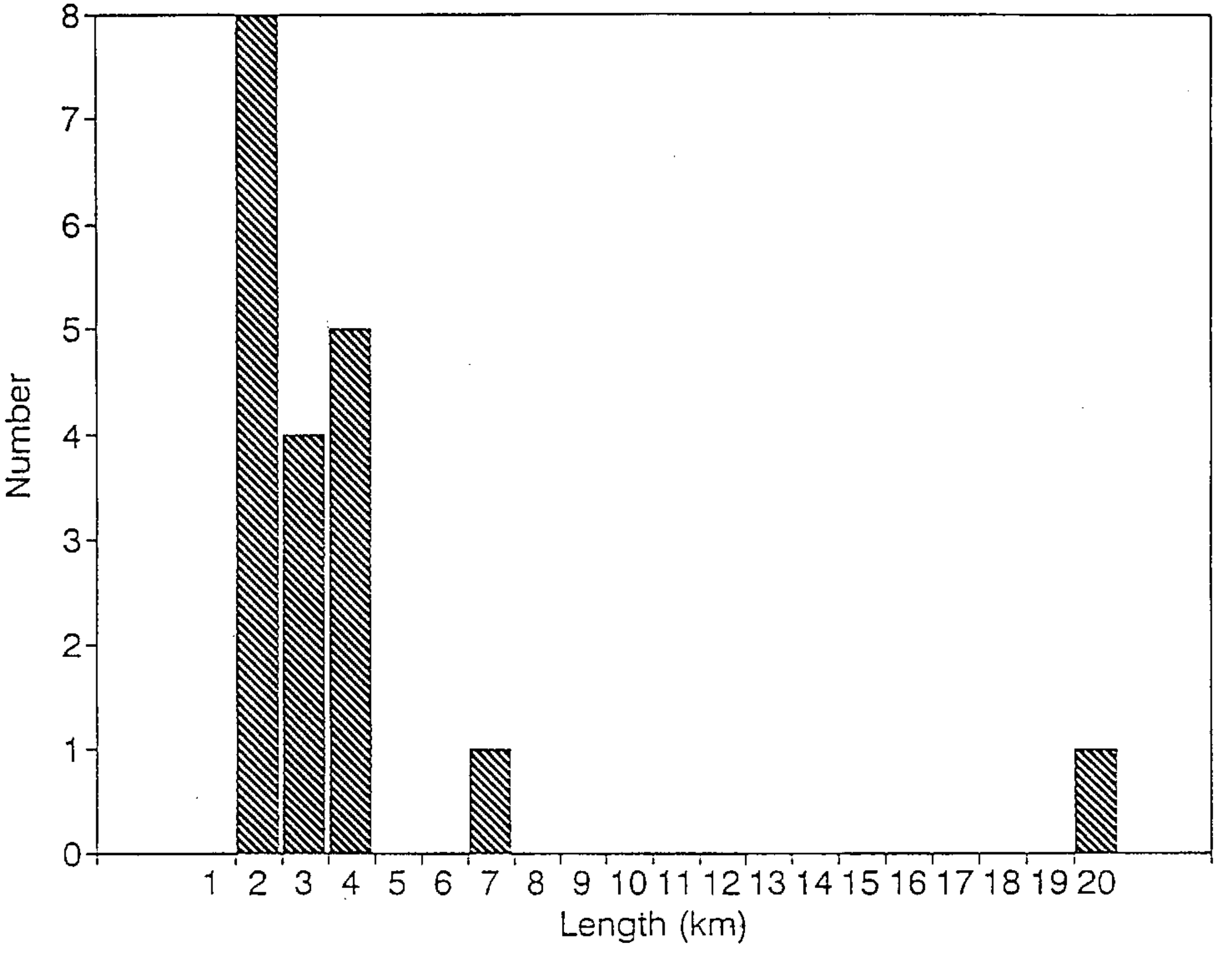

Figure 8. Number of Dam-Break Floods Versus Debris Transport Distance.

appeared to have been prevented from further migrating down Twin Creek by conifers growing adjacent to the channel. These conifers were on the order of 30 cm BHD (breast height diameter) and were no larger than much of the Alder trees that were unable to withstand the forces of the migrating organic dams that travelled through the managed forests.

4.6.2 Effects of Dam-Break Floods on Fisheries and Structures

Table 2 shows a summary list of the effects of these dam-break floods on fisheries and structures. Eleven of the twenty streams provided habitat for anadromous species before the floods occurred. The habitat appeared severely disrupted after the occurrence of the floods. Habitat for resident species was impacted similarly. The long term effects of these floods on fish habitat is unknown.

Figure 9 shows the relative impact on various engineered structures. Twelve forest roads were damaged by nine dam-break floods. In a few cases, the floods travelled through more than one road crossing. Most of the dam-break floods travelled between two to four kilometers (Figure 8) which is no longer than the distance between road crossings on some streams in managed forests.

Three state highways and one railroad grade were damaged by dam-break floods. In the narrow valleys of the Cascade and Olympic Mountains, main thoroughfares often pass very near the mountain fronts making them susceptible to effects from dam-break flooding.

At least five private dwellings were damaged from the floods. All of these dwellings were built on alluvial fans.

4.7 Significant Differences Between Dam-Break Floods and Debris Flows.

Debris flows and dam-break floods are two of the most damaging processes that occur within streams in managed forests in mountain drainage basins in the Pacific Northwest. It is important to differentiate between them for the purposes of hazard prediction. A model for predicting the initiation and travel distance of debris flows for confined mountain valleys in the Pacific Northwest was developed by Benda and Cundy (1990). No such model is available for dam-break floods. Figure 10 illustrates some of the differences between dam-break floods and debris flows, and indicates the need to consider these events separately. The frequency distribution for debris flows is recreated

Table 2. Resources Impacted by Dam-Break Floods.

		FISHERIES	STRUCTURES	
Site Number	Stream Name	Population Type	Type	Stuctural Damage
1	Bear1	anadromous	State Highway 92	damaged
2	Bear2	resident	"	"
3	Carter	resident	Railroad Grade, 2 service roads	"
4	DeForest	resident	1 forest road	"
5	Huckleberry	anadromous	3 forest roads	"
6	Ware	resident	1 forest road	"
7	Iron Maiden	anadromous	"	"
8	Virginia Falls	anadromous	"	"
9	Split	anadromous	"	"
10	H1070	anadromous	"	"
11	Maple	resident	2 forest roads	"
12	Twin	resident	no damage	no damage
13	Rainey1	resident	State Highway 12	damaged
14	Rainey2	resident	"	"
15	Olsen	resident	private dwellings	destroyed
16	Benson	anadromous	private dwellings	"
17	Finney1	anadromous	no damage	no damage
18	Finney2	anadromous	"	no damage
19	Sauk	anadromous	forest roads	damaged
20	Gwynn	anadromous	State Highway 1, private dwelling	damaged

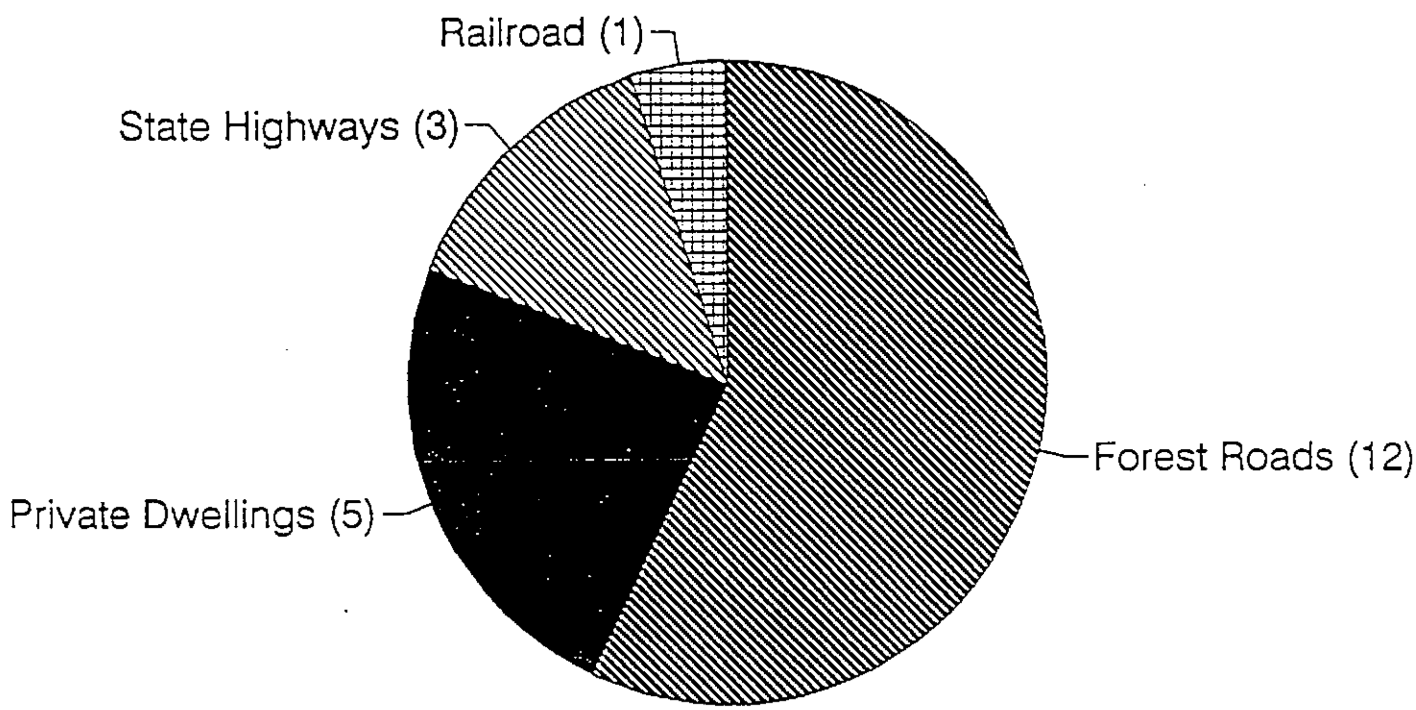

Figure 9. Numbers and Type of Engineered Structures Damaged by Dam-Break Floods.

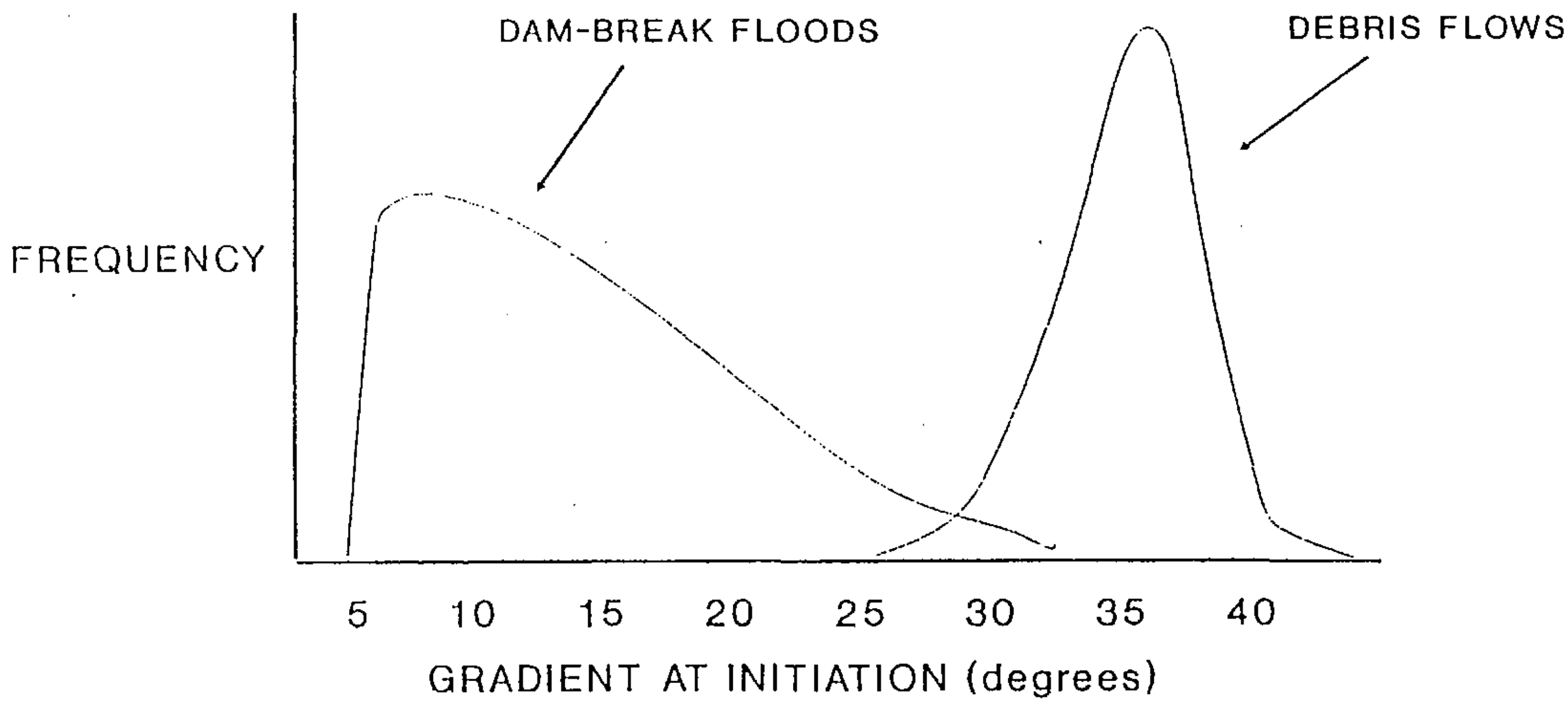

Figure 10. Approximate Frequency Distribution of Gradients at Initiation of Dam-Break Floods and Debris Flows.

from Benda (1988). One of the major objectives of our ongoing proposed research is to develop predictive tools that can be used by land managers for determining what stream features are likely to be associated with dam-break floods and their run out characteristics.

Initiation gradients vary significantly between debris flows and dam-break floods as shown in Figure 10. Debris flows originate typically on hillslopes and travel through first and second order channels. Dam-break floods were shown to originate in stream orders one through five.

The lengths and orders of channels affected by dam-break floods are summarized in Table 3. In that table we show 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. The dam-break floods are associated with first to sixth order channels. It is clear that significant habitat impacts of dam-break floods occur in second and third order channels (fourteen out of twenty failures examined) with the majority of the impact in the 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 higher order channels.

5.0 SUMMARY

Dam-break floods are a common occurrence in low order mountain channels in the managed forests of the Cascade and Olympic Mountains. The dams consist of landslide or debris flow materials but may also be solely composed of organic debris. The floods from the breaching of these dams initiated in stream orders one through five and propagate through stream order six. The flood wave accumulates woody debris in the channel as it propagates downstream which can greatly increase the volume of water impounded in the immediate vicinity of the moving dam. Length of travel is on the order of several kilometers so often roads and engineered structures are damaged in the process. Anadromous and resident fisheries habitat are impacted by these floods.

Table 3. Stream Location, Debris Travel Distance, and Relative Fraction of Stream Length Associated with Each Stream Order.

Site Number	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 Falls	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	20000					80	20
18	Finney2*	---					30	70
19	Sauk	7000					10	90
20	Gywnn	2000		10	90			

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